J Geophys (1981) 49:176–185

Journal of Geophysics

High Time-Resolution Correlation Between the Magnetic Field Behaviour at 37 R_E Distance in the Magnetotail Plasma Sheet and Ground Phenomena During Substorm Expansive Phase

V.A. Sergeev

Physical Institute of Leningrad, State University, Leningrad 198904, USSR

Abstract. The changes of the magnetic field, detected by the IMP-8 satellite during six successive well-defined substorms on 3 March 1976, are studied in relation to the typical expansive phase microstructure (microsubstorm sequence or multi-step substorm) derived from the extensive complex of ground observations, and also in relation to the thin structure of separate microsubstorms (the formation of new arcs at the poleward front of the expanding auroral bulge with simultaneous abrupt changes in the Pi2 pulsation regime of mid-latitudes). Both the successive Pi2 onsets and the moments of abrupt changes in their regime, along with the corresponding auroral phenomena, are simultaneous (usually within the 0.5 min resolution of the data) with the impulsive magnetic field variations in the plasma sheet, whose pattern at 37 R_E was found to change typically in a sequence of microsubstorms, constituting the whole expansive phase; each of them is also related to the fast particle energization.

Key words: Auroral substorm – Magnetospheric substorm – Expansive phase – Substorm microstructure

Introduction

Changes of the magnetic field and plasma properties in the magnetotail during substorms have been investigated in many papers, but it is mainly the large-scale features, having the time scale of the expansion phase duration (0.5–1 h) which have been determined unambiguously (Fairfield and Ness 1970; Hones et al. 1973; Russell and McPherron 1973; Nishida and Nagayama 1973; Hones 1979). At the same time a number of experimental results obtained recently demand a more detailed description of the magnetospheric phenomena, this being necessary for understanding and modelling of the explosive energy dissipation process operating in the magnetotail during the substorm expansion phase. The time scale of the explosive energy dissipation is often only 0.1–1 min, as suggested by the direct observation of strong impulsive electric fields (Aggson and Heppner 1977; Pedersen and Grard 1978) and particle bursts up to MeV energy (Krimigis and Sarris 1979). A study of the magnetic field and plasma particles also displays brief periods of intense variations, repeated a few times during the expansion phase (Pytte et al. 1976b, 1978; Sergeev 1977). The observation of high-energy particle bursts (Krimigis and Sarris 1979) and studies of magnetic and plasma variations (Rostoker and Camidge 1971; Sergeev 1977; Pytte et al. 1976b; Lui et al. 1977a, b) also suggest the spatial localization of the active region. In particular, its longitudinal range, is less than the magnetotail width.

Thus the process of the explosive energy transformation is apparently short-lived and localized and occurs sporadically at different regions of the magnetotail during the substorm expansive phase.

This paper is devoted to a detailed study of the magnetic field response at 37 R_E distance in the vicinity of the magnetotail plasma sheet to the discrete time structure of the substorm expansive phase. The results, combined with similar ones obtained for the 10–20 R_E distances (Pytte et al. 1976b, 1978; Sergeev 1977) are used to infer the pattern of magnetic field variations and its changes during the successive events in the whole expansion phase.

Such studies demand the independent determination of the times of explosive energy dissipation events (microsubstorms). These can be found by means of ground signatures. There have been several previous studies, where the onsets of separate microsubstorms (a series of which is also named a multi-step, multi-staged or multi-onset substorm) are defined by one or a complex of signatures: auroral expansion, rapid intensification of westward auroral electrojet, onset or abrupt changes of the mid-latitude magnetic bays, or Pi2 train onset (Clauer and McPherron 1974; Vorobjev and Rezenov 1973; Sergeev 1974, 1977; Wiens and Rostoker 1975; Pytte et al. 1976a, b; Sergeev and Yahnin 1979a, Saito et al. 1976; Untiedt et al. 1978). The summary by Sergeev and Tsyganenko (1980) shows that in practically all events under investigation the discrete structure (series of microsubstorms) is evident, if the station network used is appropriate for such studies. The microsubstorms have a duration of expansion of about 5 min with 5–20 min intervals between them, the active region can displace (or widen) both to the east and/or to the west in successive microsubstorms and new activity can arise in the region outside the previous one. The microsubstorm onsets, defined by these signatures, are synchronous with the abrupt changes of magnetic field and plasma properties in the magnetotail (Sergeev 1977; Pytte et al. 1976b, 1978).

Recent investigations have also revealed the thin structure of separate microsubstorms: the rapid auroral expansion usually proceeds through the formation of new arcs at the poleward edge of the expanding auroral bulge in 1–3 min (Sergeev and Yahnin 1978, 1979b), the times of arc formation are marked by strong impulses of the bremsstrahlung X-ray emission and by separate Pi1B bursts under the bulge and also by simultaneous changes in the characteristics (amplitude, phase, polarization) of the Pi2

0340-062X/81/0049/0176/$02.00

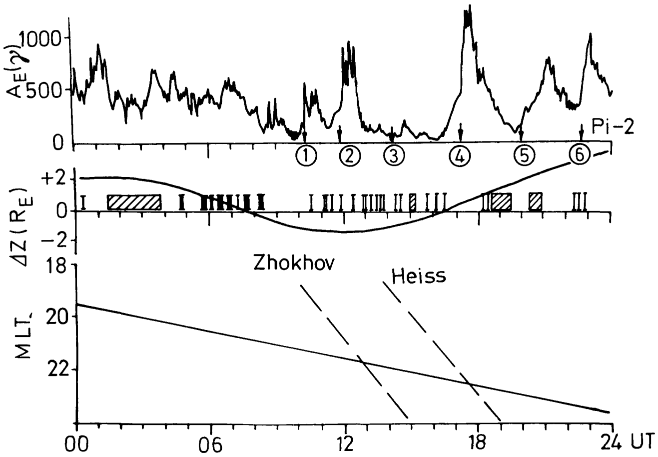

Fig. 1. *Top*. AE (γ) index (from Allen et al. 1977) for 3 March 1976, *arrows* mark the onsets of first Pi2 trains, in sequence, during each substorm event. *Center bos*: the distance of IMP-8 satellite from calculated neutral sheet position (Vette 1975), *vertical bars* indicate the times of neutral sheet crossings and hatched boxes, the gaps in the data. *Bottom*: the MLT meridian of IMP-8 projection into the ionosphere (from Tsyganenko (1979) model) and MLT positions of two all-sky cameras (coordinates in Table 1), whose data we use for detailed ground-satellite correlations

train at mid-latitudes (Sergeev et al. 1978). An attempt to correlate the magnetic variations in the magnetotail with this thin structure of the expansion phase is also undertaken in our paper.

Data

The magnetic field data in the magnetotail are the IMP-8 satellite measurements; 15.36 s averages of field components in (GSM) coordinate systems along with the standard deviation of separate 1.28 s points in 12 point sequence (SD) are used in this study. We select for the analysis the period 10–23 hours UT on 3 March 1976. Five successive substorms (events 1–2, 4–6 in Fig. 1) during this interval are rather intense and well-defined both in auroral zone and low-latitude magnetic variations and have a duration ≦2 h. The event 3 in contrast appears only in Pi2 pulsation data, and thus provides on opportunity to compare its magnetospheric signatures with the ones during intense substorm events.

During all this period the IMP-8 satellite was in a favourable location within 2 R_E from the calculated position of the neutral sheet (Vette 1975). Its data display the multiple crossings of the neutral sheet. The magnetic local time (MLT) meridian of IMP-8 projection into the ionosphere is shown also at the bottom of Fig. 1, a semi-empirical magnetospheric model of Tsyganenko (1979) being used.

For the determination of the microsubstorm onsets we used an extensive complex of ground data, including the normal magnetometer data of auroral zone stations and of the dense mid-latitude net of Soviet stations; rapid-run magnetometer (sensitivity 0.1–0.3 γ/mm at 0.2–0.02 Hz, chart speed 15 mm/min), induction magnetometer, and all-sky camera data are also used (Table 1). The most complete reconstruction of the expansive phase microstructure is possible for event 4 in Figs. 1 and 2, when the station network was optimal for the range 19-03 MLT and four all-sky cameras were operated. This substorm is also an extremely favourable event in view of its large intensity ($\gtrsim$1,500 γ in AE index and $\gtrsim$50 γ at mid-latitudes) and the isolation of its onset. The IMP-8 satellite was located within 1 R_E of the estimated neutral sheet, slightly towards the evening of the magnetotail center ($Y_{SM} \sim +5\ R_E$). Therefore we start the data presentation from this ideal event.

Experimental Data

Space-Time Microstructure of the Expansion Phase of the Ideal (Isolated, Intense) Substorm Event on 3 March 1976 (17·16 UT)

All four above-mentioned ground signatures showed consistently the onset of an explosive phase at 17:16.0–17:16.5 UT Prior to this time the smooth development of the twin-vortex current system with the pronounced westward and eastward electrojets was noted. After 16:20 the quiet auroral arcs drifted equatorwards and the magnetic field magnitude at the IMP-8 location increased smoothly.

First of all let us consider the data from the all-sky cameras (their positions are indicated in Table 1), supplemented by the information on the appearance periods of short-lived discrete ra-

Table 1. List of stations from which data have been used in this study

Station	Symbol	Type of[a] instrument	CG Latitude[b] and Longitude		Station	Symbol	Type of[a] instrument	CG Latitude[b] and Longitude	
Leirvogour	LEI	NM, RM	65.6	69	Hermanus	HER	NM	−42	81
Bear Is.	BJO	NM	71.0	110	Kaliningrad	KAL	P	50	98
Ny Alesund	NYA	NM	75.6	114	Lvov	LVO	NM	45	99
Loparskaya	LOP	ASC, NM	64.4	115	Tbilisi	TBI	NM, P	37	117
Heiss Is.	HEI	ASC	74.6	144	Ashkhabad	ASH	NM	33	130
Dixon	DIX	NM	67.7	156	Sverdlovsk	SVE	NM,RM	52	134
Norilsk	NOR	NM	63.4	161	Alma-Ata	AA	NM	38	149
Cape Cheluskin	CHE	NM	71.1	175	Novosybirsk	NOV	NM	49	159
Tixie Bay	TIX	NM	65.2	196	Irkutsk	IRK	NM	47	176
Zhokhov Is.	ZHO	ASC	70.0	210	Yakutsk	YAK	RM, P	55	200
Barrow	BAR	NM	69.5	248	Magadan	MAG	NM	53	218
College	COL	RM	65.0	261	Petropavlovsk	PET	NM, P	45	225
					Guam	GU	RM	4	212

[a] NM and RM – normal and rapid-run magnetometers, P = induction magnetometer, ASC = all-sky camera
[b] Corrected Geomagnetic Coordinates for 1980,0 epoch (Tsyganenko 1979)

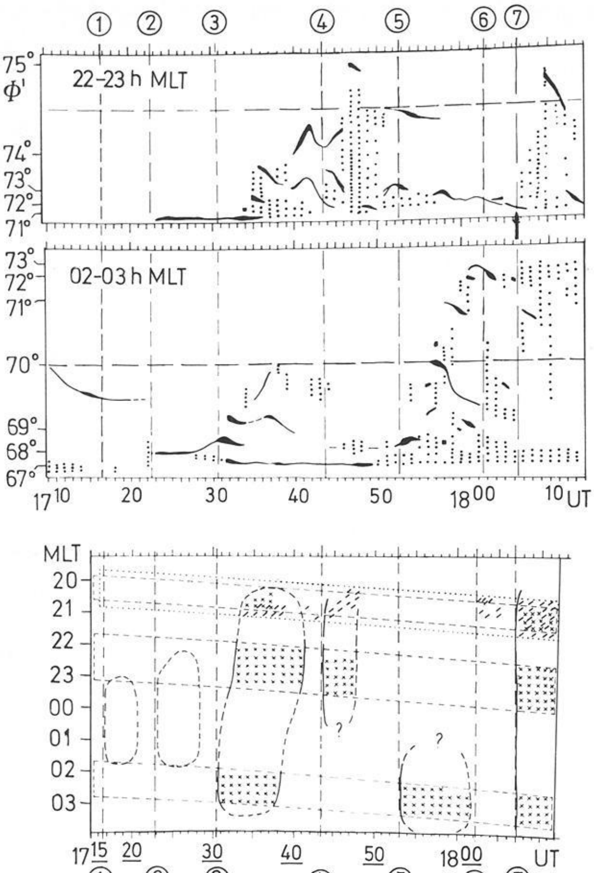

Fig. 2. *Top*: profiles of aurora position over Heiss Is. (22–23 h MLT) and Zhokhov Is (02–03 h MLT) meridians in supposition of 110-km auroral form height. *The lines and points* indicate the discrete and diffuse (and irregular) auroras, *the line thickness and density of points* show qualitatively their brightness. *Bottom:* UT-MLT diagram showing the fields of view of all-sky cameras (*broken lines*) and auroral radar at Essoila (*pinted lines*); the periods of auroral expansions and appearance of short-lived discrete radio-auroral signal (from Timofeev and Yahnin 1980) are hatched to see claerly the onsets of different activizations and their longitudinal ranges

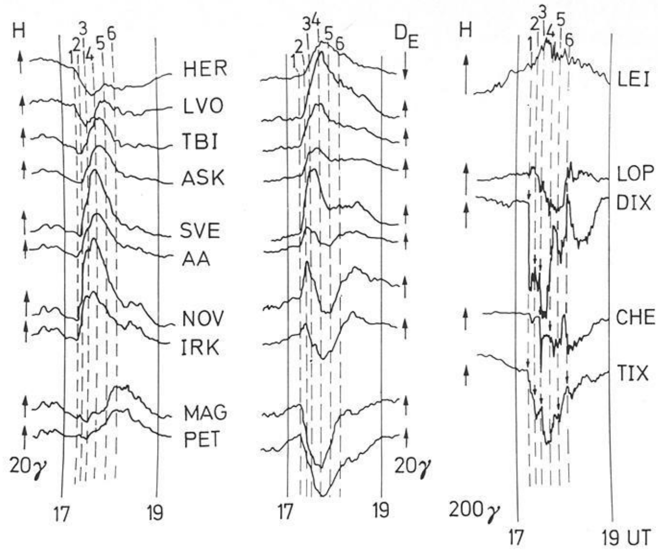

Fig. 3. Magnetograms of mid-latitude and auroral zone stations, *the vertical broken lines* indicate the onsets of separate microsubstorms

dio-auroral reflections at 95 MHz frequency, seen in the sector 20–21 h MLT in the auroral zone. The latter were presented by Timofeev and Yahnin (1981), where the close relationship of these signals to auroral expansions was well-documented. The more useful information on the dynamics of the poleward part of the auroral bulge during this event follows from the data from the most poleward stations, Heiss and Zhokhov Islands, whose data are displayed in the form of the meridional profile of auroras at the top of Fig. 2. The bottom part of this figure shows the approximate MLT location of the auroral expansion region in the form of an UT-MLT diagram.

The onset of auroral expansion is marked by the strong auroral brightening and auroral break-up at 17:16 UT (1 on Fig. 2) over the northern sky of Norilsk. At 17:23 UT (2) the brightening is evident over Zhokhov Island, and the NW portion of the auroral bulge appears at the SE horizon of Heiss Island. Until to it fades near 17:29 the westward travelling surge is situated in the sector 130–140° longitude. At 17:31 (3) the brightness of northern arcs suddenly increases over Loparskaya and Zhokhov Island, then the strong auroral expansion is evident in the data from Heiss and Zhokhov Islands (Fig. 2), and the westward edge of the auroral bulge appears over Scandinavia, coinciding with the appearance of discrete radio-auroras in this sector. The time structure of this intense expansion will be considered in more detail in the following section. The following event is less evident: at 17:42 (4) the brightening of the edge of the auroral bulge can be inferred from the data of Heiss Island and Loparskaya, followed by a small expansion after 17:44 UT. At 17:53 (5) strong brightening was detected over Zhokhov Island, followed by significant expansion; some brightening was observed at the northern bulge edge over Heiss Island, but, in contrast to the morning sector, there was no observable expansion (see Fig. 2). The definition of the next event (6) at 18:03 UT is more subjective, as it is based only on the appearance of the discrete radio-auroras in the evening sector (the auroral bulge in this sector is located polewards of the field of view at Loparskaya at this time), but the following event (7) at 18.07 UT results in fast auroral expansion, simultaneously observed in all of the sector 20-03 h MLT (Fig. 2).

The auroral zone magnetograms, displayed in Fig. 3, support the above definition of the expansion events, showing the pronounced intensifications of the westward auroral electrojet in those sectors where the auroral expansions take place. The last expansion (7) results in the sharp negative bay at Barrow (05 hours MLT), thus the MLT range of this event is very wide compared to the previous expansions.

The low-latitude bay-like disturbances (Fig. 3) also display pronounced sharp changes at the times marked. The changes of their longitudinal pattern are consistent with the evolution of MLT sectors of separate auroral expansions, shown in Fig. 2. At the onset of expansion phase (1) the positive bays in the H component started in the sector between NOV and YAK. Event (2) resulted in westward expansion ($+\Delta H$ appeared at AA, ASK, TBI, ΔD changes its sign from positive to negative at IRK). The next intense event (3) displayed the onset of $+\Delta H$ at both western and eastern stations (LVO, TBI, MAG, PET). The following events (4) and (5) are evident as $+\Delta H$ excursions only at the most western (LVO, HER) and eastern (MAG, PET) stations respectively. Very weak perturbations are associated with the fast expansion (7).

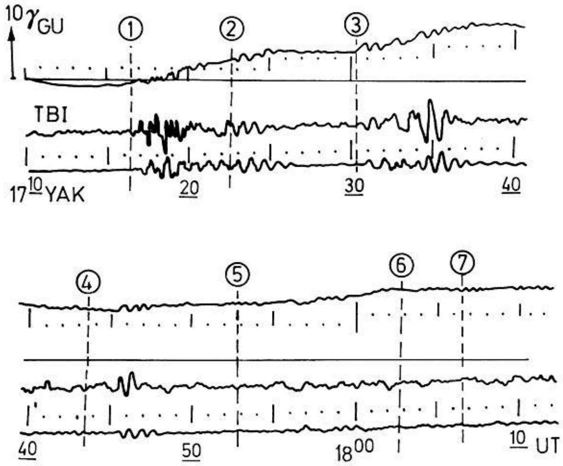

Fig. 4. Induction magnetograms from Tbilisi and Yakutsk along with the rapid-run magnetogram from Guam

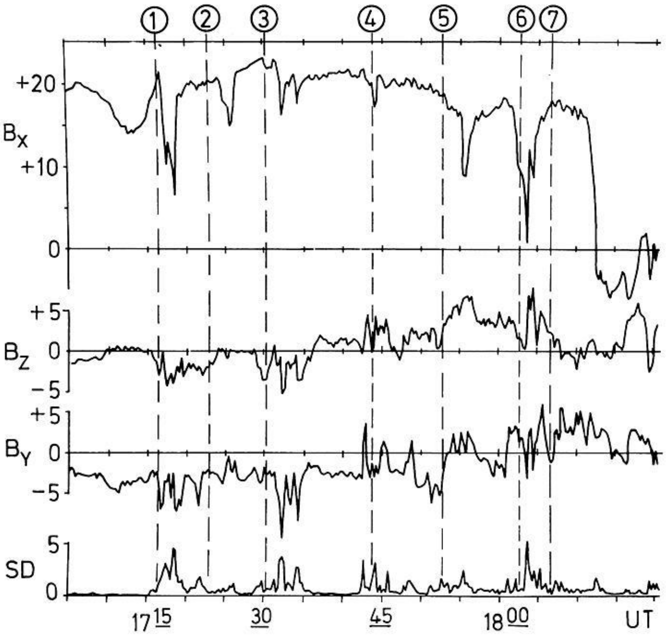

Fig. 5. 15.36 s resolution data of magnetic field components in SM coordinate system at IMP-8 satellite for event 4, *broken lines* mark the onsets of separate microsubstorms inferred from the ground data

The first Pi2 train, starting at 17:16.5 UT (Fig. 4), was characterized by the predominance of the short-period component, the intensification of pulsations without this component is evident near 17:23. At 17:30.5 the onset of a new well-defined train is apparent. These three times are in a good agreement with the onsets of auroral expansions. One more intense Pi2 train is observed after 17:45.5 UT which is two minutes after the beginning of expansion over Heiss Island, but in coincidence with the marked auroral intensifications (see auroral profile in Fig. 2). Some intensifications of pulsations can be found after the times (5) and (7) which are correlated with obvious auroral expansions, however they are not so well-defined as the trains associated with expansions (1)–(3).

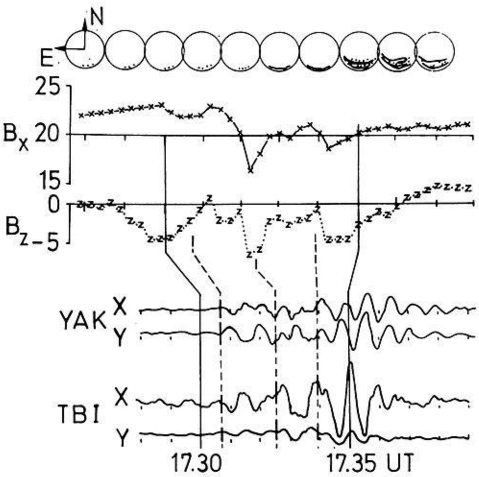

Fig. 6. Drawings of Heiss Is. ascafilms (20 s exposure frames centered at the onset of each minute), 15.36 s data points of B_z and B_x components at IMP-8 and the pulsation records from Tbilisi and Yakutsk for the most intense microsubstorm of event 4 (see text for explanation). The *lines* and *dots* on drawings corresponds to the discrete and diffuse auroras

The IMP-8 satellite was situated at this time near the northern boundary of plasma sheet, as suggested by the large value of the B_x component ($\geq 15\,\gamma$) throughout most of the event and by the significant flux of electrons with energy ≥ 85 KeV (T.P. Armstrong, private communication). Looking at the satellite magnetic field data (Fig. 5), we find impulsive magnetic field variations closely associated with times (1)–(7). The typical response of the B_x component is an impulsive decrease (1)–(6), while the B_z component decreases impulsively in a few early micro-substorms (1)–(3) and increases in the later ones (4)–(6). The impulsive variations of the B_y component and low-frequency magnetic noise (SD) intensifications are also features of microsubstorms. The last widespread expansion (7) results in a new B_z decrease and also in full expansion of the plasma sheet, following 4 min later.

Thus during the expansion phase of this ideal event we can recognize 7 activizations (microsubstorms), most of them (1), (3), (5), (7) are well documented by a complex of ground and satellite signatures and timed to within the 0.5 min resolution of the data.

Thin Structure of the Single Expansion (Microsubstorm)

The Heiss Island all-sky data are displayed in Fig. 6 for the period of the most intense microsubstorm, event (3), along with the induction magnetograms of low-latitude stations Yakutsk and Tbilisi. The latter show the onset of Pi2 trains at 17:30.6 UT, a change of phase is evident at 17:32.5 (more clearly in B_Y components at both locations) and significant amplification of the $T > 50$ s component starts at 17:34.0. These three features are clearly evident at other stations (see for example the Guam rapid-run magnetogram in Fig. 4). The first feature coincides with the auroral intensification in the post-midnight sector (Zhokhov Island, Fig. 2). Coinciding with the second feature (17:32:30), bright auroras appeared in the southern sky at Heiss Island at 17:33 and, at just this time, the formation of the westward part of the auroral bulge is evident in the all-sky data from Loparskaya, situated 30° westwards of the Heiss Island meridian. The structure which appeared at 17:33, is evident in the following frames, but at 17:35 the new bright auroral band formed polewards of the pre-existing one. Thus, in this case, the auroral expansion over the Heiss

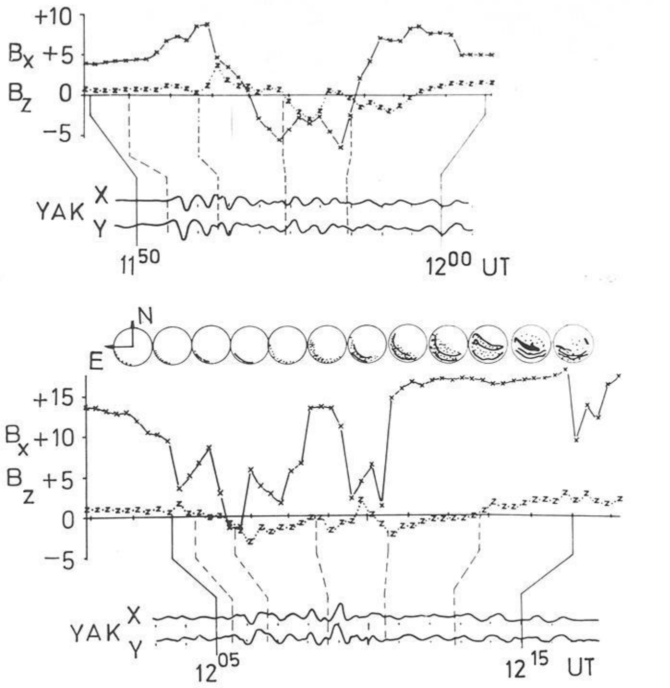

Fig. 7. The same as in Fig. 6 for 11:50–12:15 UT interval, but for Zhokhov Is. all-sky data

meridian proceeds through two stages at 17:33 and 17:35, these times of appearance of new poleward structures being correlated to the times of the two Pi2 regime changes (17:32.5 and 17:34.0), and synchronous at widely spaced (more than a thousand km) stations. At just these times (within 0.5 min accuracy) the impulsive decreases of both B_x and B_z components at the IMP-8 location are observed (Fig. 6) with similar structure in the B_y and SD components (Fig. 5). The pulsation onset at 17:30.5 is evident as a small decrease in the B_x component, but the relatively smooth decrease of the B_z component had started one minute earlier and this feature is not so evident in the B_y and SD components.

The second example concerns the substorm event (2), for which we use the all-sky data from Zhokhov station, situated this time near the MLT sector of satellite projection, as in the previous case (Fig. 1). This event started at 11:51 UT, as evidenced by the Pi2 onset (Fig. 7) and abrupt bay onset at the College rapid-run magnetogram. This first microsubstorm did not occupy the MLT sector of Zhokhov station, where the regular evening arcs were observed. The times of the abrupt changes of the Pi2 regime (phase, period, polarization) are related to the simultaneous appearance of impulsive B_z variations inside the plasma sheet, the two last times strictly coinciding with negative B_z excursions.

The second microsubstorm began at 12:05.5 as new amplification of pulsations and auroral brightening in the southern sky at Zhokhov Island, started at 12:06 and reached its maximum at 12:07. It coincides well with a new negative excursion of the B_z component in the neighbourhood of the neutral sheet. At 12:08.7 we detect a new change of Pi2 phase and a corresponding intensification. After the auroral fading at 12:08 we observe the next intensification at 12:09–12:10, when the auroras expand polewards and two bright auroral bands are seen clearly. Two more negative B_z excursions are evident this time. Between 12:12 and 12:13 the new (third) auroral form appears near the station zenith and an obvious change of Pi2 polarization (appearance of the pulsations in B_x component) is observed. At the same time the B_z component becomes positive.

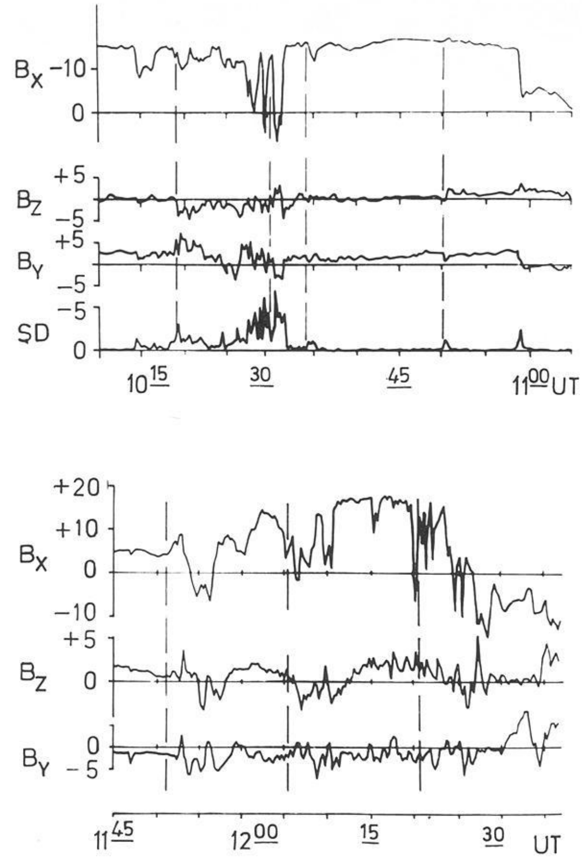

Fig. 8. IMP-8 magnetic field data for the substorm events 1 and 2 (see text for explanation)

These examples give clear evidence that the features of expansion thin structure (new arc formations at the leading edge of the bulge, with simultaneous abrupt changes of Pi2 regime and other corresponding phenomena (Sergeev and Yahnin 1978, 1979b; Sergeev et al. 1978), are intimately related to impulsive changes of the magnetic field in the plasma sheet.

Other Examples of Magnetic Field Response to Substorm Microstructure

We now present briefly the other substorm events during the interval 10–24 h UT on 3 March 1976. Accurate derivation of the full discrete structure of these events is more difficult since we do not have such a good net work of all-sky stations and rapid-run magnetometers as in the previous case. Therefore we will base our presentations on the Pi2 pulsation data, marking by broken lines the instants of their onsets and also the instants of their abrupt regime changes, which are synchronous at widely spaced mid-latitude stations. The possibilities of this method are however limited, and we can reconstruct only a part of all the microsubstorm events in the sequence (see discussion in next section).

Event 1. The expansive phase starts at 10:19, as evidenced by the onset of Pi2, low-latitude magnetic bays and electrojet intensification over College. Two more microsubstorms are seen in the Pi2 data (10:30 and 10:34). The all-sky camera at Zhokhov Island

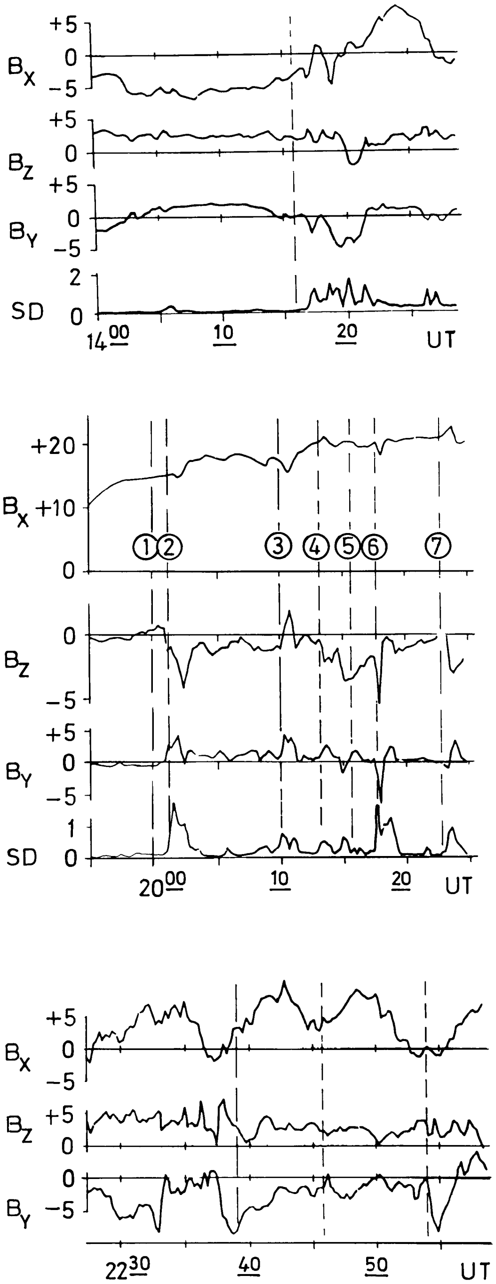

Fig. 9. IMP-8 magnetic field data for the events 3, 4, and 5

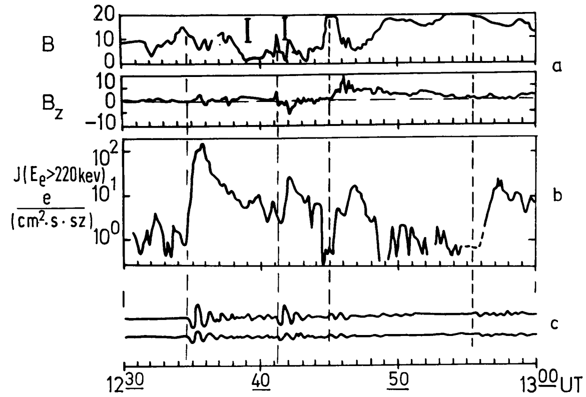

Fig. 10. IMP-8 magnetic field (*a*) and high-energy electron (*b*) data for 26, November 1973 substorm event (from Kirsch et al. 1977) combined with the induction magnetogram from Kanoya. *Vertical bars* in (*a*) denotes the times of neutral sheet crossings

was turned on at 10:35 and registrated the regular evening arcs and also the westward edge of the bulge in the eastern sky until 10:51, when the fast poleward expansion started and proceeded through the new arc formation process.

At the expansion onset we detect, at the IMP-8 position (Fig. 8), a southward turn in the magnetic field and its magnitude decreases, followed by sharp variations in all parameters, related to satellite movement with respect to the plasma sheet boundary. One of these coincides with the Pi2 onset (10:30), then the satellite exit from the plasma sheet and detects the impulsive B_x decrease during the next Pi2 onset. After the onset of auroral expansion at the 20 hours MLT meridian (10:51 UT), the smooth decrease of B_x and impulsive positive change of B_z are seen. Complete plasma sheet recovery takes place 8 min later, towards the end of auroral expansion over Zhokhov Island.

Event 2 (11 51 UT). The first two microsubstorms of this event were discussed in the previous section (Fig. 7). The satellite was located during this period inside the plasma sheet until 12:10. A new auroral expansion developed after 12:21, when brightening and subsequent poleward motion of the bulge was observed in the northern sky over Zhokhov Island until 12:27. During this time interval the satellite moved back into the expanded plasma sheet (Fig. 8) and detected the smooth decrease of magnetic field B_z component, its impulsive negative excursion at 12:26 correlating with the abrupt brightening and break-up of the northern arc. After 12:34 the stable positive B_z regime was observed at the IMP-8 location, the auroras over Zhokhov Island having already completely lost any distinct structure.

Event 3. Only one very intense Pi2 pulsation train was detected at 14:15.5 without any evident bay-like disturbances at either the auroral zone or mid-latitude stations available for this study. No drastic changes in the auroral structure and brightness were observed over Zhokhov Island (23 h MLT). At the same time, in contrast to the preceding time interval there is an obvious magnetic disturbance at the IMP-8 position (Fig. 9), which was located in the proximity of the neutral sheet ($B_z \geq B_x$). The data from the high energy particle experiment on IMP-8 (courtesy of T.P. Armstrong) also displayed the intense burst of energetic electrons (up to 1 MeV), whose intensity increased near 14:15 by more than an order of magnitude. The absence of ground signatures of this event can be understood if it was very localized in space (see the examples of this type in Sergeev and Yahnin 1979a).

Event 5. Three intense and distinct Pi2 trains displayed clear thin structure and were detected from the expansion onset at 20:00 until the gap in the satellite data (20:25). Coinciding with the times 2, 3, 4, 6, and 7 we see impulsive changes of magnetic field, mostly decreases in both B_x and B_z components and magnetic noise (SD) spikes (Fig. 9). The pulsations at the onset (20:00) were very weak. The satellite was near the plasma sheet boundary throughout this event, as evidenced by the large B_x magnitude and the high level of electron flux at energies $\geq$85 KeV.

Event 6. From the rapid-run magnetogram of Leirvogour we define the expansion onset at 22:39. The *H* component negative excursion reached $-500\ \gamma$ near 22:50 and the first *Z* component excursion was positive, showing electrojet intensification southwards of the position of Leirvogour (66° latitude). Three distinct Pi2 trains were detected up to 23:00 UT, coinciding with electrojet intensifications and poleward expansions. The satellite in this period was situated deep inside the plasma sheet ($B_x \leqq 10\,\gamma$, a few neutral sheet crossings, Fig. 9). In the presence of the continuous complex variations of magnetic field in this region it is difficult to recognize unambiguously the response to the three microsubstorms indicated. However we want to emphasize the essentially positive sign of the B_z component inside the plasma sheet near the magnetotail center during the first 20 min of very intense substorm activity, initiated at a latitude $\leqq 65°$ in the midnight auroral zone sector. The ground data available for this event are unsufficient to distinguish the microsubstorms following after 23:00 UT

High-Energy Particle Bursts as Signatures of Explosive Energy Dissipation Process During Separate Microsubstorms

The intense spikes of energetic (0.1–1 MeV) particles were detected by the JHU experiment on board the IMP-8 satellite during the events under examination. From the 5 min resolution data we have, by courtesy of T.P. Armstrong, the onsets of the substorm-related particle events are defined to be at approximately 10.18, 11:51, 14:15, 17:18, 20:00 and 22:40 UT, in good accordance with our determination of the expansion phase onset from the ground signatures.

To show the energetic particle response to the microsubstorm sequence in more detail we have used data on both the magnetic field and energetic electron flux at IMP-8 during the event on 26 November 1973, published by Kirsch et al. (1977), supplemented in Fig. 10 by the Kanoya induction magnetogram. We again see the impulsive B_z component variation at the onsets of separate Pi2 trains (microsubstorms). The remarkable coincidence of separate particle bursts and microsubstorm onsets is also obvious from Fig. 10.

Results and Discussions

Reconstruction of Discrete Microstructure of Substorms From Ground Data

In all of five successive, intense and well-defined substorms on 3 March 1976 we found the complex multistage temporal structure of the expansive phase, which thus represents a typical feature of substorms in good accordance with the other detailed studied, which are mentioned in the Introduction. A clear example of the sporadic activizations of auroral expansions and of the complex changes in their latitudinal and longitudinal ranges is provided by the data on the intense and isolated event 4.

The timing of microsubstorms represents one of the most important and difficult problems for future detailed studies of explosive energy dissipation events. The defects of the magnetic variation data obtained in the auroral zone and at mid-latitudes (inadequate net work, low time-resolution of normal magnetograms, difficulties in distinguishing the nature of distinct peaks at auroral zone stations, low level of signal/noise ratio at mid-latitudes) are well known, and in many papers most attention has been paid to the registration of mid-latitude Pi2 pulsations in view of the high time-resolution of this method and the global character of these pulsations (Pytte et al. 1976a, b; Saito et al. 1976; Sakurai and Saito 1976). Our data demonstrate, however (see Fig. 4 for example), that these pulsations are intense and well-defined only during the few first microsubstorms, whereas in the later ones their presence cannot be defined unambiguously. Thus this method is very useful but is not sufficient to indicate every microsubstorm in the sequence.

The accuracy of this method is also sometimes limited even in the cases of intense and well-defined Pi2 trains. So, in the microsubstorms 4 and 5 of event 4 the onsets of these trains were evidently delayed for a few minutes, relative to the microsubstorm signatures in auroral and magnetospheric data. Similar delays of Pi2 onset (0–2 min), when compared to the auroral brightening, were obtained by statistical analysis by Sakurai and Saito (1976). A cause of these delays, as suggested by the results of Sergeev et al. (1978), can be related to the thin structure of the separate expansion event (previons section). If the regime changes in the Pi2 train are caused by superimposed trains, originating from separate impulses (as suggested by their correlations with the abrupt changes in auroral structure and impulsive magnetic field variations in the magnetotail), the onsets of low-intensity trains might be missed in the analysis. So Sergeev et al. (1978) presented examples, where an initial brightening of the aurora resulted only in a simultaneous low intensity Pi2 pulsation, not detected at low-latitudes, but the successive formation of new arcs at the front of the expanding bulge superimposed intense Pi2 at low-latitudes. Data for the microsubstorm 5 in event 4 are similar· the intensification of Pi2 pulsations at Yakutsk (Fig. 4) is evident at 17:56.5 simultaneously with the new arc formations over Zhokhov Island (Fig. 2), but there were no observable pulsations during the very strong auroral brightening at 17:53.

Thus only the observation of auroral dynamics and intensity over the whole sector 65°–75° latitude and 20–04 h MLT provides a reliable means for the reconstruction of the full space-time history of a substorm. Unfortunately such study is possible only in extremely rare cases.

Magnetic Field Variations During Separate and Sequantial Microsubstorms with the Satellite Near the Plasma Sheet Boundary

Preliminary inspection of the data has shown that when impulsive magnetic variations accompany the onsets of microsubstorms, their character displays many individual features. A major part of these differences seems to arise from both the variety of space-time history in substorms and differences in location of the satellite relative to the regions of fast energy dissipation. We try below to infer typical patterns of microsubstorm-associated variations and their sequence in the substorm. The results, of course, are preliminary, as they are based on a limited number of events; still we feel that they are representative. The latter conclusion can be supported by reference to the large number of events analysed by Pytte et al. (1976b, 1978) and Sergeev (1977), as the features which have been pointed out can invariably be found in their data. The above-mentioned data corresponds mainly to the 10–20 R_E distance in the magnetotail.

Types of Variation. Based on the behaviour of the B_x (or $|B|$) and B_z components of the magnetic field at the microsubstorm onset, we can distinguish the four following types of variations

A. Decrease of both $|B|$ and B_z component by a few γ in magnitude.

B. Decrease in $|B|$ and increase in B_z by the same amounts.

C. A large decrease of $|B|$ of more than 5–10 γ, when the satellite is embedded into the expanded plasma sheet.

D. A short-lived large $|B|$ decrease during the transient plasma sheet expansion.

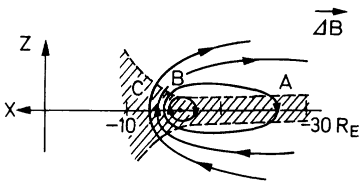

Fig. 11. The magnetic field disturbance pattern in the XOZ plane, used for explanation of magnetic field response at IMP-8 to the sequence of separate microsubstorms

All four types of magnetic field behaviour are evident in data for event 4, and partly in events 1,5. All these patterns are present in the data for the substorms which started at 09.38 UT and 14.36 UT on 4 September 1968 and at 07.52 UT on 19 August 1969, when the OGO-5 satellite was situated 20 R_E from the Earth within 3 R_E from the calculated neutral sheet position (Pytte et al. 1978). Only B and C types are evident in the data for other events in papers of Pytte et al. (1976b, 1978), when the satellite was located closer to the Earth.

Occurrence of Different Types: The changes of A and B type are typically synchronous (within one minute) with the microsubstorm onsets, determined from the ground data (see also Pytte et al. 1976b, 1978). The transient expansion type (D) is often superimposed on these variations, with the sign of B_z variation being preserved, but is sometimes delayed with respect to the A and B types (see, for example, microsubstorm 5 in event 4 and also Pytte et al. 1978).

The transient expansion-contraction of the plasma sheet can be found in papers where plasma data were analyzed. A striking example of the expansion-contraction sequence with repeated changes in the plasma flow direction was described by Hones et al. (1976), the auroral data also displaying the sequence of auroral bulge expansions (the appearance of new WTS) with similar intervals of time between them (5–20 min).

Sequences of Variation Types. During the expansion phase the magnetic field responses usually change through the sequence of microsubstorms as $A \rightarrow B \rightarrow C$ at 35 R_E distances (see also the similar example in Sergeev 1977). A similar succession is evident in the above-mentioned events in Pytte et al. 1978, and the succession $B \rightarrow C$ in other events studied in the papers by Pytte et al. (1976b, 1978). Each response type may be repeated a few times. This pattern of a change in magnetic field response through the sequence of separate microsubstorms can be easily interpreted if the pattern of magnetic field change at the substorm onset (first microsubstorm) is taken into account. In the enormous number of events observed, magnetic field signatures at the substorm onset display a B_x magnitude decrease everywhere outside the plasma sheet, a B_z decrease at or tailwards of 20 R_E distance (type A), a B_z increase earthwards of *15–20* R_E distance (type B) and the pronounced plasma sheet expansion (type C) at <15 R_E from the Earth (Nishida and Nagayama 1973; Russell and McPherron 1973; Hones 1979; Pytte et al. 1976b, 1978). Thus all these types A, B, C are observed simultaneously and differ only spatially (Fig. 11) the separation line between regimes A and B in the equatorial plane being identified as the X-type neutral line position (see next section). Therefore the trend $A \rightarrow B \rightarrow C$ can be explained as the sudden appearances of a neutral line at more tailward distances in the magnetotail

Underlying Trends in $|B|$. After the changes of A and B type, synchronous with the microsubstorm onset, the magnetic field usually recovered before the onset of the subsequent microsubstorm if it was sufficiently separated in time from the previous microsubstorm. In our cases 1, 4, 5 as well as in the above-mentioned events in Pytte et al. (1978), the following trend can be recognized: during the successive microsubstorms, resulting in an $A(B)$ magnetic variation pattern, the restored values of $|B|$ increase (decrease) in a sequence of responses of similar type. Since the Pytte et al. (1978) paper included the plasma data, showing the absence of plasma sheet particles during the periods under consideration, we infer that the intensity of the plasma sheet current tailwards of the X-type neutral line region, where the A type response is observed, according to our interpretation, *continues to increase* during the current disruption process in the near-Earth region. The relative contribution of these two parts of the current sheet (disrupted or increasing in intensity) to the observed magnetic variation apparently depends on the satellite position. The contribution of the slowly varying tailward part can dominate only when the satellite is situated near the current sheet (at $|Z| \leq 6$ R_E as follows from the statistical data of Iijima (1972), for definition of Z see Fig. 11).

Discussion. Unfortunately the data gaps in some events and difficulties in diagnosting the last microsubstorm in a sequence prevent the detailed study of magnetic field variations after complete plasma sheet recovery (C-type response). In the two cases (events 1 and 4) when such recovery was observed, it was detected a few minutes after the onset of a microsubstorm, characterized by fast expansion in the widest longitudinal sector. Pytte et al. (1978) and Hones (1979) suggested that the phase of the plasma sheet recovery tailwards of 15 R_E distance (leap, in their definition) is physically different from the preceding activizations (microsubstorms). However they base this mainly on the absence of the Pi2 pulsations at mid-latitudes and the appearance of the bulge at latitudes of 74° In the case of event 4, however, the auroral expansion reached 74° latitude at microsubstorm 3, but four later microsubstorms are evident in our data (Figs. 2–4), being qualitatively similar to event 3. The absence of clear Pi2 pulsations also can not be used to distinguish the physical nature of the microsubstorm phenomena Thus we feel that the conclusion about the existence of two different expansion modes during the expansion phase is not yet well founded.

Magnetic Field Changes Inside of the Plasma Sheet and Magnetotail Topology During the Substorm Expansion Phase

Cases when the satellite stays inside the plasma sheet at and after the substorm onset are extremely rare at distances tailwards of 15 R_E, but events 2, 3, and 6 in our study do fall into this category.

B_z Variations. During the first twenty minutes of the expansion phase of event 6 the satellite was evidently in the plasma sheet near the magnetotail center ($Y_{SM} \sim +1$ R_E). Three microsubstorms occured this time. However, only positive B_z values were detected at IMP-8. Whereas the intense ($\Delta H \sim -500\,\gamma$) westward electrojet intensification took place at latitudes $\leq 65°$ at midnight, the probability of the formation of the X-type neutral line at distances >40 R_E in the magnetotail during this period seems to be very small.

During event 2 the B_z component of the magnetic field displayed two brief decreases into the negative range during the first two microsubstorms, but in the 8 min interval between them

B_z was continuously positive ($+2.5\,\gamma$) inside the plasma sheet ($|B_x| < 10\,\gamma$). There is another similar example in Fig. 10.

These facts are compatible with the results of Lui et al. (1977a, b), showing the predominance of positive B_z values in the neutral sheet regions at tailward distances of about 30 and 60 R_E during the substorm expansion phase. Thus the region of negative B_z (if it exists) must occupy only a localized part of the magnetotail equatorial region, and the resultant magnetotail topology must be similar to that with a pair (or a few pairs) of *X*- and *O*-type neutral lines (Vasiliunas 1976).

B_s *Variations*. The impulsive character of B_s in the plasma sheet may be caused by both the brief appearance of neutral lines, and also by their continuous existence in the case where the dimensions of the B_s region contract between the microsubstorms. We are not in a position to distinguish between these possibilities from the data of one satellite. These properties, however, are in conflict with the schemes of Vasiliunas (1976) and Hones (1979), in which the dimension of the B_s region increases continuously during the expansion phase.

B_y *Variations*. The existence of the intense variation in the B_y component during microsubstorms both inside and outside the plasma sheet along with the strong B_y component in the neutral sheet ($|B_x| \approx 0$, events 3, 6), pointed out earlier by Akasofu et al. (1978), suggest the complex and essentially three-dimensional character of the magnetic disturbance, which demands a more careful investigation.

Thin Structure of Separate Microsubstorms as Possible Indicator of Tearing-Like Instability of the Magnetotail Current Sheet

Only two microsubstorm events, when auroral expansion occured in the field of view of an all-sky camera and the satellite projection into the ionosphere was situated in the same MLT sector, were suitable for detailed comparisons of all-sky and satellite data. Both these events (see above) have given distinct examples of synchronization of the southward B_z spikes at the satellite position with the formation of new auroral arcs at the leading auroral bulge, accompanied by simultaneous changes in the regime of Pi2 pulsations.

Two other examples, when the data on auroral expansion were absent, also display the distinct coincidence of magnetic field spikes and changes in the regime of Pi2 pulsations (see upper and central parts of Figs. 7 and 9 respectively). Since the successive formation of new arcs was found to be the usual feature of auroral expansion during a microsubstorm (Sergeev and Yahnin 1978, 1979b; Sergeev et al. 1978), it is important to understand the possible physical significance of the correlation obtained.

To do this we must bear in mind two consequences of the impulsive appearance of the southward B_z component in the plasma sheet. On the one hand it is evidence of the existence of the *X*-type neutral line (lines) at least during the period of expansion. On the other hand fast magnetic field variations may be naturally related to the strong impulsive electric field, whose brief appearance during the expansive phase of substorms has already been observed (Kirsch et al. 1977; Aggson and Heppner 1977; Pedersen and Grard 1978). As follows from the numerical simulation of Tsyganenko and Zaitzeva (1979), the intense arc-like structure of electron precipitation will appear in the ionospheric projection of the *X*-type neutral line when the strong dawn-dusk directed electric field is applied to this region.

The close association of the impulsive electric field with the formation of auroral arcs during expansion seems to be in line with observations of energetic particles. So, as shown by Sergeev et al. (1978), the precipitation of energetic electrons under the expanding auroral bulge appears as a sequence of short impulses, occuring synchronously with the generation of new auroral arcs and concurrent changes in the regime of irregular pulsations. On the other hand, as follows from observations of spikes of energetic particles (Krimigis and Sarris 1979) and simulations of the particle acceleration (Pellinen and Heikkila 1978), the intense inductive electric fields are very probably the source for the particle acceleration up to MeV energy. In this connection we must mention also the results of Pedersen and Grard (1978). As the typical feature of the expansion phase, they have distinguished the sequence of strong impulses of the electric field, whose repetition interval (1–2 min) is the same as that of new arc formations and the simultaneons impulses of energetic electron precipitation.

In view of this evidence we have some physical grounds for considering the process of generation of new auroral arcs at the poleward front of expanding auroral bulge as the consequence of impulsive formation of a few *X*-type neutral lines during microsubstorms. This process corresponds well to the picture of the explosive growth of the tearing-mode instability (Galeev et al. 1978; Schindler 1979). If our conclusion appears to be valid, some very important features of tearing-mode operation may be deduced from auroral data.

The Substorm Sequence, and Concluding Remarks

As shown in this and similar studies (see Introduction), the space-time history of substorms appears to be complex and variable. However it seems possible to distinguish a definite hierarchy in the construction of the substorm sequence, depending on space and time scales.

The second in this hierarchy is the microsubstorm phenomenon, operating on a time scale 5–10 min in a localized part of the magnetotail and its conjugate auroral ionosphere (see Fig. 2 for illustration). Its main physical characteristics consist in the fast (explosive-like) energy dissipation, as evidenced, for example, by the data on high-energy particles (see Fig. 10 and the statistical data of Murayama (1970), who first found the remarkable correlation of Pi2 and relativistic electron spikes). The main features of microsubstorms can be explained both consistently and quantitatively by a Birkeland loop (current disruption) model Akasofu 1977; Sergeev and Tsyganenko 1980).

The substorm as a whole apparently represents the top level of this hierarchy. It is related to the way in which the whole tail dissipates surplus magnetic energy through the sequence of localized microsubstorms.

On a more detailed level, processes important for the explosive energy transformation in a substorm, seem to be represented by what we called "thin structure" Data on the magnetospheric features of this phenomenon are very scarce at present.

To support this view of the hierarchical structure of substorms we must mention the possibility of relative independence of phenomena at different levels of hierarchy. So, for example, a single microsubstorm can occur during quiet conditions, as in the case of our event 4.

As regards the behaviour of the magnetic field in the magnetotail, we feel that the data presented in this study give clear examples of the changes, related to the microsubstorms and their thin structure. Although some preliminary results have been discussed in this paper, much more effort must be made to describe consistently the three-dimensional patterns of the related disturbances.

Acknowledgements. Magnetic field data from the IMP-8 satellite (N.F. Ness and R.P. Lepping are the principal investigators) were made accessible through WDC-A (Rockets and Satellites) and it is a pleasure to thank Dr. R.P. Lepping for additional data and information. I am also indebted to Dr. T.P. Armstrong from the Applied Physics Laboratory of John Hopkins University, who kindly provided the data from their energetic particle experiment. The auroral and ground magnetic data were obtained through WDC-B.

It is a pleasure to thank Drs. Y.A. Nadubovich, A.G. Yahnin, E.E. Timofeev, I.E. Ievenko, G.V. Starkov, L.A. Natzvalyan, Y.M. Gogatishvili for their kind assistance in receiving the different observational data and L.L. Nemtzeva and M.V. Holeva for their assistance during the preparation of paper.

References

Aggson, T.L., Heppner, J.P.: Observations of large transient magnetospheric electric fields. J. Geophys. Res. **82**, 5155–5154, 1977

Allen, J.H., Abston, C.C., Morris, L.D.: Geomagnetic data for March 1976. WDC-A report UAG-63, 1977

Akasofu, S.-I.: Physics of magnetospheric substorms. Dordrecht: D. Reidel Publ. Comp. 1977

Akasofu, S.-I., Lui, A.T.Y., Meng, C.-I., Haurowitz M.: Needs for a three-dimensional analysis of magnetic fields in the magnetotail during substorms. Geophys. Res. Lett. **5**, 283–286, 1978

Clauer, C.R., McPherron, R.L.: Mapping the local time – universal time development of magnetospheric substorms using mid-latitude magnetic observations. J. Geophys. Res. **79**, 2811–2819, 1974

Fairfield, D.H., Ness, N.F.: Configuration of the geomagnetic tail during substorms. J. Geophys. Res. **75**, 7032–7042, 1970

Galeev, A.A., Coroniti, F.V., Ashour-Abdalla, M.: Explosive tearing mode reconnection in the magnetospheric tail. Geophys. Res. Lett. **5**, 707–712, 1978

Hones, E.W., Asbridge, J.R., Bame, S.J., Singer, S.: Substorm variations in the magnetotail plasma sheet from $X = -6\ R_E$ to $-60\ R_E$. J. Geophys. Res. **78**, 109–122, 1973

Hones, E.W., Akasofu, S.-I., Perreault, P.: Associations of IMF polarity, plasma sheet thinning and substorm occurrence on March 6, 1970. J. Geophys. Res. **81**, 6029–6041, 1976

Hones, E.W.: Plasma flow in the magnetotail and its implications for substorm theories. Space Sci. Rev. **23**, 393, 1979

Iijima, T.: Relationship of magnetospheric substorms on the ground and in the distant magnetotail. Rep. Ionos. Space Res. Jp **26**, 149–157, 1972

Kirsch, E., Krimigis, S.M., Sarris, E.T., Lepping, R.P., Armstrong, T.P.: Possible evidence for large, transient electric fields in the magnetotail from oppositely directed anisotropies of energetic protons and electrons. Geophys. Res. Lett **4**, 137–141, 1977

Krimigis, S.M., Sarris, E.T.: Energetic particle bursts in the Earth magnetotail. In: Dynamics of the Magnetosphere, S.-I. Akasofu, ed: pp. 590–360. Dordrech: D. Reidel Publ. Comp 1979

Lui, A.T.Y., Meng, C.-I., Akasofu, S.-I.: Search for the magnetic neutral line in the near-earth plasma sheet: 2. Systematic study of IMP-6 magnetic field observations. J. Geophys. Res. **82**, 1547–1556, 1977a

Lui, A.T.Y., Meng, C.-I., Akasofu, S.-I.: Search for the magnetic neutral line in the near-earth plasma sheet: 3. An extensive study of magnetic field observations at the lunar distance. J. Geophys Res. **82**, 3603–3612, 1977b

Murayama, T.: Correlated occurence of energetic electron bursts in the magnetotail and geomagnetic impulsive micropulsation. Rep. Ionos. Space Res. Jp **24**, 135–147, 1970

Nishida, A., Nagayama, N.: Synoptic survey for the neutral line in the magnetotail during the substorm expansion phase. J. Geophys. Res. **78**, 3782–3796, 1973

Pedersen, A., Grard, R.: Quasistatic electric field measurements on the GEOS-1 and GEOS-2 satellites. Preprint ESLAB N81, October 1978

Pellinen, R., Heikkila, W.J.: Energization of charged particles to high energies by an induced substorm electric field within the magnetotail. J. Geophys. Res. **83**, 1544–1550, 1978

Pytte, T., McPherron, R.L., Kokubun, S.: The ground signatures of the expansion phase during multiple onset substorms. Planet. Space Sci. **24**, 1115–1132, 1976a

Pytte, T., McPherron, R.L., Kivelson, M.G., West, H.I., Hones, E.W.: Multiple-satellite studies of magnetospheric substorm: Radial dynamics of the plasma sheet. J. Geophys. Res. **81**, 5921–5933, 1976b

Pytte, T., McPherron, R.L., Kivelson, M.G., Hones, E.W., West, H.I.: Multiple-satellite studies of magnetospheric substorms: Plasma sheet recovery and the poleward leap of auroral zone activity. J. Geophys. Res. **83**, 663–678, 1978

Rostoker, G., Camidge, F.P.: Localized character of magnetotail magnetic fluctuations during polar magnetic substorm. J. Geophys. Res. **76**, 6944–6949, 1971

Russell, C.T., McPherron, R.L.: The magnetotail and substorms. Space Sci. Rev. **15**, 205–263, 1973

Saito, T., Sakurai, T., Koyama, Y.: Mechanism of association between Pi2 pulsation and magnetospheric substorm. J. Atmos. Terr. Phys. **38**, 1265–1269, 1976

Sakurai, T., Saito, T.: Magnetic pulsations Pi2 and substorm onset, Planet. Space Sci **24**, 573–575, 1976

Schindler, K.: Macroinstabilities of the magnetotail. In: Dynamics of the magnetosphere, S.-I. Akasofu, ed.: pp. 311–326. Dordrecht: D. Reidel Publ. Comp. 1979

Sergeev, V.A.: On the longitudinal localization of the substorm active region and its changes during the substorm. Planet. Space Sci. **22**, 1341–1343, 1974

Sergeev, V.A.: On the microstructure of the magnetospheric substorm. Geomagn. Res. (In Russian) **21**, 5–15, 1977

Sergeev, V.A., Yahnin, A.G.: The features of auroral expansion during the substorm explosive phase and the model of microsubstorms in the magnetosphere. Phys. Solariterr., Potsdam **7**, 23–46, 1978

Sergeev, V.A., Yahnin, A.G.: A correspondence of the substorm expansive phase signatures. Geomagn. Res (In Russian) **24**, 78–89, 1979a

Sergeev, V.A., Yahnin, A.G.: The features of auroral bulge expansion. Planet. Space Sci. **27**, 1429–1444, 1979b

Sergeev, V.A., Yahnin, A.G., Raspopov, O.M.: On the spatial-temporal structure of the expansive phase of microsubstorm. In: Dynamical processes and structure of auroral magnetosphere (SAMBO experiment) (In Russian), O.M. Raspopov, L.L. Lazutin, eds. pp. 42–54. Apatity: Kola Branch Acad. Sci. USSR 1978

Sergeev, V.A., Tsyganenko, N.A.: The Earth's magnetosphere. Moscow: Science Publ. House 1980

Timofeev, E.E., Yahnin, A.G.: On the distribution of types of the radioaurora relative to the auroral bulge. 'Polar aurora' (In Russian) **28**, in press, 1981

Tsyganenko, N.A.: The subroutines and tables for the calculation of geomagnetic field. WDC-B report 1979

Tsyganenko, N.A., Zaitzeva, S.A.: On the mechanism for the formation of quiet auroral arcs. Geomagn Res. (In Russian) **24**, 61–70, 1979

Untiedt, J., Pellinen, R., Küppers, F., Opgenoorth, H.J., Pelster, W.D., Baumjohann, W., Ranta, H., Kangas, J., Czechowsky, P., Heikkila, W.J.: Observations of the initial development of an auroral and magnetic substorm at magnetic midnight. J. Geophys. Res. **45**, 41–65, 1978

Vasiliunas, V.M.: An overview of magnetospheric dynamics. In: Magnetospheric Particles and Fields, B.M. McCormac, ed.: pp. 99–105. Dordrecht: D. Reidel Publ. Comp 1976

Vette, J. (ed.): Special IMS periods for 1976, IMS/SSC rept. N6, 1975

Vorobjev, V.G., Rezenov, B.V.: Progressive westward displacements of the region of the auroral substorm localization in conjunction with impulsive variations of the magnetic field. Inst. Ass. Geomagn. Aeron. Bull. **34**, 441–449, 1973

Wiens, R.G., Rostoker, G.: Characteristics of the development of the westward electrojet during the expansive phase of the magnetospheric substorms. J. Geophys. Res. **80**, 2109–2128, 1975

Received December 5, 1979; Revised Version October 7, 1980
Accepted January 16, 1981