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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, Vela 4A and 5B, Imp 3) during the recovery of plasma sheet thickness late in substorms are examined. Six of the nine events discussed in detail occurred within about 5 min in locations near the estimated position of the neutral sheet ($dZ \lesssim 3\ R_E$), but over wide ranges of east-west and radial separations. The time of occurrence and spatial extent of the recovery were related to the onset (defined by ground Pi 2 pulsations) and approximate location (estimated from ground mid-latitude magnetic signatures) of substorm expansions. It was found that the plasma sheet recovery occurred 10 - 30 min after the last in a series of Pi bursts, which we interpret to indicate that the recovery is not due directly to a late, high-latitude substorm expansion. The recovery was also observed to occur after the substorm current wedge had moved into the evening sector and to extend far to the east of the center of the last preceding substorm expansion. During two events the plasma sheet in the near-earth tail (geocentric distances r of 7 - 10 R_E) was observed to recover within 1 - 2 min of the recovery in the Vela orbit ($r \sim 18\ R_E$). Recent magnetic field models suggest that the field lines through the spacecraft then intercepted the earth at high magnetic latitudes (> 72^0) that are typically reached by ground activity during the 'poleward leap' late in a substorm. These concurrent plasma sheet recoveries, and three additional events observed when the satellites were at larger vertical and radial separations, indicate that the recovery is due to a thickening of the plasma sheet toward higher latitudes that occurs over a broad azimuthal scale and from ionospheric heights to beyond the Vela orbit. The spatial character of these events is substantiated by an additional 20 correlated Ogo - Vela events. These results, especially the significance of the absence of detectable Pi 2 bursts at the time of plasma sheet recoveries, are discussed in relation to current substorm models. This recovery appears to occur after the substorm expansion phase but before the beginning of the recovery phase; consequently, this phenomenon appears to represent a separate substorm phase.

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; McDiarmid and Harris, 1976; 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 tail ($r \lesssim 15$ earth radii (R_E)) [Pytte et al., 1976a] and, in particular, in the Vela orbit ($r \sim 18\ R_E$) [Hones et al., 1967; 1973; 1976a], 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 practically 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 pre-substorm thickness which often occurs near the time of a 'poleward leap' of auroral-zone activity [Hones et al., 1970; 1971a; 1973; Wolcott et al., 1976]. This recovery seems to cover a significant fraction of the tail's breadth [Hones, 1973; Hones et al., 1976a].

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 references in almost all ground models to the poleward leap, even though the associated plasma sheet recovery is such a dominant feature in the tail. This is apparently because the leap often may be accompanied by phenomena that are typical of substorm expansion onsets (auroral brightening and poleward expansion together with negative bay intensification) and can therefore not be clearly distinguished in most ground data from a late high-latitude substorm expansion. It is therefore also conceivable that the plasma sheet recovery in the Vela orbit is due simply to a substorm expansion that involves also the plasma sheet at $r \sim 18\ R_E$.

In the present paper we analyze these differences in current substorm models. We use observations of the plasma sheet obtained concurrently by two satellites during intervals characterized by substorm expansions on the ground and during the poleward leap or decay of auroral-zone activity. Our aim is to estimate the spatial characteristics of the plasma sheet recovery and its relation to the poleward leap and the azimuthal expansion of substorms. Our findings agree with previous results that the recovery is closely related to phenomena associated with the poleward leap and that it covers a wide local-time sector of the tail. In addition we show that a systematic use of magnetic Pi 2 pulsations at middle latitudes on the ground to identify substorm expansion onsets appears to be of great importance in distinguishing between phenomena associated with substorm expansions and phenomena associated with the poleward leap. Thus, we find no systematic change in plasma sheet behavior in the evening sector of the tail during long series of substorm expansions that would indicate a westward shift of tail collapses. Furthermore, we find that there were no Pi 2's associated with any of the nine plasma sheet recoveries studied in detail, even when the associated poleward leap was accompanied by a major intensification of the polar electrojet. From these results, and from the previously established close relationship between substorm expansions, plasma sheet expansions in the near-earth tail and Pi 2's, we conclude that the poleward leap and the associated plasma sheet recovery were not caused directly by an ordinary high-latitude substorm expansion. Furthermore, these simultaneous two-satellite observations clearly indicate that the plasma sheet recovery is not localized but is caused by a thickening of the plasma sheet over a wide sector of the tail that occurs almost simultaneously from ionospheric heights to beyond the Vela orbit. Such a spatial relationship would account for the close correlation between the recovery and the poleward leap whose occurrence seems to signal the beginning of a new substorm phase.

Data

The satellite data used in this paper were obtained mainly from the Ogo 5 and Vela 4A and 5B spacecraft. Brief descriptions of the relevant experiments on these spacecraft were given in e.g., Pytte et al. [1976a], Hones et al. [1972], and Bame et al. [1971], together with further references.

The geocentric solar magnetospheric (GSM) equatorial projections of satellite trajectories during the intervals in question are shown in Figure 1, superimposed upon the projection of field lines in the Mead and Fairfield [1975] magnetospheric model for magnetically disturbed conditions ($K_p \geq 2$). These field lines intersect the earth at 70° (solid lines) and 75° (broken lines) of magnetic latitudes and serve to approximately map the satellite locations to the ground.

Our timing of substorm expansion onsets are determined by the onset of Pi 2 magnetic pulsations. Such Pi 2 bursts have been shown to be closely related to individual onsets of auroral and polar magnetic substorms [Akasofu, 1968; Rostoker, 1968a; Saito, 1969; Pytte et al., 1976a,b; Sakurai and Saito, 1976]. These pulsations propagate rapidly from their sources on auroral-zone field lines to lower latitudes [Rostoker, 1968b], where they can be detected with negligible time delay. Since there are some questions as to the localized nature of Pi 2's, we use recordings from two or more stations at middle and low latitudes separated in longitude by from ∿ 30° to 75°. High-pass filtered recordings are reproduced in some figures to show the association between Pi 2 bursts and substorm activity and their relation to events observed in the plasma sheet. The approximate longitudinal region of the substorm expansions defined by Pi 2's is determined on the basis of normal mid-latitude magnetograms. This allows us to study the possible relationship between plasma sheet recovery and the time and location of a ground substorm expansion. The magnetic coordinates of ground stations are given in the figures as corrected magnetic latitude and time of local midnight in eccentric dipole time.

We have selected for detailed presentation nine substorm intervals during long periods of continuous tracking of the two satellites rather than single events. Together with 20 other correlated Ogo - Vela events, these show cases of near-simultaneous occurrences of plasma sheet recovery over a wide range of azimuthal and radial distances when the spacecraft were separated by relatively small ($\lesssim 4\ R_E$) vertical distances. From these measurements we conclude, in agreement with previous statistical results based on single-satellite data, that the recovery is due to a large-scale very rapid motion of the outer plasma sheet boundaries in a direction essentially normal to the neutral sheet. The near-coincident encounters at small neutral-sheet distances therefore probably occur within a few minutes of the first onset of the recovery, starting from closer to the midplane of the tail.

Previous studies of Ogo 5 particle measurements [e.g., Aubry et al., 1972; Kivelson et al., 1973; Buck et al., 1973; Nishida and Fujii, 1976; Pytte et al., 1976a; Pytte and West, 1978] have established the occurrence of a near-earth plasma sheet expansion at the onset of the substorm expansion phase. The Ogo 5 events presented in this paper, on the other hand, occurred in regions of the tail where the substorm-onset expansions,for reasons discussed below, are apparently not seen. For the purpose of this paper we shall refer to a plasma sheet thickening event during substorm expansions as a plasma sheet expansion; we refer to a thickening event presumable correlated with the poleward leap as a plasma sheet recovery, although the leap itself may not always be identified in the available ground data. The phenomenological differences between these two types of thickening events are discussed in the last two sections of the paper.

Observations

Multiple-Onset Substorms on September 4, 1968

Figure 2 shows auroral-zone magnetograms and riometer recordings, together with mid- 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 an onset of a substorm expansion. At ∿ 1117 UT, ∿ 20 min after the last Pi 2 onset, a sharp bay intensification occurred at College and Barrow. The Z-recordings at College suggest a poleward shift of the center of the polar 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 $\gtrsim$ 30 keV electron precipitation had expanded poleward to at least 71^{o} of latitude (Bar. Is. in the upper left panel). Thus, it seems that a poleward shift or 'leap' of activity occurred at ∿ 1117 UT, which in this case was associated with an unusually strong intensification of bay activity also at auroral-zone latitudes.

Similar features are found also during the 1346-UT substorm (right panel), during which eight Pi 2 bursts were observed. The Tixie Z-component observations indicate that the polar electrojet made four poleward excursions during the multiple expansions; this is a feature often observed during such substorms [Pytte et al., 1976b]. At ∿ 1614 UT a sharp onset of precipitation was detected at Zhelania, indicating a poleward shift of the precipitation region to higher latitudes as bay activity subsided in the auroral zone. There was, in this case, no clear poleward shift of the current system with respect to these stations, 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 onset.

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 tail; the GSM spacecraft locations are indicated at the top of the two upper panels. The vertical dashed lines in the bottom panel and the asterisks below recordings of particle fluxes indicate the onset times of Pi 2 bursts earlier identified in ground recordings (Figure 2).

The two vertical lines at 1117 and 1614 UT in Figure 3 mark the observed beginning of the most notable magnetotail event at these radial distances, namely, the late recovery 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 neutral sheet, causing both satellites to be engulfed by the plasma. Earlier we found that activity on the ground near midnight expanded to higher latitudes ($\Lambda_c > 71^\circ$) around both 1117 and 1614 UT; this is the same close relationship between the plasma sheet recovery and the poleward leap as was found in a number of previous cases [Hones et al., 1970; 1971a; 1973; Wolcott et al., 1976].

It is interesting here to estimate the approximate orientation of the expanding plasma sheet boundary near the time of its encounter at Ogo. During the 1117-UT recovery there was a sharp positive (westward) deflection in the B_Y component, which we interpret as due to field-aligned currents that were directed away from the earth and located near the expanding boundary. If these boundary currents define a current sheet, whose orientation near the satellite can be estimated on the basis of the field measurements, we find that the boundary at the time of the encounter was nearly parallel to the X_{sm} - Y_{sm} plane, the sheet normal pointing northward and a few degrees tailward. When the boundary reached Vela sometime between 1112 and 1120 UT, in the interval between successive store-mode data samples, Vela was $\sim$ 1.5 R_E higher than Ogo above the X_{sm} - Y_{sm} plane, but the distance along the $\sim$ 1117-UT current sheet normal was apparently less than 1 R_E. This initially almost horizontal plasma sheet boundary indicates that the expansion occurred essentially in the Z_{sm} direction, which is consistent with the observations made during other substorms presented below. This would also imply that the apparent velocity in the anti-sunward direction would be much higher than in the Z_{sm} direction in this region [c.f. Meng et al., 1970; Akasofu et al., 1970; Hones et al., 1971b].

These two plasma sheet recoveries at Vela are seen also in recordings at lower particle energies (Figure 4); the two sharp rises in average energy ($\bar{E}$) and energy density (U) correspond to the previously identified satellite entries into the plasma sheet. Although the plasma sheet is defined strictly by the low-energy particle population [Montgomery, 1968], low- and high-energy particles usually occupy the same region in space during plasma sheet thickening events and can therefore both be used to trace the plasma sheet. Since energetic particle data are most readily avaiable we use these to identify other plasma sheet recovery events.

It is probable that the region of more energetic particles near the outer plasma sheet boundary connects to the field-line reconnection region where particle acceleration apparently takes place. In this same boundary region enhanced earthward plasma flow is often observed [Lúi et al., 1977a].

There was sometimes a weak increase in the B_Z component at Ogo near the times of Pi 2 bursts on the ground (vertical dashed lines in Figure 3). Some Pi bursts were also followed by transient increases of particle fluxes. Three successive particle events are shown in more detail in Figure 5, together with another similar event observed during the weak 1850-UT substorm. In contrast to the plasma sheet recoveries, these electron and proton bursts have a duration of only 5 - 10 min. Their internal structures are independent of detector-scan orientation and pitch-angle sampled (see West et al. [1973] for a description of this Ogo experiment); they were therefore probably not due to drifting groups of particles or to changes in their pitch-angle distributions. Instead it seems that shortly after a new substorm onset, identified by a Pi 2 burst and a tail B_Z increase, Ogo intermittently entered field lines connected to the reconnection region, possibly as a result of a transient expansion of the plasma sheet upward towards the satellite as the magnetic field became more dipolar.

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.

In summary, these two-satellite observations show that the evening plasma sheet at r ∿ 18 - 20 R_E remained thin throughout the two expansion phases, which lasted for ∿ 90 and ∿ 150 min respectively. Transient (5 - 10 min duration) bursts of energetic particles were observed a few minutes after some Pi 2 bursts, 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 satellites. The recovery of the plasma sheet occurred at both satellites within about 5 min of a poleward leap of auroral-zone activity.

Multiple-Onset Substorms on September 6, 1969

The two examples of plasma sheet recovery examined in the previous section 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 previous two events, the events on this day were also accompanied by clear mid-latitude magnetic signatures.

The three substorms starting at about 0232, 0507, and 1006 UT, respectively, were characterized by a rather rapid growth and decay of auroral-zone bay intensities (Figure 6). Thus, the corresponding plasma sheet recoveries at Ogo (solid vertical lines) occurred within about an hour of the first Pi 2 but about 30, 10, and 25 min, respectively, after the last clear Pi 2 onset. These recoveries also occurred near or just after the time of maximum magnetic disturbances in the auroral zone and at mid-latitudes

The mid-latitude magnetic signatures during the 0507 and 1006 UT substorms allow us to estimate the approximate location with respect to the satellites of the disturbed local-time sector, in particular, the central meridian ($\Delta D = 0$) and eastern and western edges (minimum and maximum ΔD) of the substorm current wedge [McPherron et al., 1973; Wiens and Rostoker, 1975; Pytte et al., 1976b]. It appears that at the time of the 0605-UT recovery the central meridian was located near 2230 MLT (Tucson) and that the western edge had moved west of Victoria and Sitka to near 2000 MLT (Honolulu). Similarly, at $\sim$ 1110 UT the central meridian was near 2230 MLT (Sitka) with the western edge near 2100 MLT (Toolangi). The eastern edge seems in both cases to have been to the east of San Juan, or later than 0200 and 0600 MLT, respectively.

The simultaneous Ogo 5 and Vela 5B measurements obtained at 2000 - 2200 and 0000 - 0300 MLT, respectively, are shown in Figure 7. The Ogo particle data exhibit plasma sheet variations similar to those observed in the same local-time sector on September 4, 1968 as described in the previous section. 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. The IMF data in the bottom panel of Figure 7 indicate a northward turning near the 1110-UT plasma sheet recovery whereas there seems to be no clear IMF signatures at the time of the preceding recoveries.

The Vela satellite was probably very close to the neutral sheet at the time of the 0605-UT recovery at Ogo. The drop-out of particle fluxes that usually precedes a plasma sheet recovery was therefore not seen at Vela in this case. However, the particle fluxes did recover to higher 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). 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 $\sim$ 1046 UT.

As indicated by the mid-latitude magnetic signatures in Figure 6, the 0605- and 1110-UT plasma sheet recoveries occurred near the time when the western edge of the current wedge had reached the 2000 - 2100 MLT sector, which was also the approximate local time of Ogo. However, the recovery at Ogo can not be explained simply by a westward expansion of the active sector of the tail to include the location of Ogo. The simultaneous Vela data clearly show that the same recoveries occurred at similar radial distances also at 0100 - 0200 MLT.

The difficulties often involved in distinguishing between ground activity associated with substorm expansions and with the poleward leap can be illustrated by comparing the 1046-UT negative bay on this day with the apparently equivalent event on the same stations at 1117 UT on September 4, 1968 (Figure 2). As the present analysis has shown, there are significant differences between the two events. Thus, the September 6, 1969 event was accompanied by a mid-latitude positive bay onset and a clear Pi 2, and by a large-scale plasma sheet thinning; the subsequent recovery of the plasma sheet occurred ∿ 25 min later in conjunction with a poleward shift of the electrojet (which started near College at ∿ 1110 UT). The September 4, 1968 event, on the other hand, was accompanied by no detectable Pi 2 but by a plasma sheet thickening and a poleward leap near midnight. This shows that the end of a substorm expansion sequence cannot be determined unambiguously on the basis of auroral-zone data alone. The plasma sheet recovery, on the other hand, together with the absence of Pi 2 bursts, seems to provide a much clearer indication that a substorm recovery is in progress.

Magnetospheric Substorms on July 16, 1969

The events discussed in the previous sections suggest that the thickening of the plasma sheet during the poleward leap takes place also at higher latitudes closer to the earth. This is supported by measurements from Ogo 5 and Vela 5B on July 16, 1969.

The auroral-zone magnetograms shown in Figure 8 indicate four intervals of substorm activity, starting at about 1005, 1330, 1708, and 1859 UT, respectively. Mid-latitude magnetograms (not shown) indicate that the 1005- and 1859-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 9). At the time of the 1042-UT recovery the two spacecraft were separated mainly in the Z direction, Vela being in the high-latitude tail lobe. The delay of about 60 min between the plasma sheet encounter at Ogo and the first encounter at Vela, ∿ 4 R_E higher above the neutral sheet, however, seems not to reflect a continuous motion in the Z-direction. This is indicated by the similar intensity variations seen at both satellites around 1200 UT, with the main peak at Ogo apparently occurring 3-4 min later at Vela. The 1342-UT recovery at Ogo, on the other hand, reached Vela ∿ 8 min later, although their vertical separation was as large as 5.5 - 6.0 R_E.

The two events of main interest here occurred at ∿ 1722 and 1924 UT, in both cases about 15 min after a Pi 2 onset. At these times Ogo was in the southern hemisphere at -26^o and -35^o dipole latitude, respectively. The corresponding north latitude of the earth intersects of the field line through Ogo, determined by field-line tracing in the Mead-Fairfield MF73D model, was then ∿ 71^o and ∿ 73^o. At the same times the estimated foot point of the Vela field line was near 72^o latitude. This indicates that, as a first approximation according to this time-independent field model, both spacecraft were on field lines typically reached by ground activity during a poleward leap.

The 1722- and 1924-UT recoveries occurred within 1-2 min at the two spacecraft over radial distances of ~ 7 and $\sim 10\ R_E$ 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 towards higher latitudes both in the Vela orbit and closer to the earth at this particular stage in the substorms.

The flow of plasma near Vela in the plasma sheet boundary region during these two events has been studied previously by Lui et al. [1977a]. They found that the flow was directed generally sunward during both intervals of plasma sheet thickening but that there was an interval of anti-sunward flow just before 1924 UT. Such a reversal from anti-sunward to sunward flow has previously been associated with a tailward shift of an X-type neutral line from earthward to tailward of the Vela satellite [Hones, 1973]. The simultaneous thickening at Ogo and Vela during intervals of sunward flow is consistent with our observations of enhanced electron precipitation at latitudes higher than those reached during the preceding substorm expansions. This would also be in agreement with the results of Lundblad et al. [1978] that the high-latitude precipitation boundary for > 100-keV protons at $\sim$ 1500 km altitude was located around 70° magnetic latitude during substorm expansions but moved to $\sim 75^o$ in association with substorm recoveries.

The bottom panel of Figure 9 shows the north-south component of the IMF at Explorer 41, located at $r \sim 28\ R_E$ near noon. It is seen that the four plasma sheet recoveries at Ogo occurred either during northward IMF or near the time of a northward turning. The plasma sheet thinnings, on the other hand, were associated with a southward IMF. These thinnings, which might be interpreted as due to a decay of particles late in the substorm, occurred during satellite motions both towards and away from the tail's midplane and concurrently in locations above and below this plane. They appear therefore to be truly large-scale reductions in the plasma sheet cross section.

Multiple-Onset Substorms on April 8, 1966

The last event examined here has been studied previously by Hones et al. [1970, 1973] and Meng et al. [1970], but is included to show that the above results may be extended to larger radial distances. This event also illustrates the relation between plasma sheet recovery and the end of a series of substorm expansions.

The upper part of Figure 10 shows the observations of > 45 keV electron fluxes obtained by the Vela 3A and Imp 3 spacecraft, together with the corresponding auroral-zone magnetograms. The two satellites were located in the early morning sector and at radial distances of ~ 19 and $\sim 28\ R_E$, respectively. As pointed out by Hones et al. [1970, 1973], the motion of the polar electrojet towards the zenith at Baker Lake around 0500 UT was correlated with the plasma sheet recovery which reached Vela at 0456 and Imp at 0510 UT. This recovery was preceded by eleven isolated

Pi 2 bursts, shown in the lower part of Figure 10, and the recovery at Vela occurred about 25 min after the last Pi 2. Mid-latitude magnetograms show no indication that this recovery, or the weak partial recovery at Vela around 0300 UT, was due to a substorm expansion that occurred in the local time sector of the satellites (∿ 0100 MLT); on both occasions the central meridian had moved west of 2200 MLT (Fredericksburg and Tucson, respectively), or about 3 hours of local time farther to the west of the satellites.

Another important feature illustrated by this event is the gradual decrease of particle fluxes at Vela for more than 3 hours during the long series of Pi 2 bursts. The continuous bay activity in the morning sector of the auroral zone (Leirvogur) and the absence of any clear plasma sheet recovery around 0300 UT, indicate that the whole period from 0120 to 0440 UT of Pi 2 bursts and bay intensifications should be regarded as one substorm, consisting of eleven substorm expansions. The events discussed in the previous section have indicated that a plasma sheet recovery is the clearest indication that a series of substorm expansion has ended and a substorm recovery is in progress. We here again see that there is no clear plasma sheet recovery after individual expansions, only at the end as ground activity dies away.

Statistical Results

The eight correlated Ogo and Vela events discussed above were selected to illustrate the plasma sheet behavior as observed by two satellites at locations ranging from local early evening to late morning hours. In this section we summarize the main features of these eight and 20 other correlated events, all of which are listed in Table I, and compare the spatial characteristics with those of the events examined above.

The observed time delays of plasma sheet thickening events with increasing spacecraft distances in the dZ, ϕ, and r directions are plotted in Figure 11. These events appear to fall into three categories, depending on their temporal and spatial characteristics. The first category (22 events, shown as black dots) consists of plasma sheet recoveries observed at the two spacecraft within $\sim$ 20 min over distances ranging up to $\sim$ 6 R_E in the direction normal to the tail's midplane, $\sim 53^0$ in azimuth, and $\sim$ 10 R_E in the radial direction. A least-squares fit to a linear function between the time delays ΔT and the parameters ΔdZ, $\Delta\phi$, and Δr indicates a significant correlation only between ΔT and ΔdZ. The regression line indicated in Figure 11a corresponds to a velocity component in the dZ-direction of about 40 km/sec. This is close to the value of $\sim$ 60 km/sec obtained by Hones et al. [1973] on the basis of single-satellite measurements of time delays between auroral-zone bay recovery and plasma sheet recovery at r $\sim$ 18 R_E. Our analysis also shows some coupling between ΔdZ and Δr which is consistent with the approximate orientation of the expanding plasma sheet boundary inferred above. Of the eight events discussed here all but one (event 10 in Table I) belong to this category.

The second category consists of three events (10, 22, 24; open squares in Figure 11) that were observed when one of the satellites was more than about 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. This indicates a non-uniform thickening or a slowing down of the thickening speed with time.

The third category consists of three events (6,9, and 17; open triangles) during which the plasma sheet was observed to expand at Ogo (r $\sim$ 10 - 14 R_E) while it was thinning at Vela (r $\sim$ 18 R_E). This different plasma sheet behavior 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 of an X-type neutral line in the region between the two spacecraft [Pytte et al., 1976a]. The longer time delays observed for these events may then reflect the tendency for the X-line to remain relatively stationary in this 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 this category is also reflected in the long delays often observed between the first Pi 2 and the plasma sheet recovery (e.g. on September 4, 1968; Figure 3).

Summary and Discussion

We have examined nine 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 near the time of a poleward leap of ground activity or during the decay of auroral-zone bays, in agreement with numerous events previously discussed by Hones and co-workers. In six cases of relatively small spacecraft distances from the neutral sheet ($dZ \lesssim 4\ R_E$), the recoveries at Ogo and Vela occurred within less than 5 min; in the two remaining cases ($\sim$ 1200 and $\sim$ 1400 UT on July 16, 1969 when dZ was $\sim$ 6.5 R_E), the delays were about 64 and

8 min, respectively. Two events (1722 and 1924 UT on July 16, 1969) were observed almost simultaneously in the Vela orbit ($r \sim 18\ R_E$) and at high magnetic latitudes in the near tail ($r \sim 7 - 10\ R_E$). Field-line tracings in the Mead and Fairfield [1975] MF73D model indicate that Ogo and Vela were then on nearly the same field line, which in both cases mapped to the ionosphere at latitudes that are usually reached by ground activity during the poleward leap. Other events occurred when both spacecraft were in regions of the tail typically traversed by the Vela satellites but separated by a wide range of distances in the GSM X and Y directions. A ninth event observed by Vela and Imp 3 indicates that the above relations extend out to at least $\sim 30\ R_E$.

These spatial relations, which also agree with the main features observed during an additional 20 events (Table I and Figure 11), are evidence that the late plasma sheet recovery is due to a thickening of the plasma sheet over a significant fraction of the tail's length and breadth which occurs essentially in a direction perpendicular to the neutral sheet or onto higher L shells. As discussed below, this is in contrast to the possibly more localized plasma sheet expansions that occur mainly in the near-tail region and during substorm expansions on the ground.

The plasma sheet recoveries examined in this paper were preceded by as many as eleven Pi 2 bursts on the ground. These magnetic pulsations were observed at stations separated by more than 35^{o} of longitude and are indications of individual onsets of substorm expansions. Seven of the eight recoveries at Ogo and Vela reached the spacecraft within 10 to 28 min of the last in such a series of Pi 2 onsets. These time delays are also comparable with the time interval between successive bursts. Since these near-coincident plasma sheet encounters occurred at small distances from the estimated position of the neutral sheet and seem to result from a rapid motion essentially in the ± Z directions, it seems reasonable to assume that these encounters also represent closely the earliest onset times of the associated plasma sheet thickening. Therefore, since 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 plasma sheet thickening started at the time of a Pi 2.

This relationship of plasma sheet recovery to substorm expansions on the ground is independently indicated also by mid-latitude standard magnetograms. In cases when the presence and location of the substorm current wedge clould be clearly determined, it was found that the recovery occurred 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 independently of a Pi 2 burst. 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 during the poleward leap seems not to agree with the observations of Wolcott et al.[1976] that auroral-zone magnetic pulsations intensified both at the time of auroral break-up and during the poleward leap and plasma sheet recovery. The latter pulsation event, however, was probably associated with the observed poleward shift of the westward electrojet over the station, rather than being an indication of a separate substorm expansion. This is because there was no detectable Pi 2 onset at that time at another station located a little farther to the south of the auroral zone.

Observations of the IMF north-south component were available during eight of the nine intervals examined. It seems that the plasma sheet recoveries sometimes occur near the time of a northward turning of the IMF. In fact, one event (∿ 1345 UT on July 16, 1969) apparently was mainly an effect of a clear northward turning since the preceding substorm signatures were quite weak. It seems likely that the long sequence of Pi 2 bursts that preceded the recoveries on September 4, 1968 and on April 8, 1966 (no IMF data available) occurred during long intervals of predominantly southward B_Z, and that such a sequence of substorm expansions can be interrupted in conjunction with a northward turning of the IMF.

It has been suggested that this interruption of substorm expansions 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 neutral line to move tailward [Pytte et al., 1976a; Vasyliunas, 1976]. Such a build-up may be related to a reduced transport of newly closed magnetic flux away from the near tail due to a reduced demand for closed flux on the dayside following a northward turning. It may also occur if the reconnection rate significantly exceeds the earthward return rate. The plasma sheet recovery may therefore be caused indirectly by the last stronger substorm expansion and start near the peak of that expansion. Thus, the duration of the expansion phase of a substorm, or the time interval between the first Pi 2 and the plasma sheet recovery, may depend on the interrelations between the dayside merging and various magnetospheric convection rates. Since this interval may last for $\lesssim$ 30 min to more than two hours, there seems to be little basis for the idea that the thickening of the plasma sheet starts near the earth early in a substorm, reaching $r \sim 18\ R_E$, purely by coincidence, near the time that activity on the ground approaches its highest latitudes.

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 by invoking the formation and later tailward motion of an X-type neutral line [Aubry et al., 1972; Russell, 1972; Hones et al., 1973; Nishida and Nagayama, 1973; McPherron et al., 1973; Pytte et al., 1976a], the observational evidence for the existence of such a near-earth neutral line has recently been called into question [Lui et al., 1976, 1977b,c; 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 the magnetic signatures and the low- and high-energy particle data near the region of an assumed neutral line during substorm onsets [Hones, 1977; Caan and Hones, 1977] 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. [1976a], indicates that the neutral line, at least at this stage in a substorm, often has a crosstail extension much larger than that anticipated for a 'fireball'.

Our results can also be compared with an often quoted model by Rostoker and Camidge [1971] for the azimuthal dynamics of the plasma sheet (left panel of Figure 12). The main idea of this model is that during 'complex substorms', which consist of quasi-periodic intensifications of the polar electrojet, successive substorm expansions occur in separate local-time sectors (A, B, C) that are shifted progressively farther west. According to this model, a satellite at any radial distance will experience a plasma sheet expansion (shown here as a diamagnetic decrease in the B_X component since these authors used only magnetic field data) only when it is located within the 'collapsing' sector. We note that this model is essentially equivalent to the Wiens and Rostoker [1975] model for a stepwise westward expansion of the polar electrojet, although the latter authors show estimated successive electrojet locations in partly overlapping rather than spatially separated sectors.

The right panel of Figure 12 shows an alternative model for the same type of substorms, where the more recent idea of an X-type neutral line as well as the results of the present study are included. The wedge-like region of an expanded plasma sheet is here limited on the tailward side by the X-line. (The part of this line along which enhanced reconnection is assumed to take place is for simplicity shown to be oriented east-west rather than to curve away or towards the earth [Russell, 1977].) Plasma sheet expansions during the substorm expansion phase occur here within the wedge (in partly overlapping sectors) and are probably accompanied by an average azimuthal expansion of the wedge, as indicated in the figure.

The bottom right traces summarize the observational basis for our model. At r ∿ 12 R_E near midnight (region A near the center of the wedge), the plasma sheet experiences multiple expansions in a one-to-one correspondence with ground Pi 2 bursts and auroral-zone bay intensifications [Pytte et al., 1976a]. At the same time, the tailward plasma sheet (region A' tailward of the wedge) is thinning and remains thin until after maximum auroral-zone bay activity [Hones et al., 1967; 1973]. In the evening sector at r ∿ 18 R_E (region C, initially to the west of the wedge), there is an initial thinning also (see also Akasofu et al. [1971]), but transient particle-flux increases and magnetic perturbations indicative of field-aligned currents are observed during intervals of Pi 2 activity. Such apparently sporadic entries of the satellite into the wedge region may also have caused the multiple plasma sheet thinning and thickening events observed by Vela 5A at 2100 - 2200 MLT during multiple westward traveling surges on the ground [Hones et al., 1976b].

Rostoker and Camidge [1971] attributed the observed absence of magnetic field responses in the tail, during multiple substorm expansions on the ground, to the azimuthally localized nature of these onsets both on the ground and in the tail. However, they were not able to show that a collapse did occur at about the same radial distance but in a neighboring sector of the tail. In view of our studies of multiple-satellite measurements from various regions of the tail we suggest that the lack of response to substorm expansions pointed out by these authors was due to the radial distance to their satellite (∿ 30 R_E), not to its location in azimuth with respect to the substorm activity. Thus, their observations appear to have been obtained tailward of the wedge. Such a separation into two different stages of plasma sheet thickening, which was suggested earlier by Hones et al. [1973], would indicate that the above models of Rostoker and co-workers should be modified to take into account the radial and azimuthal characteristics of plasma sheet dynamics during substorm expansions and during the poleward leap. This would also require a more extended use of Pi 2 pulsations as indicators of substorm expansions.

Our results may also affect the definition of the various substorm phases. The classical model of the auroral substorm by Akasofu [1964] defines the start of the recovery phase as the time when auroral activity has reached its highest latitude and starts to return towards the equator. The phenomena discussed in this 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

On the basis of two-satellite measurements obtained in different local-time sectors of the tail, we have examined the phenomenological differences between plasma sheet thickening events during substorm expansions and during the poleward leap of auroral-zone activity. During an early stage of a substorm, multiple expansions of the plasma sheet often occur in the near-earth region of the tail ($r \lesssim 18\ R_E$); during a later stage the plasma sheet recovers to about or larger than pre-substorm thickness over an extended azimuthal and radial region of the tail. This recovery, which can be identified as a separate phenomenon in the near-earth tail only at high magnetic latitudes (by a satellite not already located deep within the plasma sheet), also seems to extend down to ionospheric heights, causing a poleward expansion of particle precipitation during the poleward leap. The early near-tail plasma sheet expansions are accompanied by ground Pi 2 bursts and seem to result from bursts of enhanced field-line reconnection along a near-earth neutral line. The late plasma sheet recovery, on the other hand, may be explained by a tailward motion of that line and an enhancement of reconnection in a more distant location. This seems to re-establish the plasma sheet on more high-latitude field lines. These differences in the spatial coverage and temporal relations to substorm expansions (there was no detectable Pi 2 onset at the time of the plasma sheet recovery), indicate that the two stages of plasma sheet thickening should be treated as physically different phenomena. It is especially important to determine what processes cause the series of substorm expansions to stop and a poleward leap to occur, eventually leading to substorm recovery.

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Table 1. Spacecraft locations and temporal relations during correlated plasma sheet events

Event No.	Date	Plasma sheet thickening at Vela Time (UT)	Location X_{sm}	Y_{sm}	Z_{sm}	$dZ_{ns}^{\S}$	Sat.	Plasma sheet thickening at Ogo Time (UT)	Location X_{sm}	Y_{sm}	Z_{sm}	$dZ_{ns}^{\S}$	Time diff. Ogo - Vela (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	1040-50	-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

*Store-mode data, onset times uncertain by ± 4 min †Mainly heating of plasma

§According to formula by Fairfield and Ness [1970]

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Figure Captions

Figure 1 GSM equatorial projections of satellite orbits during the intervals studied in this paper. The spacecraft distances above the estimated position of the neutral sheet, according to the formulas of Fairfield and Ness [1970] and West et al. [1978], are indicated at the beginning and end of each interval. Equatorial projections of magnetic field lines in the Mead and Fairfield [1975] MF73D ($K_p \geq 2$) model for 0^0 dipole tilt are superimposed on the satellite orbits.

Figure 2 Auroral-zone riometer recordings and magnetograms during two substorm intervals on September 4, 1968, together with high-pass filtered rapid-run magnetograms from mid-latitude stations. The College and Tixie Z-component magnetograms are included to show latitudinal motions of the center of the polar electrojet. Vertical dashed lines indicate substorm expansion onsets (Pi 2) whereas vertical solid lines mark the time of plasma sheet recovery in the evening sector of the tail. Local magnetic midnight, marked by dots, is ~ 1830 at Dixon and ~ 1900 UT at Zhelania.

Figure 3 Ogo 5 and Vela 4A measurements of the plasma sheet at 1800 - 2200 MLT in the tail on September 4, 1968. Vertical broken lines and asterisks mark the times of Pi 2 bursts on the ground. Discrete Vela data points were obtained during low bit rate tracking. The lower panel shows the north-south component of the IMF at Explorer 34 (before ∿1400 UT, located at ∿20 R_E in front of the magnetosphere) and at Explorer 33 (after ∿1400 UT, at high latitudes near the front of the magnetosphere).

Figure 4 Average energy $\bar{E}$ and energy density U of low-energy electrons at Vela 4A on September 4, 1968. Vertical lines indicate the recovery of hotter plasma.

Figure 5 Details of transient particle bursts at Ogo 5 observed in the evening sector of the tail during Pi 2 activity on the ground.

Figure 6 Auroral-zone and mid-latitude magnetograms on September 6, 1969. Vertical broken lines indicate substorm expansion onsets, whereas solid lines mark the onset of plasma sheet recovery at Ogo.

Figure 7 Observations of particle fluxes and magnetic fields at Ogo 5 (2000-2200 MLT) and particle fluxes at Vela 5B (0000 - 0300 MLT) in the magnetotail on September 6, 1969. Vertical broken lines indicate the onset of substorm expansions on the ground. The bottom panel shows the B_Z component of the IMF at Explorer 35 (∿60 R_E from the earth at ∿0800 LT).

Figure 8 Auroral-zone magnetograms on July 16, 1969. Vertical broken lines are substorm expansion onsets, solid lines onsets of plasma sheet recovery at Ogo 5.

Figure 9 Ogo 5 and Vela 5B measurements in the plasma sheet on July 16, 1969. Vertical broken lines are substorm expansion onsets, solid lines the onset of plasma sheet recovery at Ogo. The dZ_{NS}-values for Ogo given in parenthesis are estimated distances from a near-tail curved "neutral" sheet that tapers into the magnetic equatorial plane at $r \sim 5\ R_E$ [West et al., 1978].

Figure 10 Measurements of >45 keV electrons at Vela 3A ($r \sim 18\ R_E$) and at IMP 3 ($r \sim 27\ R_E$), together with ground standard and pulsation magnetograms on April 8, 1966. The two satellites were moving away from the neutral sheet and were at ~0500 UT located at $dZ \sim 3.4$ and $6.4\ R_E$, respectively. The pulsation recordings shown in the bottom panel are high-pass filtered rapid-run recordings. Typical Pi 2 amplitudes are $3 - 5_\gamma$.

Figure 11 Summary of the main temporal and spatial relations observed during 28 plasma sheet thickening events at Ogo 5 and Vela. The time delays between the observed onset of thickening at the two spacecraft with their increasing separations in the a) direction approximately normal to the neutral sheet, b) GSM longitude and c) radial direction have been plotted, using different symbols for events belonging to the three categories discussed in the text. The numbers labeling open squares and triangles refer to event numbers given in Table I. The least-squares fit indicated in Figure 11a is at the 95% confidence level.

Figure 12 Two different phenomenological models of plasma sheet dynamics during substorm expansions and during the poleward leap. The left-hand model [Rostoker and Camidge, 1971] assumes that successive multiple expansion onsets occur in adjacent sectors of the tail. In the right-hand model we propose that each expansion onset uccurs within essentially the same wedge-like region of the near tail, and therefore in partly overlapping locale-time sectors, but that the wedge on the average expands in azimuth in the course of a substorm. The plasma sheet signatures postulated by Rostoker and Camidge (lower left) are also compared with signatures that have been observed by pairs of satellites during different but temporally and morphologically similar substorms (lower right).

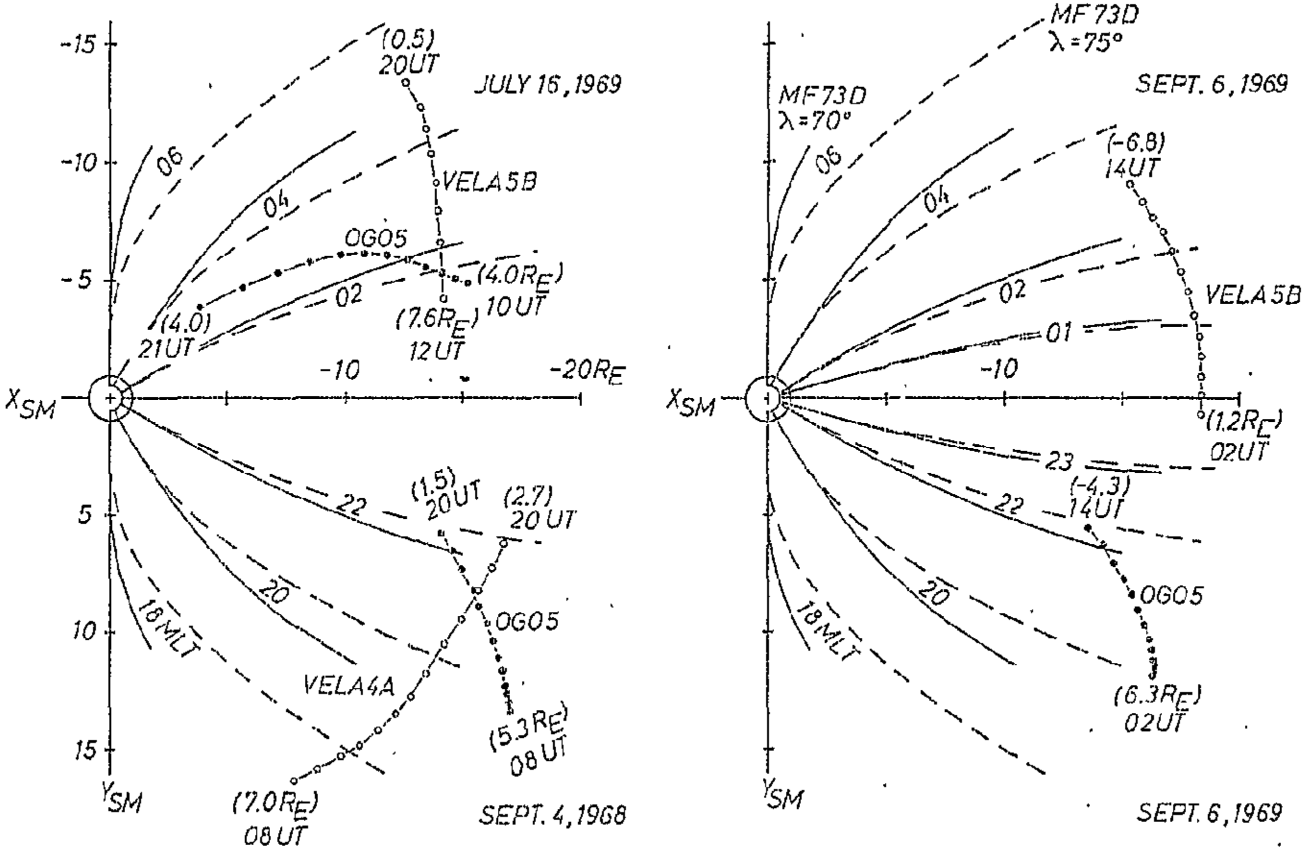
JULY 16, 1969
SEPT. 4, 1968
SEPT. 6, 1969
SEPT. 6, 1969
MF73D
λ=75°
MF73D
λ=70°
VELA5B
OGO5
VELA4A
(0.5)
20UT
(4.0)
21UT
(4.0RE)
10UT
(7.6RE)
12UT
(1.5)
20UT
(2.7)
20 UT
(5.3RE)
08 UT
(7.0RE)
08 UT
(-6.8)
14UT
(1.2RE)
02UT
(-4.3)
14UT
(6.3RE)
02UT
06
04
02
01
23
22
20
18MLT
-15
-10
-5
5
10
15
-10
-20RE
XSM
YSM

Figure 1

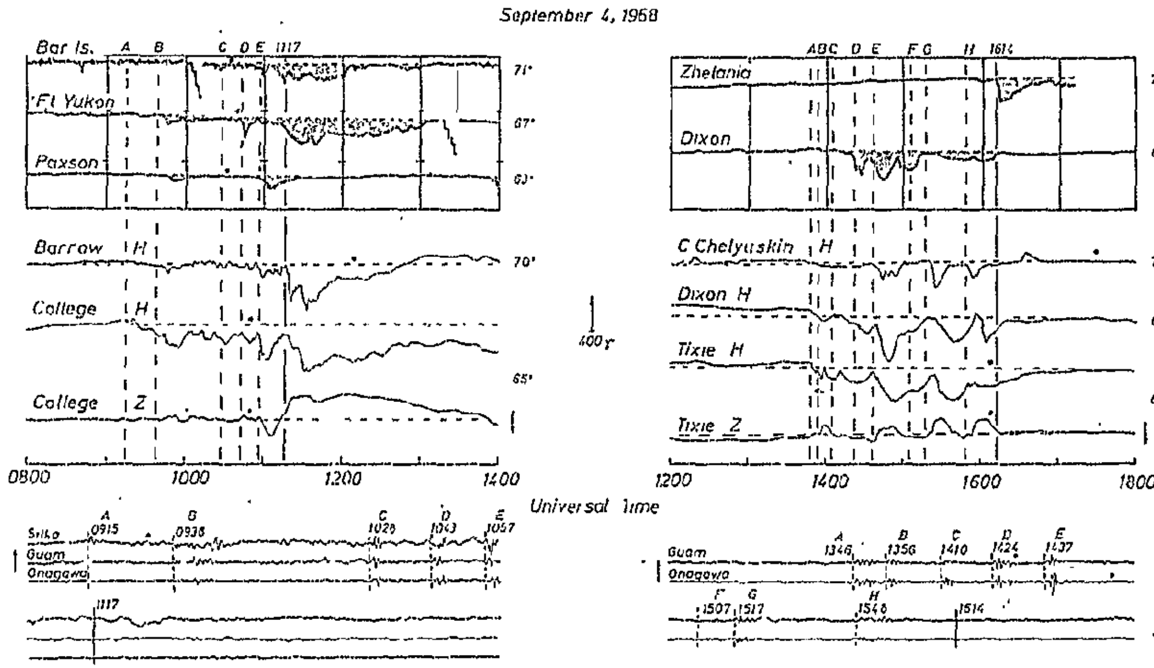
September 4, 1958
Bar Is.
Ft Yukon
Paxson
Barrow H
College H
College Z
Zhelania
Dixon
C Chelyuskin H
Dixon H
Tixie H
Tixie Z
400γ
0800
1000
1200
1400
1600
1800
Universal Time
Sitka
Guam
Onagawa
0915
0938
1020
1043
1057
1117
1346
1356
1410
1424
1437
1507
1517
1546
1614

Figure 2

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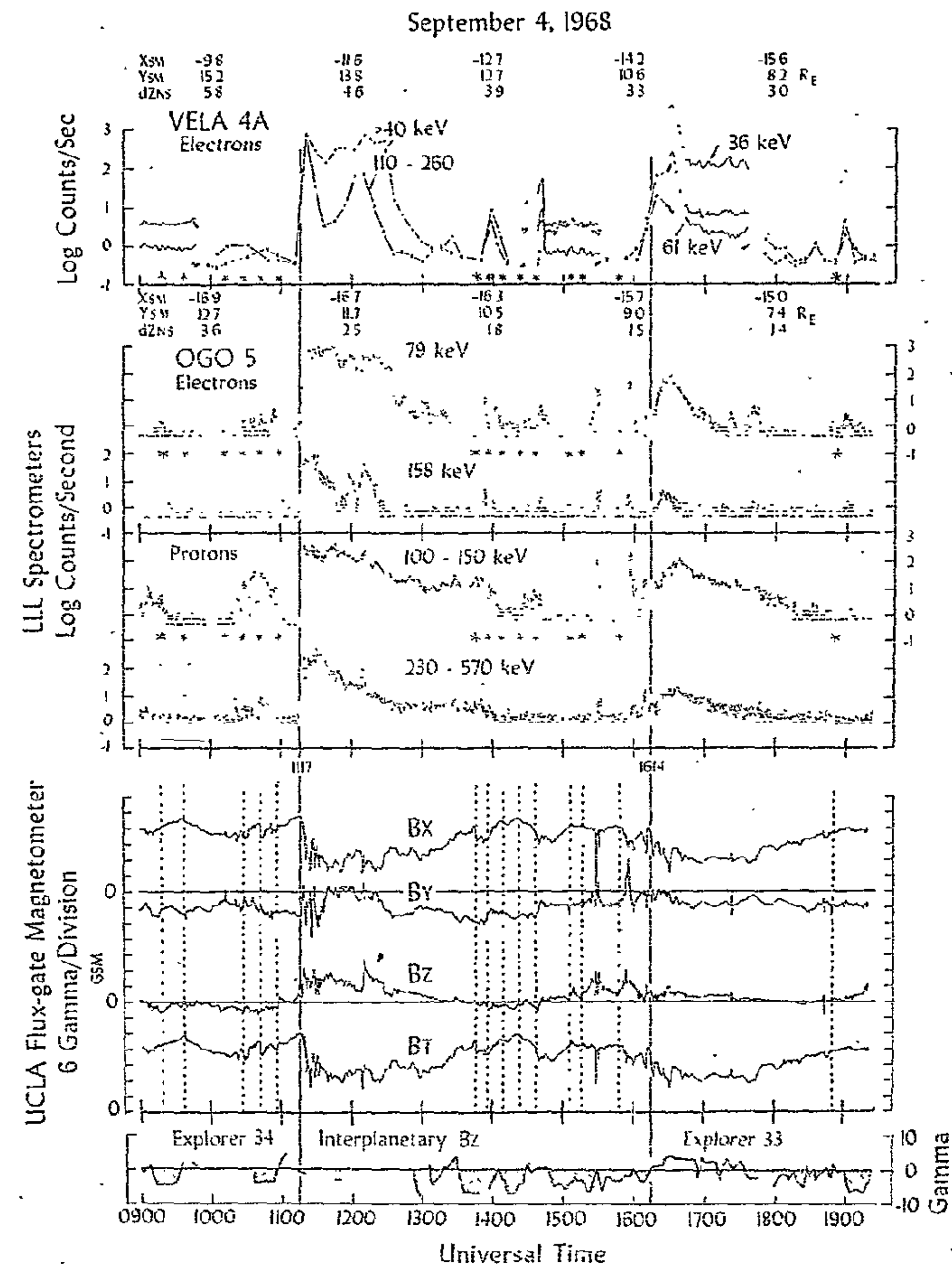
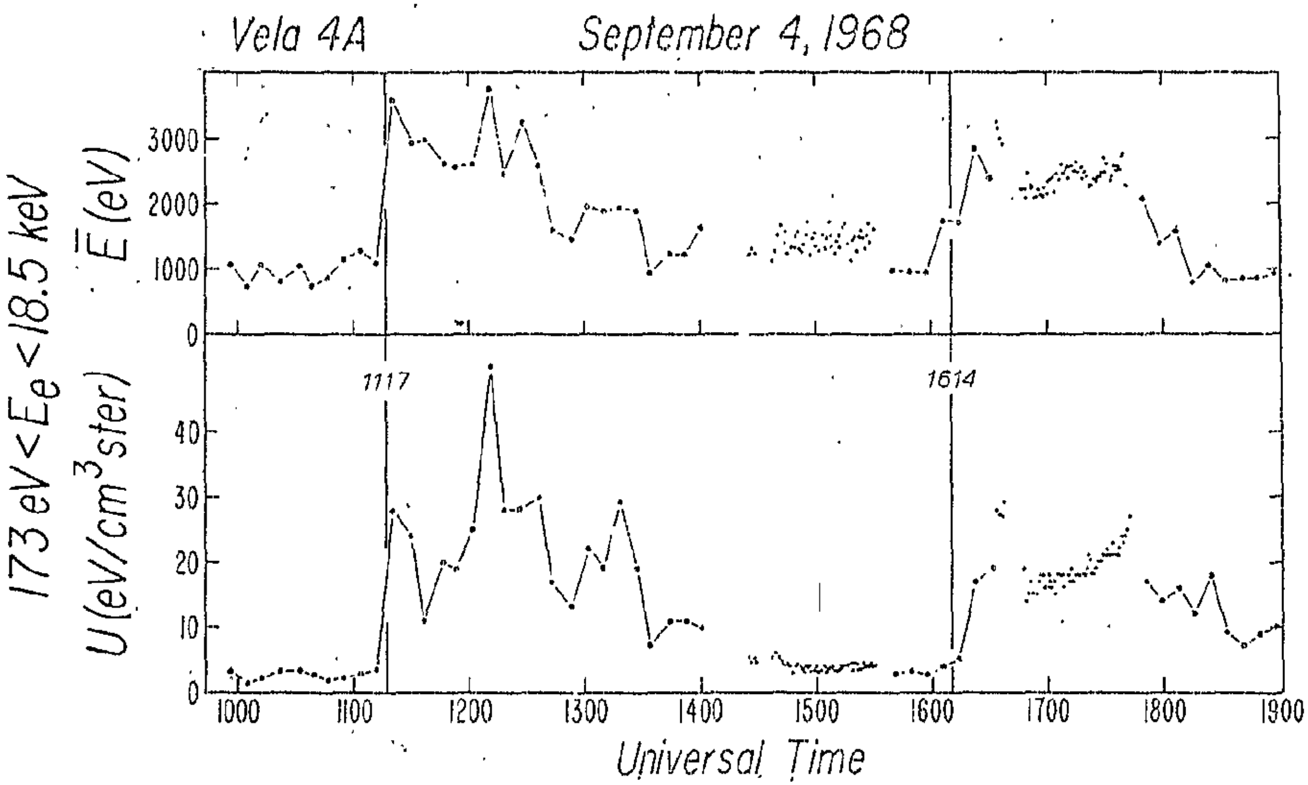


Figure 3



Vela 4A
September 4, 1968
173 eV < E_e < 18.5 keV
$\bar{E}$ (eV)
U(eV/cm^{3}ster)
1117
1614
Universal Time

Figure 4

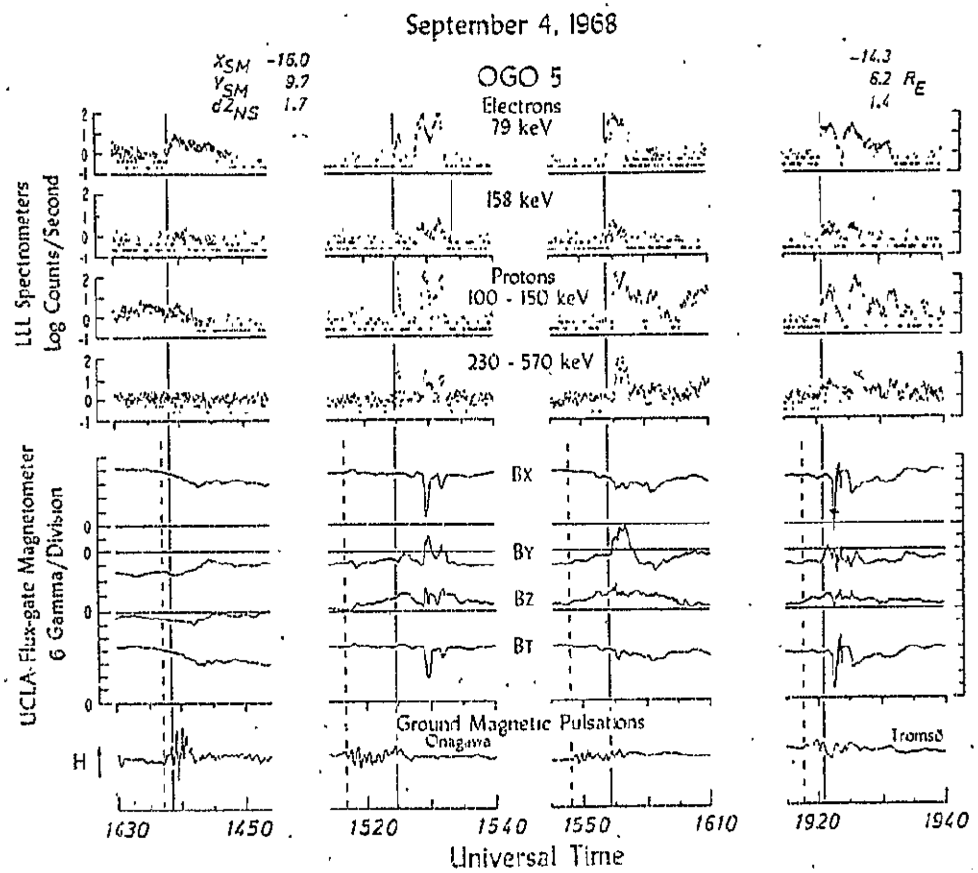


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Figure 5

September 6, 1969

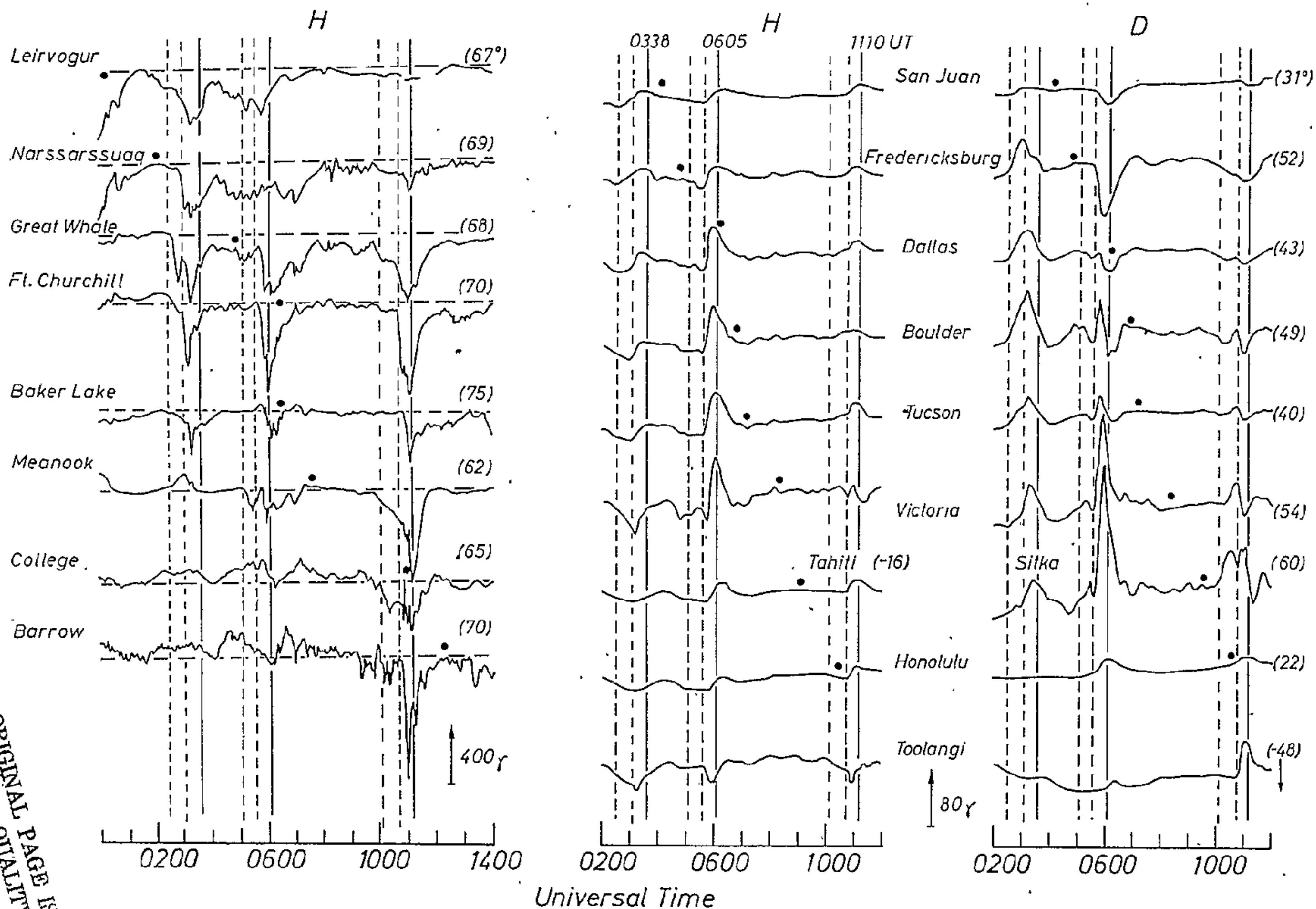
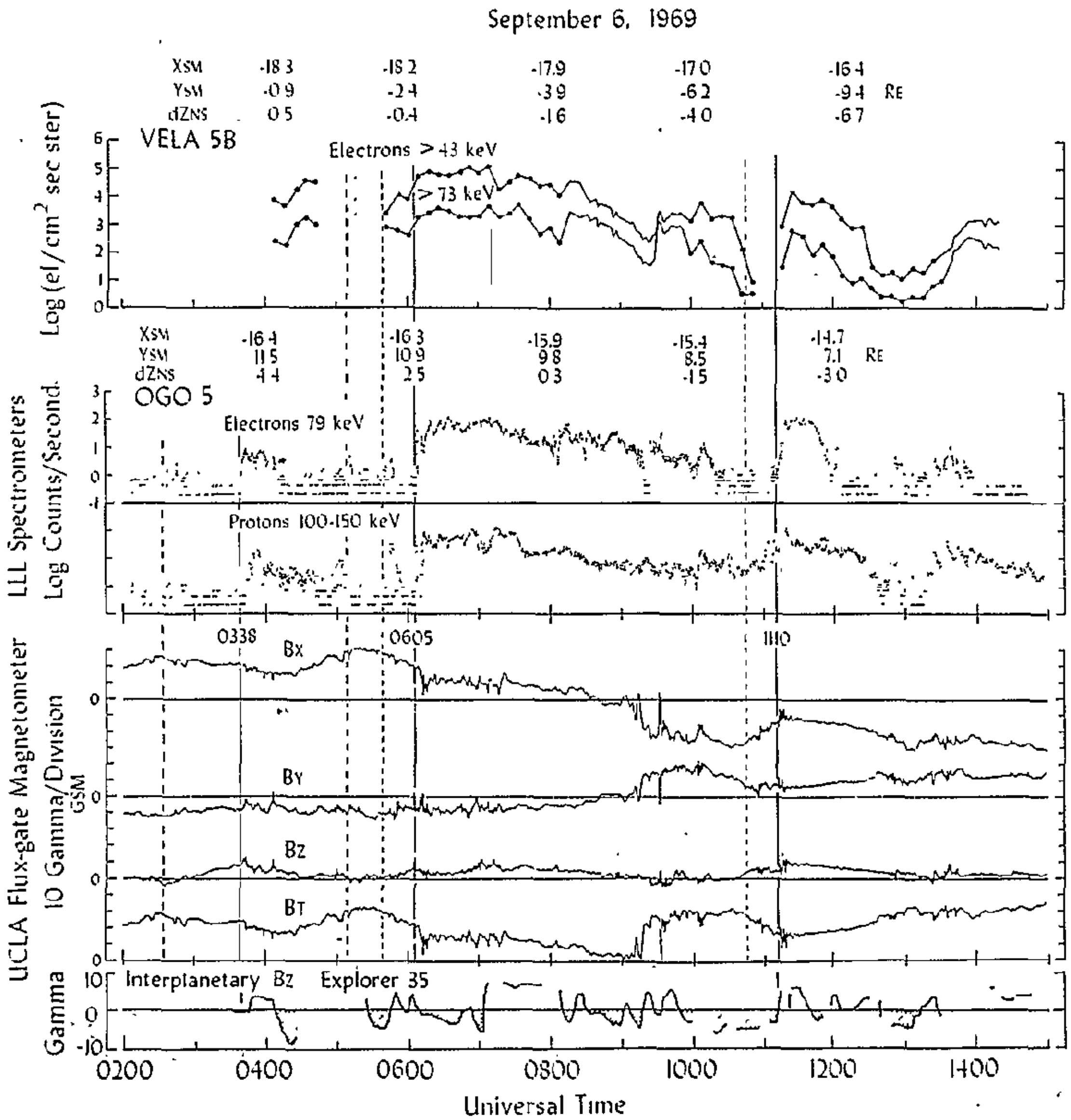


Figure 6



September 6, 1969
XSM -18.3 -18.2 -17.9 -17.0 -16.4
YSM -0.9 -2.4 -3.9 -6.2 -9.4 RE
dZNS 0.5 -0.4 -1.6 -4.0 -6.7
VELA 5B
Electrons > 43 keV
> 73 keV
Log (el/cm² sec ster)
XSM -16.4 -16.3 -15.9 -15.4 -14.7
YSM 11.5 10.9 9.8 8.5 7.1 RE
dZNS 4.4 2.5 0.3 -1.5 -3.0
OGO 5
Electrons 79 keV
Protons 100-150 keV
LLL Spectrometers
Log Counts/Second
0338
0605
1110
BX
BY
BZ
BT
GSM
UCLA Flux-gate Magnetometer
10 Gamma/Division
Interplanetary BZ Explorer 35
Gamma
0200 0400 0600 0800 1000 1200 1400
Universal Time

Figure 7

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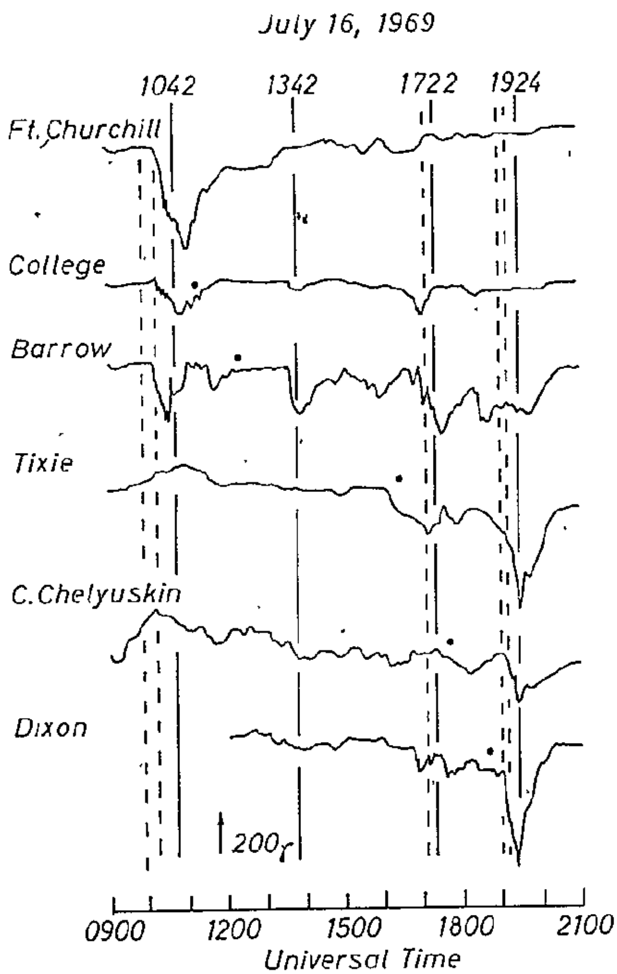
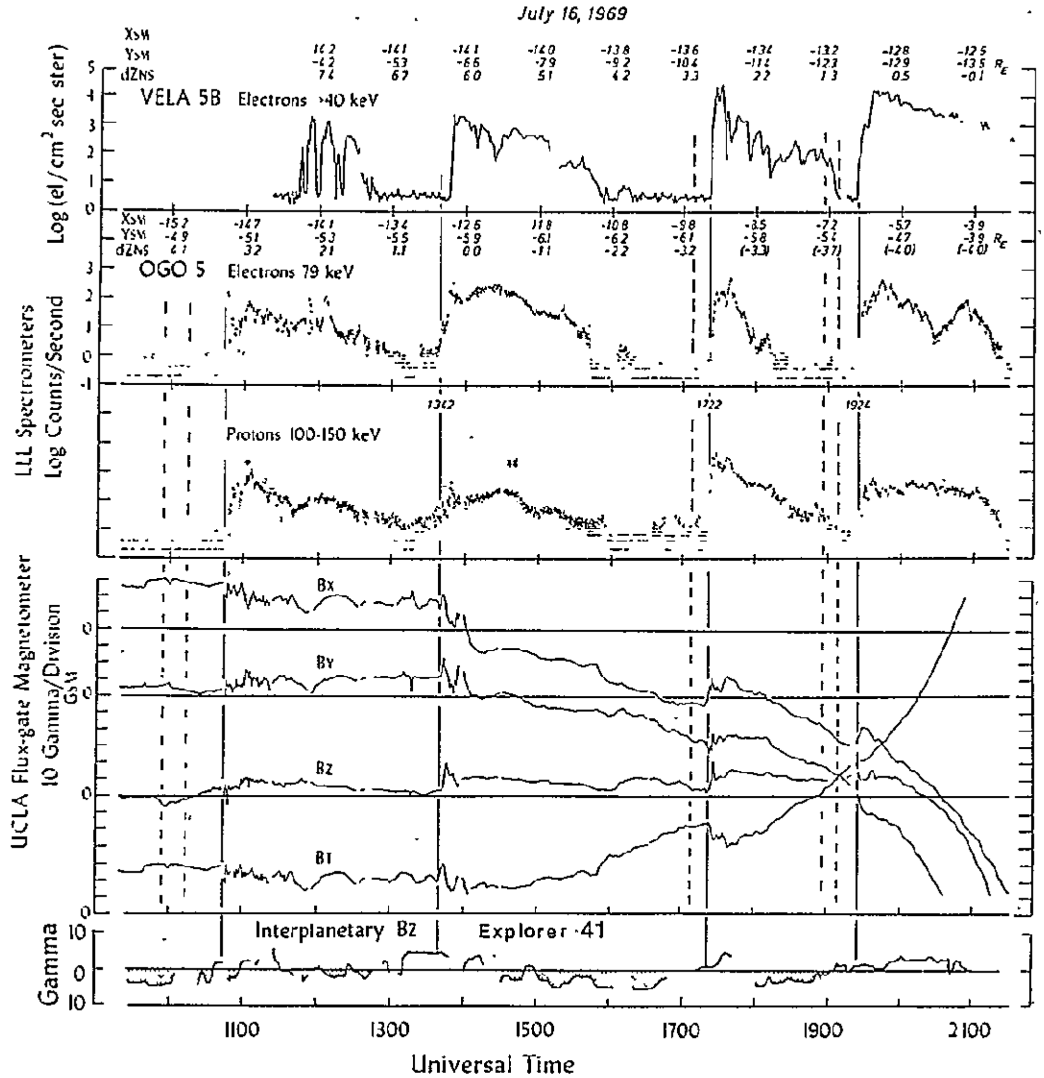


Figure 8



July 16, 1969
VELA 5B Electrons >40 keV
Log (el/cm² sec ster)
OGO 5 Electrons 79 keV
LLL Spectrometers Log Counts/Second
Protons 100-150 keV
UCLA Flux-gate Magnetometer 10 Gamma/Division GSM
Bx
By
Bz
BT
Interplanetary Bz
Explorer 41
Gamma
1100
1300
1500
1700
1900
2100
Universal Time

Figure 9

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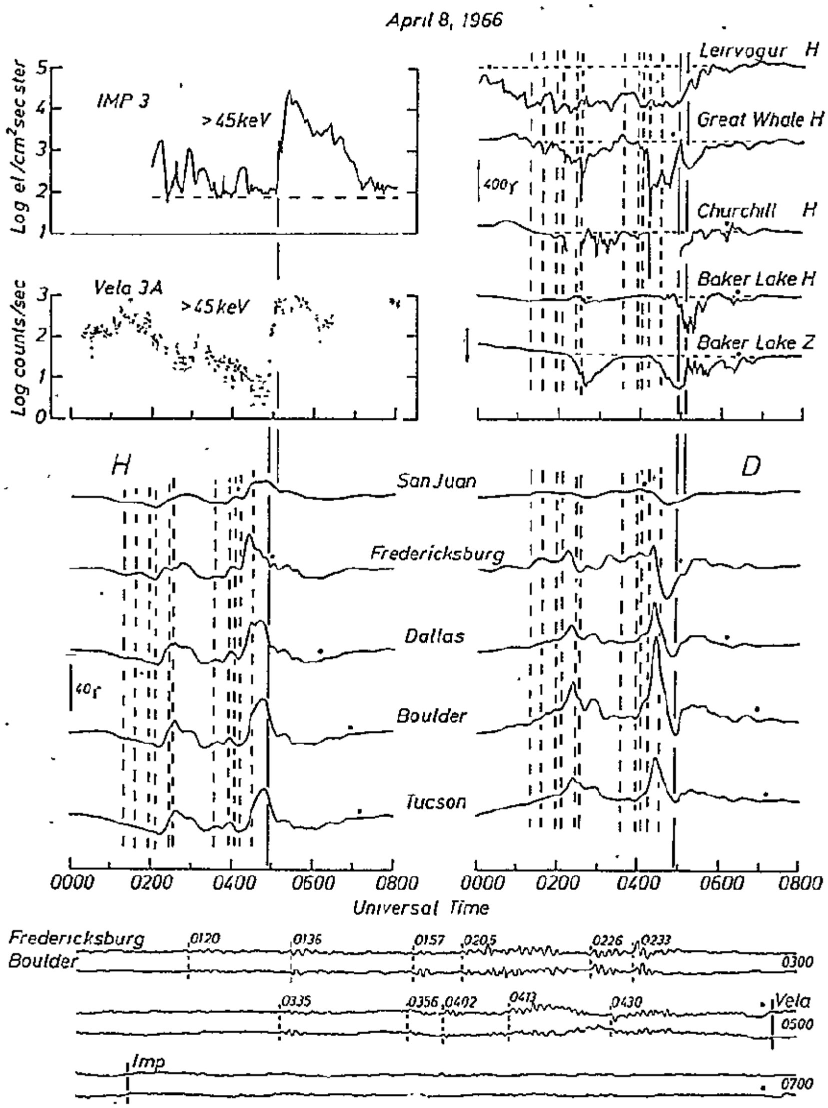

Figure 10

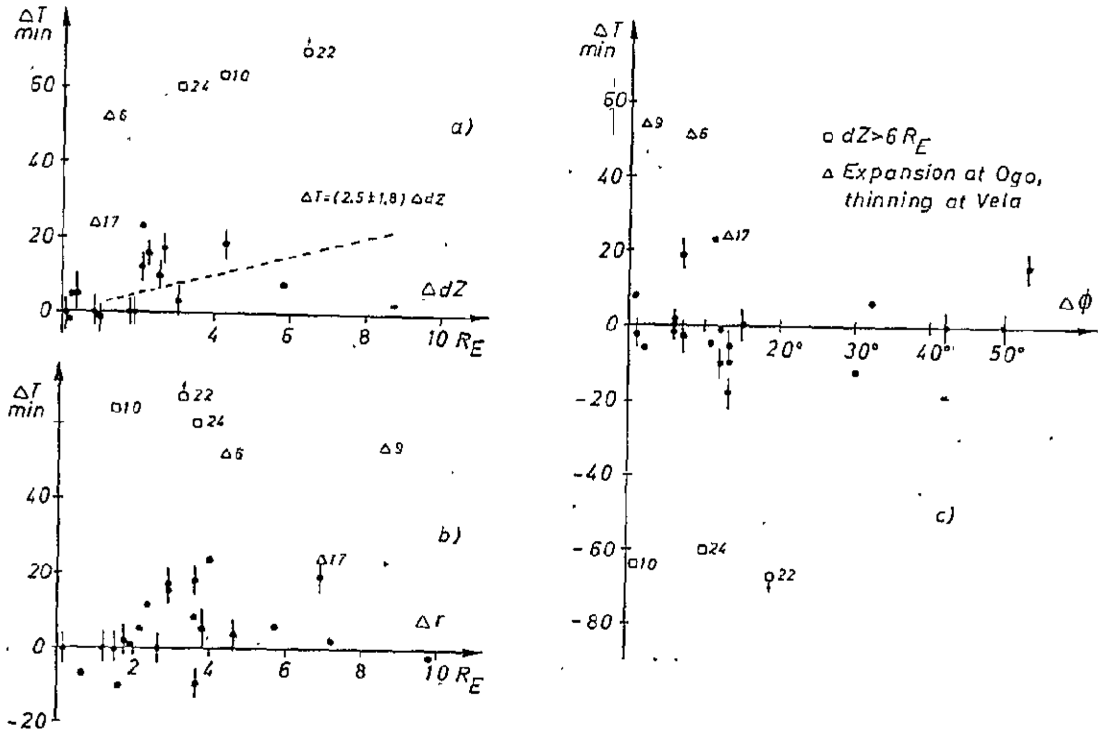
ΔT min
a)
ΔT=(2,5±1,8) ΔdZ
ΔdZ
10 R_E
b)
Δr
10 R_E
c)
□ dZ>6 R_E
Δ Expansion at Ogo, thinning at Vela
Δφ

Figure 11

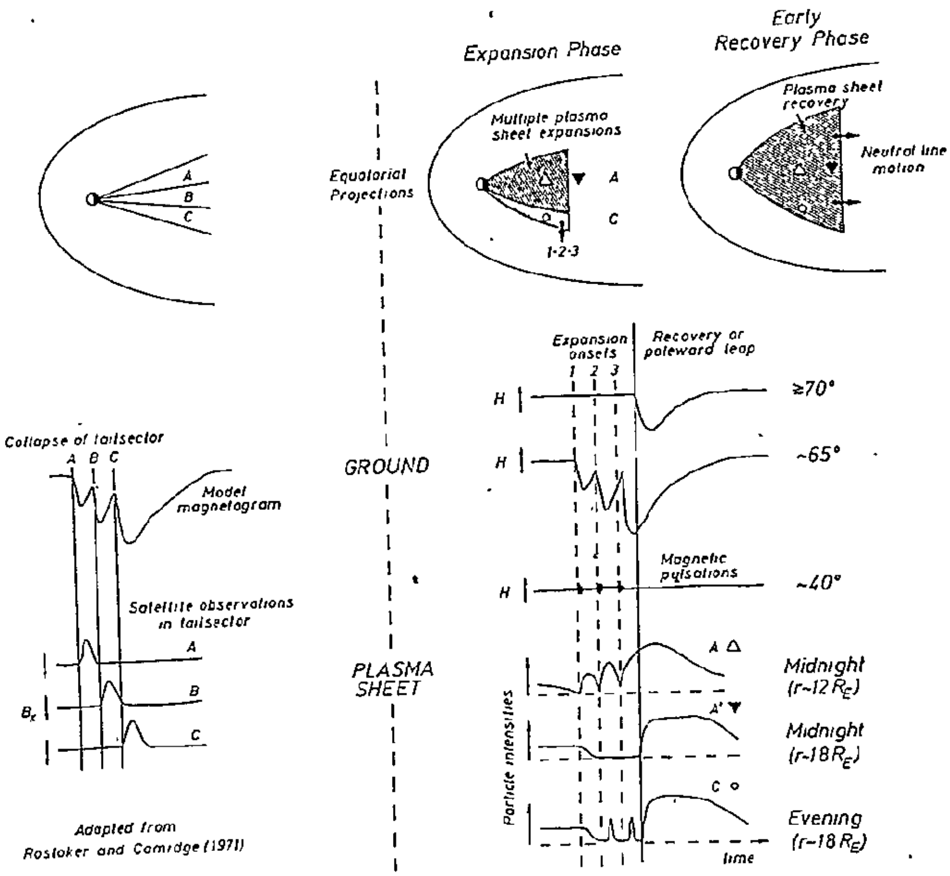
Expansion Phase
Early
Recovery Phase
Multiple plasma
sheet expansions
Plasma sheet
recovery
Neutral line
motion
Equatorial
Projections
A
B
C
1-2-3
Expansion
onsets
1 2 3
Recovery or
poleward leap
H
≥70°
~65°
~40°
Magnetic
pulsations
GROUND
PLASMA
SHEET
Collapse of tailsector
A B C
Model
magnetogram
Satellite observations
in tailsector
B_x
Particle intensities
Midnight
(r~12 R_E)
Midnight
(r~18 R_E)
Evening
(r~18 R_E)
time
Adapted from
Rostoker and Camidge (1971)

Figure 12