MULTIPLE-SATELLITE STUDIES OF MAGNETOSPHERIC SUBSTORMS: PLASMA SHEET RECOVERY AND THE POLEWARD LEAP OF AURORAL ZONE ACTIVITY

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Abstract. Particle observations from pairs of satellites (Ogo 5 and Vela 4A and 5A) during 28 plasma sheet thickening events are examined. These data indicate that thickening of the nighttime plasma sheet during substorms occurs in two main stages, one early stage of single or multiple expansions of the near-earth (geocentric distances r $\lesssim$ 15 R_E) plasma sheet at the onset of substorm expansions (Pi 2 bursts) on the ground and another later stage of plasma sheet recovery that starts near the time of maximum auroral zone bay activity and is characterized by a large-scale thickening toward higher latitudes that occurs over a broad azimuthal scale and from ionospheric heights to beyond the Vela orbit (r $\sim$ 18 R_E). A detailed analysis of two-satellite observations during eight plasma sheet recoveries is presented, showing events that occurred within 5 min in widely separated locations at small (<4 R_E) distances from the tail's midplane and events that occurred concurrently in the Vela orbit and at high latitudes in the near-earth region. Some events were accompanied by clear signatures of a poleward leap (to >71^o magnetic latitude) of electron precipitation and the westward electrojet that probably corresponded to an expansion poleward of the ionospheric projection of the recovering plasma sheet. The eight plasma sheet recoveries occurred 10-30 min after a Pi 2 burst on the ground, and mid-latitude magnetograms showed no indications of a near-coincident formation of a substorm current wedge in the local time sector of the spacecraft; this indicates that the plasma sheet recoveries and the poleward leaps were not caused directly by a late high-latitude substorm expansion. Instead, these phenomena seem to represent a transition phase between a substorm expansion sequence and a substorm recovery.

Introduction

Recent studies of the magnetospheric substorm using ground magnetic and auroral observations have revealed that substorms often have multiple expansion phase onsets [Kisabeth and Rostoker, 1971; Clauer and McPherron, 1974; Wiens and Rostoker, 1975; Pytte et al., 1976a, b; Kamide et al., 1977] and that the westward polar electrojet sometimes expands westward in an impulsive, steplike fashion [Wiens and Rostoker, 1975]. The latter feature would indicate a similar steplike progression of activity also in the geomagnetic tail, as was originally suggested by Rostoker and Camidge [1971]. However, examinations of the plasma sheet dynamics in the near-earth region (r $\lesssim$ 15 R_E) [Pytte et al., 1976a] and in the Vela orbit (r $\sim$ 18 R_E) [Hones et al., 1967, 1973, 1976] have shown no clear evidence of such azimuthally localized phenomena in the tail. Thus the plasma sheet expansion signatures in the near tail during multiple-onset substorms, as observed by a single satellite near midnight, are nearly identical for each onset; there seems to be no systematic change with time indicative of successive onsets occurring in separate or in progressively westward moving sectors. In the more distant tail, where the plasma sheet thins during this early phase of the substorm, the most spectacular event is the plasma sheet recovery to about or greater than presubstorm thickness. This recovery too is apparently not localized but may cover a significant fraction of the tail's breadth [Hones, 1973].

Another apparent discrepancy between current substorm models based on ground data and models based largely on plasma sheet observations is the absence of any specific reference in almost all ground models to the 'poleward leap' of auroral zone activity. This phenomenon occurs late in substorms and is characterized by a sudden poleward displacement of bright auroras and of the westward electrojet from auroral zone (65^o-70^o) to low polar cap ($\sim$75^o) magnetic latitudes [e.g., Hones et al., 1970, 1971; Wolcott et al., 1976]. This same phenomenon is apparently responsible for the recently identified poleward displacement (to $\sim$75^o) of a detached region of field-aligned currents that seems to occur near the time of maximum auroral zone bay activity [Iijima and Potemra, 1978]. However, it may be significant that the identification of a poleward leap seems to have been aided by the observed close temporal relation of these auroral and ground magnetic signatures with the recovery of the plasma sheet in the Vela orbit [Hones et al., 1973, and references therein]; auroral data and standard magnetograms alone are often not sufficient to distinguish the poleward leap from a high-latitude substorm expansion. The incorporation of the leap as a separate phenomenon in ground substorm models therefore seems to depend on the existence of a set of ground signatures by which these phenomena can be separated. If no such signatures exist, it would indicate that the recovery of the plasma sheet in the Vela orbit is due simply to a

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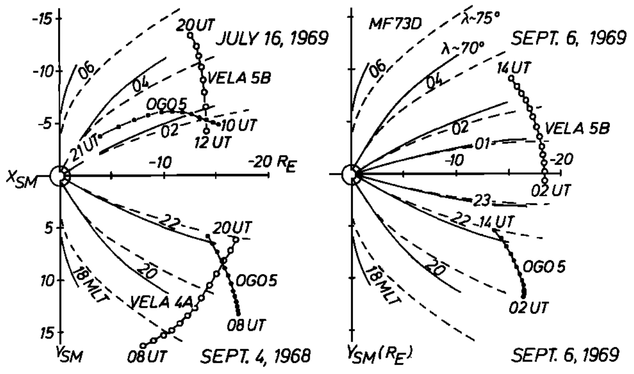

Fig. 1. GSM equatorial projections of satellite orbits during the intervals studied in this paper, superimposed upon the projections of magnetic field lines in the Mead and Fairfield [1975] MF73D model for 0° dipole tilt.

substorm expansion that involves also the plasma sheet at r ∿ 18 R_E.

The purpose of the present paper is to analyze these differences in current substorm models and to examine the nature of the poleward leap. To do this, we first show examples of clear signatures of a poleward leap (at the time of plasma sheet recovery) that were not accompanied by ground Pi 2 magnetic pulsations; this absence of Pi 2's appears to be an important feature which separates the poleward leap from a substorm expansion. Next we present a detailed analysis of eight cases of plasma sheet recovery in different local time sectors of the tail that occurred near the time of maximum auroral zone bay activity but from 10 to 30 min after the last in a series of Pi 2. Six of these recoveries were observed within a time interval of less than 5 min by two satellites located at relatively small distances from the tail's midplane (dZ ≲ 4 R_E). The absence of a near-coincident Pi 2 burst is a clear indication that the plasma sheet recoveries too were not caused by a substorm expansion. Finally, we show that the plasma sheet recovery is not localized but may occur at widely spaced satellites (>15 R_E east-west) and extend from the Vela orbit to the high-latitude near-earth region of the tail. These spatial characteristics, which appear to differ from those observed during substorm expansions, do not indicate westward progressing or azimuthally localized plasma sheet phenomena in the tail. A model for plasma sheet dynamics during substorms based on these observations is therefore proposed.

Data

The magnetotail measurements used in this paper were obtained from the Ogo 5 and Vela 4A and 5B satellites. Brief descriptions of the relevant instruments are given by West et al. [1973], Hones et al. [1972], and Bame et al. [1971].

We have selected for detailed presentation eight substorm intervals during periods of continuous tracking of the Ogo and Vela satellites. The geocentric solar magnetospheric (GSM) equatorial projections of satellite trajectories are shown in Figure 1, superimposed upon the projection of field lines in the Mead and Fairfield [1975] magnetospheric field model for magnetically disturbed conditions (Kp ≥ 2). These field lines intersect the earth at 70° (solid curves)

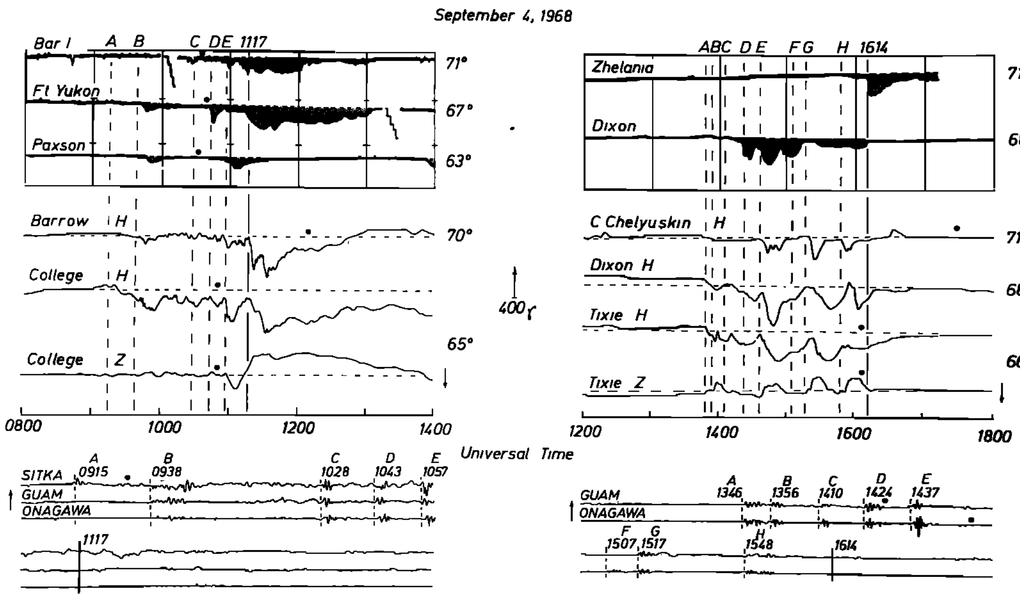

Fig. 2. Auroral zone riometer recordings (upper panels) and magnetograms (middle panels) and magnetograms (middle panels), together with high-pass-filtered rapid run magnetograms from mid-latitude and low-latitude stations (bottom panels) during two substorm intervals on September 4, 1969. Vertical dashed lines mark substorm expansion onsets as identified by the Pi 2 bursts; vertical solid lines mark the start of a poleward leap of auroral zone activity to ≳71° corrected magnetic latitude. Local magnetic midnight (eccentric dipole time), indicated by dots, is at ∿1830 at Dixon and at ∿1905 UT at Zhelania.

and 75° (dashed curves) magnetic latitudes and serve to approximately map the satellite locations to the ground.

While previous studies of Ogo 5 particle measurements have established the occurrence of a near-earth expansion of the plasma sheet at the onset of substorm expansion [Aubry et al., 1972; Kivelson et al., 1973; Buck et al., 1973; Nishida and Fujii, 1976; Pytte et al., 1976a; Pytte and West, 1978], the Ogo data presented here were obtained at such high magnetic latitudes or in the more distant regions of the tail where these substorm onset expansions, for reasons discussed below, are apparently not seen. Instead these data show plasma sheet thickening events of the type previously known mainly from studies of Vela data. Since the two types of thickening events appear to have different spatial and temporal characteristics, we shall refer to a thickening during ground-identified substorm expansions as a plasma sheet expansion and refer to thickening presumably correlated with a poleward leap as a plasma sheet recovery, though the leap itself may not always be identified in available ground data.

Our timing of substorm expansion onset is determined by the onset of Pi 2 magnetic pulsations; such bursts have been shown to be closely related to individual onsets of auroral and polar magnetic substorms [Rostoker, 1968; Saito, 1969; Pytte et al., 1976a, b; Sakurai and Saito, 1976]. Since there are some questions as to the localized nature of Pi 2's, we have used recordings from two or more stations at middle and low latitudes separated in longitude by from ∿30° to ∿75°.

The approximate longitudinal region of the substorm current wedge at the times of Pi 2's and at the times of plasma sheet recoveries is determined on the basis of its characteristic signatures in ground mid-latitude standard magnetograms [McPherron et al., 1973; Wiens and Rostoker, 1975; Pytte et al., 1976b].

Observations

Multiple-Onset Substorms on September 4, 1968

Figure 2 shows auroral zone magnetograms and riometer recordings, together with mid-latitude and low-latitude magnetic pulsation data, during two substorm intervals on September 4, 1968. During the 0915 UT substorm (left panel) there were five separate bursts of Pi 2 pulsations, each of which we regard as the onset of a substorm expansion. At ∿1117 UT, about 20 min after the last Pi 2, a sharp bay intensification occurred at College and Barrow. The Z recordings at College suggest a poleward shift of the center of the westward electrojet at about that time, from south ($\Delta Z > 0$) to north ($\Delta Z < 0$) of College. Furthermore, a few minutes earlier the region of ≳30-keV electron precipitation had expanded poleward to at least 71° latitude (Bar I in the upper left panel). These are the typical signatures of a poleward 'leap' of auroral zone activity.

Similar features are found also during the subsequent 1346 UT substorm (right panel), during which eight Pi 2 bursts were observed. At

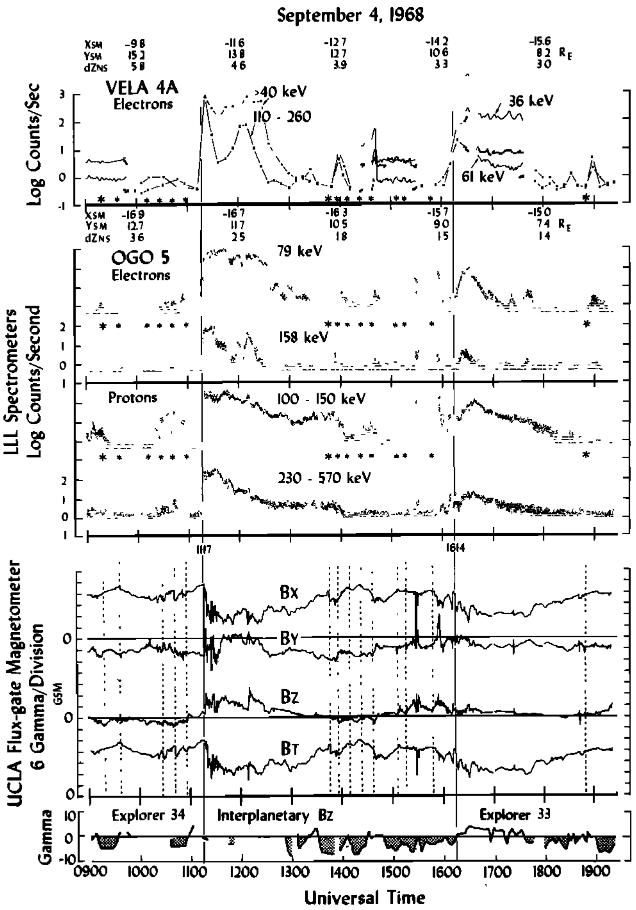

Fig. 3. Observations of energetic particles and magnetic field at Ogo 5 and of particles at Vela 4A at 1800-2200 MLT in the tail on September 4, 1968. Distances from the estimated position of the tail's midplane (dZ_{NS}) are calculated by using the Fairfield and Ness [1970] formula. Discrete Vela data points were obtained during low bit rate tracking. Vertical dashed lines and asterisks mark the times of ground Pi 2 bursts. The IMF B_Z data (bottom panel) were obtained from the Explorer 34 (before 1400 UT, located at ∿20 R_E near noon) and the Explorer 33 satellites (after 1400 UT, at high latitudes near the front of the magnetosphere).

∿1614 UT a sharp onset of precipitation was detected at Zhelania, indicating a poleward leap of the precipitation region to higher latitudes as bay activity subsided in the auroral zone. In this case there was no clear signature of a poleward shift of the current system, but the positive H disturbances at Cape Chelyuskin around 1630 UT indicate continued activity to the north of that station. We therefore believe that a poleward leap occurred at ∿1614 UT, about 25 min after the last Pi 2.

Figure 3 shows measurements of magnetic field and energetic particles at Ogo 5 and measurements of particles at Vela 4A in the evening sector of the magnetotail during these two substorm intervals; the GSM spacecraft locations are given at the top of the two upper panels. The vertical solid lines at 1117 and 1614 UT mark the observed beginning of the most notable magnetotail event at these radial distances, namely, the recovery

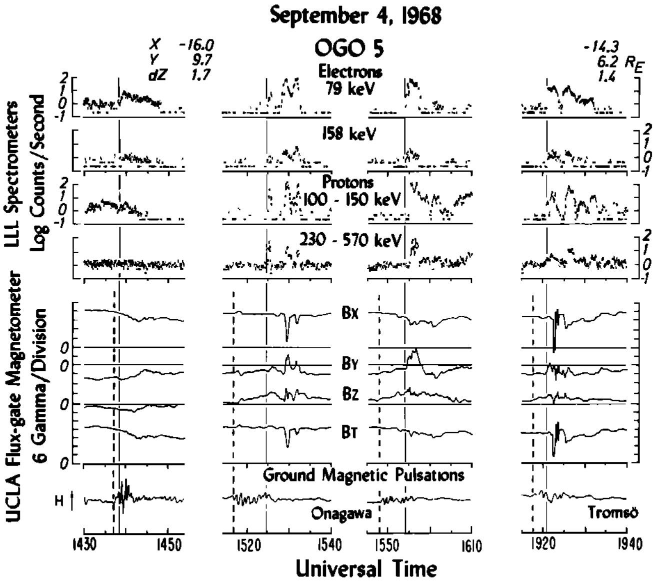

Fig. 4. Details of transient electron and proton bursts observed at Ogo 5 in the evening sector of the tail during Pi 2 activity on the ground.

of the plasma sheet [Hones et al., 1967]. At these times there was a large increase in particle intensities at both Ogo and Vela, indicating a thickening of the plasma sheet as its outer boundaries expanded away from the tail's midplane. Earlier, we found that activity in the auroral zone near midnight expanded to higher latitudes ($\Lambda > 71^{\circ}$) around both 1117 and 1614 UT. This is the same close relationship between the plasma sheet recovery and the poleward leap that was found in a number of previous cases [Hones et al., 1970, 1971, 1973; Wolcott et al., 1976]. Here we see that the recoveries occurred well (∿20 min) after the last in a series of Pi 2 bursts.

It is interesting here to estimate the approximate direction of propagation of the expanding plasma sheet boundary. During the 1117 UT encounter at Ogo there was a sharp positive (westward) deflection in the B_Y component, which we interpret as being due to field-aligned currents that were directed away from the earth and located near the expanding boundary. If the boundary currents define an extended current sheet, the sheet normal is defined by $\underline{B} \times \Delta\underline{B}(t)$, where $\underline{B}$ is the unperturbed field and $\Delta\underline{B}$ is the perturbation caused by the sheet currents. Just before the satellite's entry into the plasma sheet the boundary apparently was nearly parallel to the GSM X-Y plane, the sheet normal pointing northward and a few degrees tailward. This almost horizontal boundary indicates that the plasma sheet expanded essentially in the Z direction, which is consistent with two-satellite observations during other substorms presented below.

Preceding these plasma sheet recoveries, there were some transient (5- to 10-min duration) increases in electron and proton fluxes. Three successive particle events are shown in Figure 4, together with another similar event observed during the weak substorm starting around 1850 UT. These particle bursts occurred shortly after a Pi 2 on the ground, but there was no systematic shortening of the time delays between Pi 2's and particle burst onsets suggestive of a source region located progressively closer to the Ogo satellite. Our interpretation of these transient bursts is discussed in the summary and discussion section of this paper.

The bottom panel of Figure 3 shows the interplanetary magnetic field (IMF) B_Z component observed by Explorers 33 and 34. The available data show that the IMF was predominantly southward during the multiple substorm expansions and that the 1614 UT recovery occurred near the time of a clear northward turning of the field.

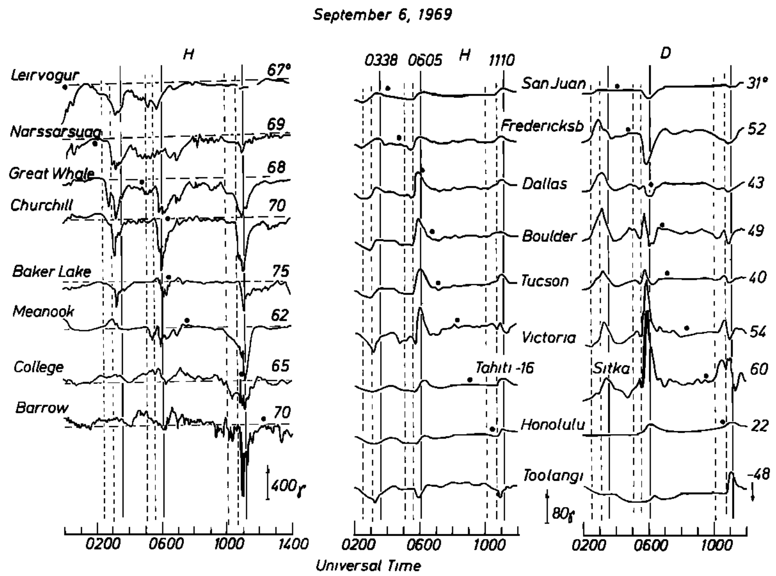

Fig. 5. Auroral zone and mid-latitude magnetograms on September 6, 1969. Vertical dashed lines indicate substorm expansion onsets, and solid lines onsets of plasma sheet recovery at Ogo 5 (see Figure 6). Corrected magnetic latitudes are given for each station.

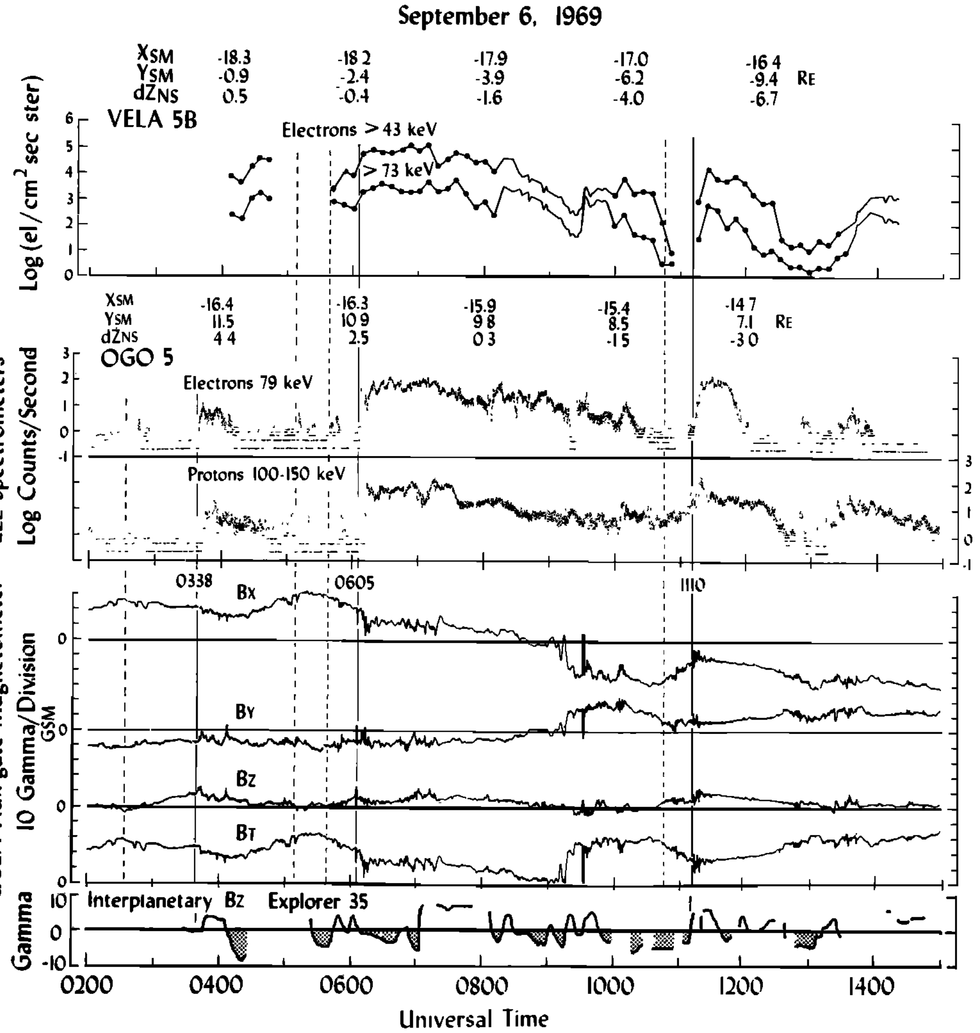

Fig. 6. Observations of plasma sheet recoveries at Ogo 5 (2000-2200 MLT) and Vela 5B (0000-0300 MLT) on September 6, 1969. Vertical dashed lines indicate onsets of substorm expansions on the ground. The bottom panel shows the IMF B_Z component at Explorer 35 ($\sim$60 R_E from the earth at $\sim$0800 LT).

Multiple-Onset Substorms on September 6, 1969

The previous two examples of plasma sheet recovery were observed when the two satellites were located in the evening sector of the tail. The recoveries could therefore have been due to a westward shift or expansion of the disturbed sector of the tail to include the locations of the satellites rather than covering a large range of local time as we have suggested. To study this possibility further, we next present observations obtained on September 6, 1969, when one satellite was located in the early evening sector and another in the early morning sector of the tail. In contrast to the two previous events the events on this day were also accompanied by clear mid-latitude magnetic signatures. These signatures allow us to estimate the longitudinal location and extent of the substorm current wedge.

Figure 5 shows the auroral zone (left panel) and mid-latitude (center and right panels) magnetograms during three substorm intervals on this day. The three substorms starting at about 0232, 0507, and 1006 UT where characterized by a rather rapid growth and decay of auroral zone bay intensities. The associated recoveries of the plasma sheet at Ogo, marked in Figure 5 by solid vertical lines, occurred near or just after the time of maximum ground magnetic activity and about 30, 10, and 25 min, respectively, after the last clear Pi 2 onset (Pi 2's are marked by dashed vertical lines).

The simultaneous Ogo 5 and Vela 5B measurements obtained at 2000-2200 and 0000-0300 MLT, respectively, are shown in Figure 6. The Ogo particle data exhibit plasma sheet variations similar to those observed in the same local time sector on September 4, 1968 (see the previous subsection). Again this demonstrates that the eveningside plasma sheet at these radial distances remains thin during the expansion phase except for short-duration bursts of particles during Pi 2 activity on the ground. At the time of the second (0605 UT) plasma sheet recovery at Ogo, the Vela satellite was probably very close to the tail's midplane, and the flux dropout that usually precedes a plasma sheet recovery was therefore not seen at Vela in this case. However, the particle fluxes did recover to higher

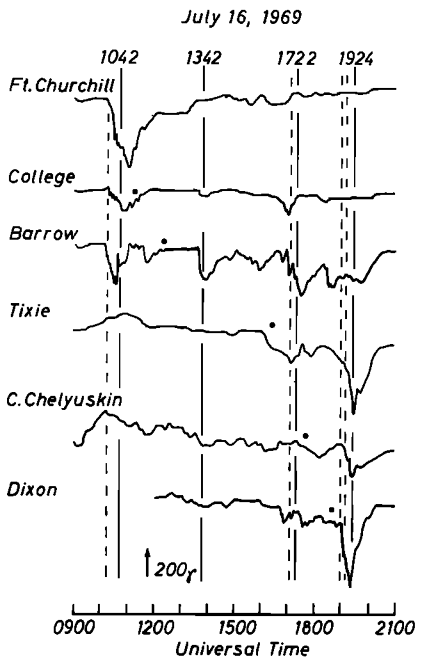

Fig. 7. Auroral zone magnetograms on July 16, 1969. Vertical dashed lines mark substorm expansion onsets, and solid lines onsets of plasma sheet recovery at Ogo 5 (see Figure 8).

stable levels within minutes of the recovery at Ogo. The 1110 UT recovery, on the other hand, was seen clearly also at Vela and therefore occurred over a local time sector of at least 5 hours ($\gtrsim$15 R_E east-west). This near simultaneity of plasma sheet recoveries over this large region of the tail, which we consider quite remarkable, clearly demonstrates the large-scale character of such events. The plasma sheet was also thinning near both satellites before the main bay intensification at ∿1046 UT.

The mid-latitude magnetic signatures shown in Figure 5 indicate that the 0605 and 1110 UT plasma sheet recoveries occurred near the time when the western edge of the substorm current wedge (defined as the region of maximum D perturbations) had reached the local time sector of Ogo (Honolulu at about 2000 MLT and Toolangi at about 2100 MLT for the two substorms). However, the recovery at Ogo cannot be explained simply by a westward expansion of the active sector of the tail to include the location of Ogo. This is because the simultaneous Vela data clearly show that the same recoveries occurred at similar radial distances also at 0100-0200 MLT, which was in both cases to the east of the central meridian of the wedge.

The problem discussed in this paper of distinguishing between auroral and magnetic features associated with substorm expansions and with the poleward leap can be illustrated by comparing the signatures accompanying the 1046 UT negative bay onset on this day with those accompanying the apparently equivalent onset at the same stations at 1117 UT on September 4, 1968 (Figure 2). As the present analysis has shown, however, there are significant physical differences between the two bays when magnetotail and Pi 2 data are looked at. Thus the September 6, 1969, bay was accompanied by clear ground substorm expansion signatures such as a mid-latitude positive bay and a Pi 2 burst and by a large-scale plasma sheet thinning at r ∿ 18 R_E; the subsequent recovery of the plasma sheet occurred about 25 min later in conjunction with a poleward shift of the electrojet (which started near College at ∿1110 UT). The September 4, 1968, bay, on the other hand, was accompanied by no such signatures and occurred at the time of a plasma sheet thickening at 18 R_E and a poleward leap of activity near midnight. Thus although the end of a substorm expansion sequence cannot unambiguously be determined on the basis of auroral zone data alone, the plasma sheet recovery, together with the absence of Pi 2 bursts, seems to provide a clear indication that a substorm recovery is in progress. On this background we divided the 7-hour interval of continuously enhanced AE activity from ∿0900 to ∿1600 UT on September 4, 1968 (Figure 2), into two separate substorms, with expansion phases lasting for about 90 and 150 min and each ending with a plasma sheet recovery and a poleward leap.

Magnetospheric Substorms on July 16, 1969

The events discussed in the previous subsections suggest that the large-scale thickening of the plasma sheet during a poleward leap is accompanied by a poleward expansion of the auroral zone precipitation region. If there is also a poleward expansion of the ionospheric projection along field lines of the outer boundary of the plasma sheet, there should be a thickening of the plasma sheet towards higher magnetic latitudes also closer to the earth than 15-18 R_E. Such a spatial correlation is supported by measurements from Ogo 5 and Vela 5B on July 16, 1969.

The auroral zone magnetograms shown in Figure 7 indicate four intervals of substorm activity, starting at about 1000, 1330, 1710, and 1900 UT. Mid-latitude magnetograms (not shown) indicate that the 1000 and 1900 UT substorms were centered near local midnight, whereas the other expansions apparently were too weak to cause clear mid-latitude signatures.

The plasma sheet variations associated with these four substorm intervals are readily identified in the Ogo and Vela measurements obtained in the early morning sector of the tail (Figure 8). The four recoveries of the plasma sheet started near the time of maximum auroral zone magnetic activity (solid vertical lines in Figure 7).

The plasma sheet events of main interest here are those occurring at ∿1722 and ∿1924 UT, in both cases about 15 min after a Pi 2 onset (we shall return to the two preceding recoveries later). At these times the Ogo satellite was as close to the earth as 7-10 R_E and at -26° and -35° dipole latitude (in the southern hemisphere), respectively. The corresponding north invariant latitude of the ionospheric intercept of the field line through Ogo, determined by field line tracings in the Mead-Fairfield MF73Q magnetic field model, was then ∿71° and ∿73°. At the same times the estimated latitude of the foot of the Vela field line was near 72°. This indicates that as a first approximation according to this time-independent field model, both space-

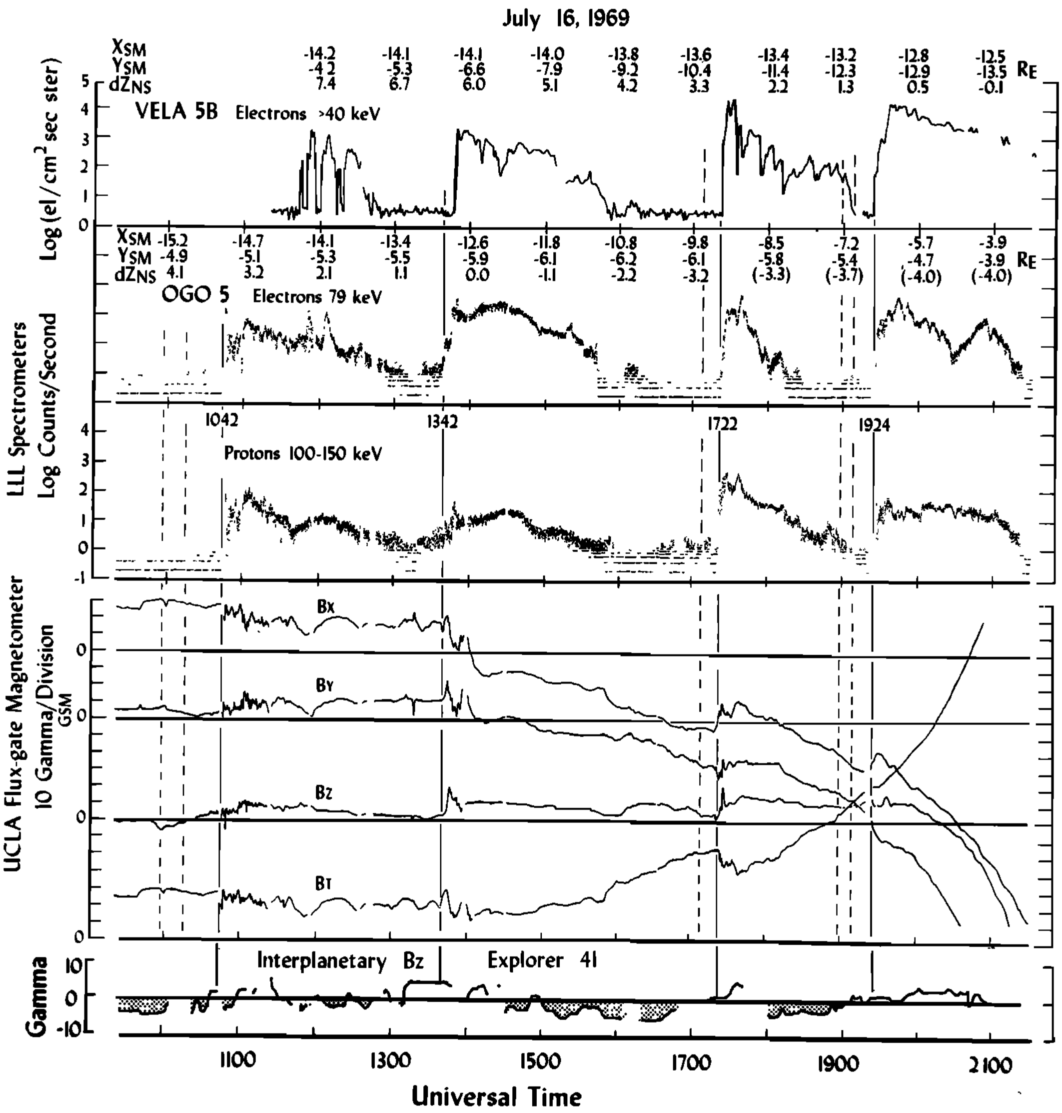

Fig. 8. Ogo 5 and Vela 5B measurements in the plasma sheet on July 16, 1969. Vertical dashed lines indicate substorm expansion onsets on the ground, and solid lines the onsets of plasma sheet recovery at Ogo. The dZ values for Ogo given in parentheses are estimated from a near-earth curved 'neutral' sheet that tapers into the magnetic equatorial plane at r $\sim$ 5 R_E [West et al., 1978].

craft were on field lines typically reached by ground activity during a poleward leap.

The 1722 and 1924 UT recoveries occurred at both spacecraft within an interval of $\sim$2 min over radial separations of $\sim$7 and 10 R_E, respectively. Also, the plasma sheet boundary reached first the satellite whose field line apparently intercepted the earth at the lowest latitude (Ogo at 1722 and Vela at 1924 UT). This is additional evidence for the large-scale character of these events and clearly supports our interpretation that the thickening occurred toward higher latitudes both in the Vela orbit and closer to the earth at this particular stage in the substorms.

Other important features of these same plasma sheet events have been reported in two recent studies. First, Pytte et al. [1978] compared the Vela and Ogo electron energy spectra obtained just inside the recovered plasma sheet with near-coincident, near-conjugate spectra obtained by the Esro 1A satellite near the ionospheric (1000-km altitude) high-latitude precipitation boundary. From the observed close correspondence between the shape of the energy spectra and the absolute directional intensities at all three satellites they concluded that the essentially isotropic electron fluxes at Vela and Ogo were the likely source for the low-altitude precipitation. Furthermore, field line tracings in the MF73Q model during these and other Esro passes through the high-latitude precipitation region indicated the foot of the Vela and Ogo field lines to be located poleward of the precipitation boundary when these satellites were in the tail lobe but equatorward of the boundary when they were located within the plasma sheet. Since the precipitation boundary typically is found at lower latitudes during the expansion phase ($\lesssim 70^\circ$) than during the recovery phase ($\sim 75^\circ$) [e.g., Lundblad et al., 1978], there are good reasons to believe that the recovery of the plasma sheet, which in these two cases was observed concurrent-

TABLE 1. Spacecraft Locations and Temporal Relations During Correlated Plasma Sheet Events

Event	Date	Plasma Sheet Thickening at Vela						Plasma Sheet Thickening at Ogo					Ogo-Vela
		Time	Location				Satellite	Time	Location				Time difference
		UT	X_{sm}	Y_{sm}	Z_{sm}	dZ_{ns}*		UT	X_{sm}	Y_{sm}	Z_{sm}	dZ_{ns}*	min
1	July 1, 1968	1810†	-11.9	-11.9	7.2	3.5	4A	1812	-11.1	-10.3	6.7	2.3	2 ± 4
2	July 1, 1968	2356†	-9.9	-15.2	2.5	2.5	4A	2327	-7.2	-8.7	1.9	-	-19 ± 4
3	Aug. 12, 1968	1213†	-16.5	2.9	7.3	3.9	4A	1210	-13.1	0.7	4.2	0.8	-3 ± 4
4	Sept. 4, 1968	1117†	-11.0	13.6	5.5	4.8	4A	1117	-16.6	12.1	4.0	1.8	0 ± 4
5	Sept. 4, 1968	1614†	-14.2	10.0	5.8	3.3	4A	1614	-15.7	8.8	4.3	1.6	0 ± 4
6	Sept. 4, 1968	2240	-17.7	3.8	3.2	2.0	4A	2148	-12.8	4.7	3.1	0.8	-52
7	June 27, 1969	2225	-10.9	-13.5	6.0	4.0	5B	2230	-15.0	-12.6	6.2	3.7	5
8	July 14, 1969	0132	-13.9	-8.4	8.6	6.4	5A	0126	-10.6	-6.9	0.4	-	-6
9	July 14, 1969	0450†	-12.9	-10.8	7.5	6.1	5A	0356	-7.7	-6.0	-0.7	-	-54 ± 4
10	July 16, 1969	1146	-14.2	-4.1	10.9	7.5	5B	1042	-14.9	-4.8	6.2	3.4	-64
11	July 16, 1969	1350	-14.1	-6.6	9.7	6.1	5B	1342	-13.0	-5.8	3.9	0.3	-8
12	July 16, 1969	1724	-13.5	-10.9	5.9	3.0	5B	1722	-9.3	-6.0	0.1	-3.2	-2
13	July 16, 1969	1924	-13.0	-12.6	3.1	0.9	5B	1925	-6.5	-5.1	-2.2	-	1
14	July 18, 1969	1906	-14.5	-8.0	7.9	3.2	5A	1907	-17.7	-5.5	7.8	2.6	1
15	July 26, 1969	2235†	-16.2	-4.4	6.9	3.4	4A	2218	-14.9	-4.5	2.6	-0.7	-17 ± 4
16	Aug. 8-9, 1969	0005	-17.0	-4.9	5.0	2.8	5B	2342	-14.2	-1.2	1.6	-0.7	-23
17	Aug. 9, 1969	0317	-16.6	-6.7	3.4	2.3	5B	0253	-11.3	-2.0	-0.4	-1.4	-24
18	Aug. 10, 1969	1605	-11.9	8.7	10.9	6.9	5A	1555	-18.0	7.9	10.7	6.5	-10
19	Aug. 13, 1969	1040†	-16.2	3.7	7.7	5.4	5B	1040-1050	-18.5	9.1	7.9	5.9	0-10 ± 4
20	Aug. 13, 1969	1720†§	-17.3	4.6	3.9	-0.6	5B	1732	-18.9	4.8	7.2	2.7	12 ± 4
21	Aug. 13, 1969	2143	-16.7	-7.7	0.3	-2.5	5B	2136	-18.0	2.3	5.7	2.5	-7
22	Aug. 27, 1969	0628	-14.3	8.9	7.3	7.4	5B	0400	-14.6	3.6	0.8	1.0	-148
23	Aug. 31, 1969	1740†	-10.2	11.8	9.6	7.4	5B	1730	-16.9	12.3	6.9	4.8	-10 ± 4
24	Sept. 5, 1969	1415	-13.4	11.2	5.6	3.6	5B	1515	-13.5	16.0	6.7	6.7	60
25	Sept. 5, 1969	1700†	-15.4	8.2	5.8	2.9	5B	1718	-14.8	14.8	7.8	7.2	18 ± 4
26	Sept. 6, 1969	0605†	-18.2	-2.5	-1.3	-0.6	5B	0605	-16.2	10.9	1.9	2.5	0 ± 4
27	Sept. 6, 1969	1110†	-16.7	-7.1	-2.9	-4.1	5B	1110	-15.0	7.6	-1.1	-2.3	0 ± 4
28	Sept. 6, 1969	1340†	-15.6	-8.8	-3.9	-6.1	5B	1324	-14.1	6.3	-1.4	-3.8	-16 ± 4

*According to formula by Fairfield and Ness [1970].
†Store mode data, onset times uncertain by ±4 min.
§Mainly heating of plasma.

ly at r ∿ 7-10 and 18 R_E, extended down to ionospheric heights.

Second, Lui et al. [1977] analyzed the flow of plasma at Vela in the plasma sheet boundary region and found that the flow was generally sunward during both intervals of plasma sheet thickening. Just before the 1924 UT recovery there was a reversal from antisunward to sunward flow, a signature previously associated with a tailward shift of an X type neutral line from earthward to tailward of the Vela satellite near the time of plasma sheet recovery [Hones, 1973, 1977]. The simultaneous thickening at Ogo and Vela during intervals of sunward flow is consistent with our observations of a poleward expansion of enhanced precipitation to high (>71°) magnetic latitudes during the poleward leap and with the typically high-latitude (∿75°) location of the precipitation boundary at this late stage in substorms.

Statistical Results

The eight correlated Ogo and Vela events presented above were selected to illustrate the plasma sheet behavior as observed by two satellites at locations ranging from early evening to late morning hours. In this section we summarize the main features of these and 20 other events (see Table 1) and compare their average spatial characteristics with those observed during individual events.

In Figure 9 we have plotted the time difference ΔT between the onset of plasma sheet thickening at Ogo and at Vela as a function of spacecraft separation in the vertical (dZ), azimuthal (ϕ), and radial (r) directions. These 28 events appear to fall into three different categories, depending on their temporal and spatial characteristics. The first category (22 events, shown as black dots) consists of plasma sheet recoveries that were observed within ∿20 min at both spacecraft over spacecraft distances ranging up to ∿6 R_E in the direction normal to the tail's midplane, ∿53° in the azimuthal direction, and ∿10 R_E in the radial direction. A least squares fit to a linear function between ΔT and ΔdZ, Δϕ, and Δr indicates a significant increase of ΔT with increasing distance only in the dZ direction. The regression line shown in Figure 9a for these events corresponds to a velocity component in the dZ direction of about 40 km/s. This is close to the value of ∿60 km/s obtained by Hones et al. [1973] on the basis of single-satellite measurements of delays between auroral zone bay recovery and plasma sheet recovery at 18 R_E. Our analysis also shows some coupling in the correlation function between ΔdZ and Δr which is consistent with the approximate orientation of the expanding plasma sheet boundary inferred above. Of the eight events presented earlier, all but one (event 10 in Table 1) belong to this first category.

The second category consists of three events (10, 22, and 24; open squares in Figure 9) that were observed when one of the satellites was more than ∿6.5 R_E from the tail's midplane. The time delays were then 60 min or more, which is much longer than expected on the basis of time delays observed at smaller dZ. Two of these events were observed when the most distant satellite was moving toward the midplane of the tail (the situation in the third case is not clear), indicating that the late entry of this satellite into the plasma sheet was caused by its motion into a virtually stationary plasma sheet rather than by a prolonged thickening. This interpretation can be illustrated by the two first events shown in Figure 8. At the time of the 1042 UT recovery at Ogo, Vela was at dZ ∿ 7.5 R_E and about 4 R_E vertically above Ogo. That the long delay of 64 min does not reflect a continuous motion of the boundary from Ogo to Vela is consistent with the short delay of only 8 min observed during the second (∿1340 UT) event when Vela was at dZ ∿ 6 R_E but apparently farther away from the Ogo satellite than it was during the preceding event.

The third category consists of three events (6, 9, and 17; open triangles in Figure 9). During these events the plasma sheet was observed to expand at Ogo in the near-earth region of the tail (r ≲ 15 R_E) while it was first thinning and then recovering 28-54 min later at Vela (r ∿ 18 R_E). This different behavior of the plasma sheet in the same local time sector of the tail but at different radial distances has previously been explained in terms of a model involving the formation and later tailward motion from earthward to tailward of Vela of an X type neutral line [Pytte et al., 1976a]. The longer delays observed for these cases may reflect the tendency for the X line to remain virtually stationary in the near-earth region until the end of the expansion phase when it appears to move tailward.

None of the events examined here belong to this last category. However, the long delays observed for these events are also reflected in the long delays often observed between the first Pi 2 of a substorm and the subsequent plasma sheet recovery (this delay was ∿90 and ∿150 min for the two substorms on September 4, 1968 (Figures 2 and 3)).

Summary and Discussion

Spatial Characteristics of Plasma Sheet Recovery

We have presented detailed examinations of eight cases of two-satellite measurements of the late plasma sheet recovery obtained from locations in the early evening to late morning hours of the magnetotail. These recoveries occurred

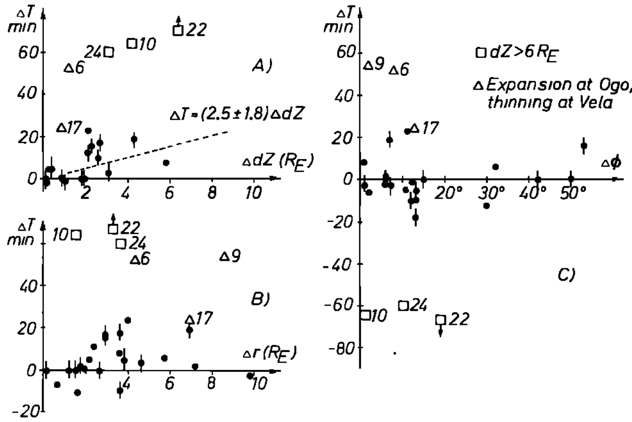

Fig. 9. Summaries of the main temporal and spatial relations observed during 28 plasma sheet thickening events, showing the time difference ΔT between onsets of thickening at Ogo 5 and Vela as a function of spacecraft separations in a direction approximately normal to the tail's midplane (ΔdZ) and in the GSM longitudinal (Δφ) and radial (Δr) directions (ΔT is reckoned positive in the direction of increasing dZ, φ, and r). Events of particularly long time delays, marked with open symbols and labeled with numbers given in Table 1, belong to special categories discussed in the text. The regression line in the upper left diagram is at the 95% confidence level of a linear least squares fit.

near the time of a poleward leap of auroral zone activity or during the decay of auroral zone bays. In six cases of relatively small spacecraft distances from the tail's midplane (dZ ≲ 4 R_E) but a wide range of east-west separations, the recoveries at Ogo and Vela occurred within a time interval of less than 5 min. In the two remaining cases (∿1200 and ∿1400 UT on July 16, 1969; Vela was at dZ ∿ 7.5 and 6 R_E, respectively) the delays were 64 and 8 min, respectively. This marked increase of time delays when one satellite was far from the midplane (dZ ≳ 6.5 R_E) suggests that the plasma sheet in this region typically thickens to ∿6 R_E half-thickness in 10-20 min and that the much longer delays are caused by the motion of the distant satellite toward the midplane into a thick, virtually stationary plasma sheet.

Two events on July 16, 1969, were observed concurrently in the Vela orbit (r ∿ 18 R_E) and at high magnetic latitudes in the near-earth tail (r ∿ 7-10 R_E). Field line tracings in the Mead and Fairfield [1975] MF73Q model indicate that Ogo and Vela were then on field lines which mapped to the ionosphere at latitudes typically reached by auroral zone activity during a poleward leap.

These spatial relations, which also agree with the main features observed during an additional 20 two-satellite events (Table 1 and Figure 9), are evidence that the plasma sheet recovery is due to a thickening of the plasma sheet over a significant fraction of the tail's breadth which occurs essentially in a direction perpendicular to the tail's midplane toward higher L shells and from ionospheric heights to beyond the Vela orbit.

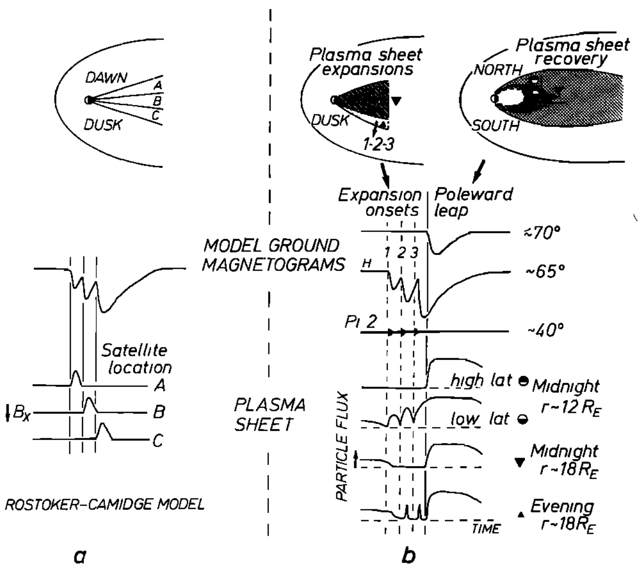

Fig. 10. Two different phenomenological models for the plasma sheet dynamics during multiple-onset magnetospheric substorms. The Rostoker and Camidge [1971] model proposes that successive expansion onsets occur in adjacent westward shifted sectors of the tail, whereas our alternative model proposes that each onset occurs within a wedgelike region, shown in the upper middle diagram, that probably expands in azimuth. The plasma sheet recovery (upper right diagram) is a separate thickening event that covers a larger radial and apparently also a larger azimuthal region of the tail than the early plasma sheet expansions.

Relations of Plasma Sheet Recovery to Substorm Expansions

The plasma sheet recoveries examined in this paper, though they were not approximately coincident with ground Pi 2 bursts, were preceded by as many as eight such bursts. These magnetic pulsations were observed at stations separated by more than 30° longitude and are indications of individual onsets of substorm expansions. Seven of the eight recoveries at Ogo and Vela reached both spacecraft from 10 to 28 min after the last in such a series of Pi 2 onsets. Since these near-coincident plasma sheet encounters occurred at small distances from the estimated position of the tail's midplane and seem to result from a rapid motion essentially in the ±Z direction, it seems reasonable to assume that these encounters also represented closely the earliest onset times of the associated plasma sheet thickening. Although at least one satellite was generally within about an hour of local time of a ground station that had been observing the preceding Pi 2 bursts, we find no indication that this thickening started at the time of a Pi 2.

This relationship of plasma sheet recovery to substorm expansions on the ground is also indicated independently by mid-latitude standard magnetograms. In cases when the presence and approximate location of the substorm current wedge could be clearly determined, it has been found that the recovery may be observed by spacecraft in the tail even when the last substorm expansion was centered farther away from one or both spacecraft than were the preceding onsets. Also, there seems to have been no new wedge formation near the spacecraft at the time of a plasma sheet recovery. It appears, therefore, that these recoveries were not caused directly by any separate substorm expansion which happened to occur in, or to include, the local time sector of the satellites.

The absence of Pi 2 pulsations near the time of a poleward leap seems not to agree with the observations of Wolcott et al. [1976] during two substorms that auroral zone magnetic pulsations intensified both at the time of auroral breakup and during the poleward leap. The latter pulsation activity, however, was probably associated with the more turbulent ionospheric region near the westward electrojet, the jet being observed to pass over the station at that time, rather than associated with a separate substorm expansion. This interpretation is supported by the absence of any detectable Pi 2 onsets during the poleward leaps at another station located at mid-latitudes a little farther to the south.

Relations of Plasma Sheet Recovery to Substorm Modeling

To discuss these results in relation to the questions raised in the introduction, we compare in Figure 10 two models for magnetotail dynamics during multiple-onset substorms. The main idea of the Rostoker and Camidge [1971] model, shown schematically in Figure 10a, is that successive substorm expansions occur in separate local time sectors (A, B, C) that are shifted progressively farther west in the course of a substorm. According to this model, a satellite at any radial distance will experience a plasma sheet thickening (shown here as a diamagnetic decrease in the main (B_X) field component since these authors used only magnetic field data) only when it is located within the 'collapsing' sector.

Figure 10b shows an alternative model for the same type of substorms, where the temporal and spatial developments of substorm effects in the tail have been illustrated by the two different types of plasma sheet thickening events proposed. This model includes the more recent idea of a near-earth ($r \sim 15\ R_E$) X type neutral line. The upper left part shows the wedgelike region of activity during the substorm expansion phase and an expanding plasma sheet earthward of the X line, whereas the upper right part shows a noon-midnight cross section at a later stage through the recovered plasma sheet. The different and much larger spatial coverage of the recovery in comparison with the plasma sheet expansions is indicated by different shading.

The lower part of Figure 10b summarizes the observational basis for our model. At midnight near the center of the wedge ($r \sim 12\ R_E$) the low-latitude plasma sheet often experiences multiple plasma sheet expansions, in partly overlapping rather than separated local time sectors, in a one-to-one correspondence with ground Pi 2 bursts [Pytte et al., 1976a]. These expansions are probably accompanied by an average westward expansion of the wedge, as indicated in the figure. In this near-earth region the recovery of the plasma sheet can be identified as a separate phenomenon only at high latitudes (by a satellite not already deep inside the expanded plasma sheet). Our comparison with other ground and near-ionospheric observations indicates that the recovery extends to ionospheric heights, thus accounting for the poleward expansion of particle precipitation during the poleward leap.

In the region tailward of the wedge near midnight ($r \sim 18\ R_E$) the plasma sheet thins early in a substorm and recovers near the time of maximum auroral zone bay activity [Hones et al., 1967, 1973]. A satellite in this region may detect only small magnetic effects during the near-earth multiple expansions, except possibly near the midplane. This may be the situation described by Rostoker and Camidge [1971], showing small magnetic effects at $r \sim 30\ R_E$, but interpreted by them to indicate azimuthally localized activity. However, they were not able to show that such effects were present at about the same radial distance but in a neighboring sector of the tail.

In the evening sector at $r \sim 18\ R_E$ the plasma sheet appears to thin early in substorms, later to be followed by transient particle flux increases during Pi 2 activity on the ground. These electron and proton bursts may be indicative of the satellite entering field lines connected to an acceleration region, possibly the reconnection region. Some bursts were preceded by magnetic B_z increases which started at the onset of Pi 2's and which are consistent with the satellite initially being in the tail lobe inside the wedge. The particle bursts may then correspond to a temporary upward expansion of the plasma sheet. They appear, therefore, to be of a different type than the bursts observed near the midplane in and tailward of the Vela orbit [Hones et al., 1973], but accompanied by negative B_Z [Terasawa and Nishida, 1976].

An important aspect of our model is the identified distinct transition from the substorm expansion phase to the interval of plasma sheet recovery. The duration of the expansion phases examined here, which we define as the interval between the first Pi 2 in a series and the plasma sheet recovery, ranged from $\lesssim$30 min to more than 2 hours. Thus there seems to be little basis for the idea that the thickening starts near the earth early in a substorm, reaching the Vela orbit, purely by coincidence, near the time that activity on the ground approaches its highest latitude. Instead our observations show that the recovery may occur concurrently in the near-earth region and in the Vela orbit at the time of a distinct change in magnetotail dynamics.

Previous studies of plasma sheet recoveries [Hones et al., 1973; Hones, 1977] have suggested that the recovery at 18 R_E is related to a tailward motion of the X line from earthward to tailward of that location. As is shown in the present paper, the recovery often occurs after a long series of substorm expansions. Observations of the IMF B_z component (bottom panel of Figures 3, 6, and 8) indicate that these substorm expansions occurred during southward IMF and that the plasma sheet recovery sometimes appear to be triggered externally by a northward turning.

It has been suggested that an interruption of substorm expansions, leading to plasma sheet recovery, may occur as a result of a tailward pressure that is built up in the near-earth region of the tail during enhanced field line reconnection, choking the earthward magnetospheric convective flow and eventually forcing the X line to move tailward [Pytte et al., 1976a; Vasyliunas, 1976]. Since it is likely that this buildup is influenced by both the dayside merging rate and the tail reconnection rate, the plasma sheet recovery may be triggered both externally and internally. In the latter case the recovery may be caused indirectly by the last stronger substorm expansion and start near the peak of that expansion.

While the plasma sheet recovery, as well as the different plasma sheet dynamics early in a substorm in locations earthward and tailward of $r \sim 15\ R_E$, can be explained consistently in terms of a near-earth neutral line model [Russell, 1972; Hones et al., 1973; Nishida and Nagayama, 1973; Pytte et al., 1976a], the observational evidence for the existence of such a line has been recently called into question [Lui et al., 1976; Akasofu, 1977]. Also, it has been claimed [Frank et al., 1976] that the processes previously associated with a neutral line occur within a spatially limited 'fireball' (overall dimension 1-5 R_E) rather than along an extended line. However, recent more detailed examinations of both magnetic signatures and the low- and high-energy particle data near the region of an assumed neutral line during substorm onset [Hones, 1977; Caan and Hones, 1978] show that most of this criticism can be answered in terms of this near-earth neutral line model. Also, the large-scale character of the plasma sheet recovery, as shown also by Hones et al. [1976], indicates that the neutral line, at least at this late stage in a substorm, often has a cross-tail dimension much larger than that anticipated for a 'fireball.'

These results may also influence the definition of the various substorm phases. According to the classical definitions of Akasofu [1964] based on observations of the auroral substorm, the substorm recovery phase starts when activity has reached its highest latitude and starts to return toward the equator. The phenomena discussed in the present paper, the plasma sheet recovery and the poleward leap, appear to occur after and separated from the substorm expansion phase but before the beginning of the recovery phase. Apparently, plasma sheet recovery does not belong to either phase but may represent a separate phase lasting for 10-20 min and located in time between the two classical phases.

Conclusions

The present analysis of 28 two-satellite observations of plasma sheet thickening events shows no indication of a systematic westward progression in the tail predicted by current substorm models or of any continuous radial motion expected if the thickening started near the earth at the first substorm expansion, reaching the Vela orbit, purely by coincidence, near the time that auroral zone activity reached its highest latitude. Instead we find evidence that the thickening during substorms occurs in two stages, one early stage of plasma sheet expansions in the near-earth tail near the onsets of substorm expansions (Pi 2 bursts) on the ground and another later stage of plasma sheet recovery covering a wide sector of the tail and ranging from ionospheric heights to beyond the Vela orbit. The signatures on the ground accompanying the plasma sheet recovery, an enhancement of particle precipitation and magnetic activity at low polar cap latitudes in the absence of Pi 2 bursts, probably correspond to an expansion poleward of the ionospheric projection along field lines of the recovering plasma sheet.

These relations indicate that the plasma sheet recovery and the poleward leap are not caused directly by a high-latitude late substorm expansion but rather can be explained in terms of a tailward motion of the tail reconnection region. Our results also indicate that the plasma sheet recovery and the poleward leap may provide the clearest signatures during prolonged enhanced AE activity that a substorm expansion sequence has ended and that a substorm recovery is in progress.

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References

Akasofu, S.-I., The development of the auroral substorm, Planet. Space Sci., 12, 273, 1964.

Akasofu, S.-I., Physics of Magnetospheric Substorms, p. 300, D. Reidel, Hingham, Mass., 1977.

Aubry, M. P., M. G. Kivelson, R. L. McPherron, and C. T. Russell, A study of the outer magnetosphere near midnight at quiet and disturbed times, J. Geophys. Res., 77, 5487, 1972.

Bame, S. J., E. W. Hones, Jr., S.-I. Akasofu, M. D. Montgomery, and J. R. Asbridge, Geomagnetic storm particles in the high-latitude magnetotail, J. Geophys. Res., 76, 1566, 1971.

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.

Caan, M. N., and E. W. Hones, Jr., Comment on 'Search for the magnetic neutral line in the near-earth plasma sheet, 2, Systematic study of Imp 6 magnetic field observations' by A. T. Y. Lui, C.-I. Meng, and S.-I. Akasofu, J. Geophys. Res., 83, 2719, 1978.

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.

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

Frank, L. A., K. L. Ackerson, and R. P. Lepping, On hot tenuous plasmas, fireballs, and boundary layers in the earth's magnetotail, J. Geophys. Res., 81, 5859, 1976.

Hones, E. W., Jr., Plasma flow in the plasma sheet and its relation to substorms, Radio Sci., 8, 979, 1973.

Hones, E. W., Jr., Substorm processes in the magnetotail: Comment on 'On hot tenuous plasmas, fireballs, and boundary layers in the earths's magnetotail' by L. A. Frank, K. L. Ackerson, and R. P. Lepping, J. Geophys. Res., 82, 5633, 1977.

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.-I. Akasofu, P. D. Perreault, S. J. Bame, and S. Singer, Poleward expansion of the auroral oval and associated phenomena in the magnetotail during auroral substorms, 1, J. Geophys. Res., 75, 7060, 1970.

Hones, E. W., Jr., S.-I. Akasofu, S. J. Bame, and S. Singer, Poleward expansion of the auroral oval and associated phenomena in the magnetotail during auroral substorms, 2, J. Geophys. Res., 76, 8241, 1971.

Hones, E. W., Jr., J. R. Asbridge, S. J. Bame, M. D. Montgomery, S. Singer, and S.-I. Akasofu, Measurements of magnetotail plasma flow with Vela 4B, J. Geophys. Res., 77, 5503, 1972.

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.

Hones, E. W., Jr., S.-I. Akasofu, J. H. Wolcott, S. J. Bame, D. H. Fairfield, and C.-I. Meng, Correlated observations of several substorms on February 17, 1971, J. Geophys. Res., 81, 1725, 1976.

Iijima, T., and T. A. Potemra, Large-scale characteristics of field-aligned currents associated with substorms, J. Geophys. Res., 83, 599, 1978.

Kamide, Y., S.-I. Akasofu, and E. P. Rieger, Coexistence of two substorms in the midnight sector, J. Geophys. Res., 82, 1620, 1977.

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

Kivelson, M. G., T. A. Farley, and M. P. Aubry, Satellite studies of magnetospheric substorms on August 15, 1968, 5, Energetic electrons, spatial boundaries, and wave-particle interactions at Ogo 5, J. Geophys. Res., 78, 3079, 1973.

Lui, A. T. Y., C.-I. Meng, and S.-I. Akasofu, Search for the magnetic neutral line in the near-earth plasma sheet, 1, Critical reexamination of earlier studies on magnetic field observations, J. Geophys. Res., 81, 5934, 1976.
Lui, A. T. Y., E. W. Hones, Jr., F. Yasuhara, S.-I. Akasofu, and S. J. Bame, Magnetotail plasma flow during plasma sheet expansions: Vela 5 and 6 and Imp 6, J. Geophys. Res., 82, 1235, 1977.
Lundblad, J. Å., F. Søraas, and K. Aarsnes, Substorm morphology of >100-keV protons, Sci./Tech. Rep. 108, Dep. of Phys., Univ. of Bergen, Bergen, Norway, 1978.
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, 1973.
Mead, G. D., and D. H. Fairfield, A quantitative magnetospheric model derived from spacecraft magnetometer data, J. Geophys. Res., 80, 523, 1975.
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.
Nishida, A., and N. Nagayama, Synoptic survey for the neutral line in the magnetotail during substorm expansion phase, J. Geophys. Res., 78, 3782, 1973.
Pytte, T., and H. I. West, Jr., Ground-satellite correlations during presubstorm magnetic field configuration changes and plasma sheet thinning in the near-earth magnetotail, J. Geophys. Res., 83, 3791, 1978.
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., 81, 5921, 1976a.
Pytte, T., R. L. McPherron, and S. Kokubun, The ground signatures of the expansion phase during multiple-onset substorms, Planet. Space Sci., 24, 1115, 1976b.
Pytte, T., J. Å. Lundblad, F. Søraas, E. W. Hones, Jr., and H. I. West, Jr., Three-satellite measurements and field-line mapping of the outer plasma sheet boundary from r ∿ 1.2 to ∿ 18 R_E during substorms, Geophys. Res. Lett., 5, 585, 1978.
Rostoker, G., Macrostructure of geomagnetic bays, J. Geophys. Res., 73, 4217, 1968.
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 configuration of the magnetosphere, in Critical Problems of Magnetospheric Physics, edited by E. R. Dyer, National Academy of Sciences, Washington, D. C., 1972.
Saito, T., Geomagnetic pulsations, Space Sci. Rev., 10, 319, 1969.
Sakurai, T., and T. Saito, Magnetic pulsations Pi 2 and substorm onset, Planet, Space Sci., 24, 573, 1976.
Terasawa, T., and A. Nishida, Simultaneous observations of relativistic electron bursts and neutral-line signatures in the magnetotail, Planet. Space Sci., 24, 855, 1976.
Vasyliunas, V. M., An overview of magnetospheric dynamics, in Particles and Fields in the Magnetosphere, edited by B. M. McCormac, D. Reidel, Hingham, Mass., 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.
West, H. I., Jr., R. M. Buck, and M. G. Kivelson, On the configuration of the magnetotail near midnight during quiet and weakly disturbed periods: Magnetic field modeling, J. Geophys. Res., 83, 3805, 1978.
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.
Wolcott, J. H., M. B. Pongratz, E. W. Hones, Jr., and R. W. Peterson, Correlated observations of two auroral substorms from an aircraft and from a Vela satellite, J. Geophys. Res., 81, 2709, 1976.

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