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Substorm Time Sequence and Microstructure on 11 November 1976*

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Abstract. Two substorms of different character are studied by means of data recorded on 11 November 1976 both on the ground and in the solar wind. The first, rapid and widespread substorm occurred at the end of a period of almost constant, intense magnetospheric convection. The second, weak, shortlived and localized substorm was preceeded by variable magnetospheric convection that was obviously controlled by changes in the interplanetary magnetic field. In spite of the large differences in the extent and strength of the substorms, obvious similarities in their temporal development were found. Prior to both substorms, growth-phase-type energetic electron precipitation was recorded. During the expansion phases, each impulsive arc brightening as well as each auroral arc formation at the leading edge of the auroral bulge was accompanied by a burst of energetic electron precipitation, by a burst of Pi pulsations and by an impulsive change of the equivalent ionospheric currents recorded in the auroral zone. At mid-latitudes a sharp change in the amplitude and phase of Pi2 pulsations was observed. The fine structure observed represents discrete steps in the development of the expanding auroral bulge, that were separated by 1–3 min from each other. Details of the bulge development and of the altitudes of different auroral structures within the bulge are given. The role of variations in the interplanetary magnetic field on the development of the substorms is discussed.

Keywords: Auroral absorption – Auroral altitude – Auroral bulge – Convection bay – Growth phase – Interplanetary magnetic field – Microsubstorm – Multiple onset – Pi2 – PiB – Substorm

Introduction

The concept of magnetospheric substorm (Akasofu, 1968), being historically a large step towards an understanding of magnetospheric disturbances, does not contain (both in the initial and modified form; Akasofu, 1977; McPherron, 1979) a detailed description of the development of different ionospheric and magnetospheric phenomena during a substorm. Hence, one of the most important and urgent tasks in magnetospheric physics is to learn more about the time sequence and the phenomenology of substorms (Roederer, 1977).

Three recent findings seem to be of special importance in this respect. First, it was established that intense magnetic disturbances (on the global scale) and bright discrete auroral arcs can occur for long times without any signatures of substorm expansion both on the ground and in the magnetotail (Kokubun et al., 1977; Sergeev, 1977; Pytte et al., 1978a; Fairfield et al., 1981). These observations were explained as a manifestation of enhanced magnetospheric convection (for a more comprehensive discussion see Sergeev and Tsyganenko, 1980).

Second, it was recognized that common expansion related features, observed both on the ground and in the magnetotail, may repeat several times with durations of 5–10 min and repetition intervals between 5 and 30 min. These individual events, called microsubstorms (Sergeev, 1974) or substorm intensifications (Rostoker et al., 1980), correspond to time intervals of explosive energy dissipation from the magnetotail into the ionosphere (Sergeev, 1981). Each event seems to be fairly localized both in the magnetotail and in the ionosphere (Wiens and Rostoker, 1975; Clauer and McPherron, 1974; Sergeev, 1974; Vorobjev and Rezhenov, 1973; Saito et al., 1976; Pytte et al., 1976a, b, 1978b; Sergeev and Yahnin, 1979a; Baumjohann et al., 1981).

Third, the last result that has to be mentioned in this context is the fine structure of each microsubstorm. Sergeev and Yahnin (1979b) have recently shown that auroral expansions usually proceed through formation of new structures at the poleward border of the auroral bulge. Signatures of similar step-like processes were found in balloon X-ray measurements (Pytte et al. 1976c; Melnikov et al., 1978), in cosmic noise absorption recordings and in Pi2 pulsation data (Sergeev et al., 1978), as well as in magnetic field variations recorded in the magnetotail (Sergeev, 1981).

* Main results of this study were presented at the Second Workshop on IMS Observations in Northern Europe held at Bad Lauterberg, Federal Republic of Germany, 1978

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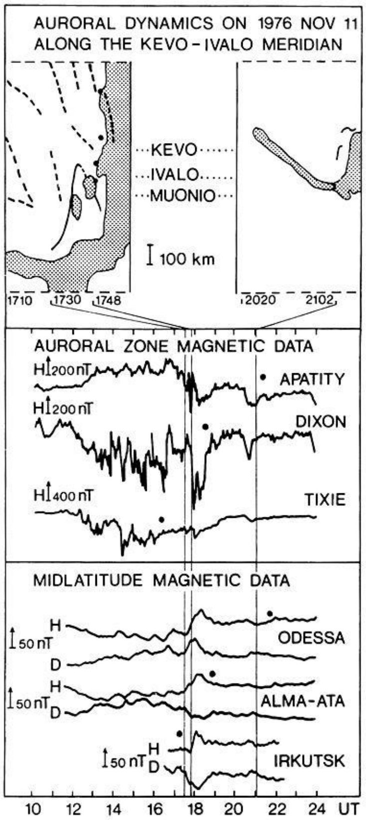

Fig. 1. Position of auroras (*dots:* diffuse and irregular auroras; *lines* and *thick points:* discrete auroras) along the Ivalo meridian under the assumption of 100 km height of auroras (*top panel*); magnetograms of a few auroral zone (*center panel*) and mid-latitude stations (*bottom panel*) for 11 November 1976. Black dots in the magnetograms denote local magnetic midnight at the respective stations

In our opinion, to proceed further in the studies on substorm time sequence the following necessary steps have to be taken:

1) To document more precisely the local features of the whole magnetospheric substorm;

2) To study more extensively the relationship between local and global substorm features;

3) To check the consistency of the phenomenological models proposed for the different types of disturbances (e.g. intense isolated substorms, prolonged intense disturbances, small and localized substorms).

These three aspects form the main topic of the present study. Our data were recorded by extensive networks of all-sky cameras, riometers, induction magnetometers and by a two-dimensional array of magnetometers operated in the Northern Europe during the International Magnetospheric Study, IMS, 1976–79. Balloon X-ray measurements were made during one of the events. The whole data set provides an opportunity to study local substorm features with a time resolution better than one minute. The information on the global magnetic effects and mid-latitude Pi2 pulsations were obtained from standard observatory data.

The two substorms under examination are not "typical" in the "classical" sense (intense, isolated, duration about 1 h). The expansion phase of the first event started at 1730 UT (Fig. 1) at the end of an interval of prolonged and intense auroral zone activity. The second event, starting at about 2100 UT was preceded by a bay-like disturbance of 30 min duration in the auroral zone and at mid-latitudes that looked like an isolated substorm, but, as we shall show later, was just a worldwide magnetic bay occurring during the substorm growth phase (Pellinen et al., 1982). No evident worldwide effects were observed during the subsequent weak, short-lived and fairly localized expansion phase.

Instrumentation and Methods of Data Handling

The main observation sites, their coordinates and instrumentation are listed in Table 1.

In addition to the standard magnetic observatory data rapid-run magnetograms and pulsation recordings (0.01–0.2 Hz) from Borok, Kaliningrad and Lovozero were available for the analysis. Pulsation recordings in a higher frequency range (0.1–2 Hz) were made at Kevo, Sodankylä, Oulu and Nurmijärvi. For the second event data of the Scandinavian Magnetometer Array (SMA) were also available. The locations of the SMA stations and details on the instrumentation can be found in Küppers et al. (1979).

A description of the Finnish riometer chain used in this study is given in Ranta (1978).

On 11 November 1976 all-sky cameras were operated at Esrange (near Kiruna), Kevo, Ivalo and Muonio at a speed of 1 frame/min. Technical data on the Finnish all-sky cameras are given in Hyppönen et al. (1974). The positions of auroral forms were calculated from simultaneous all-sky photographs by fitting the digitized lower border of an auroral arc from two different stations, using the position and altidues as variable parameters (for details see Kaila, 1981).

Details of the SAMBO-76 campaign and the balloon data used in this study can be found in Zhulin et al. (1978) and Melnikov et al. (1978). Three balloons were located at latitudes between Ivalo and Sodankylä and longitudes between Muonio and Ivalo during the second event (see Fig. 8b).

Interplanetary magnetic field (IMF) data obtained by the IMP-8 satellite, were available for the entire period.

Observations

On 11 November 1976 two separate auroral substorms were recorded in the Scandinavian region from 1730–1800 UT and from 2030–2110 UT. Below, these substorms will be treated in the following way: Mid-latitude magnetic bays (McPherron et al., 1973; Sergeev, 1974; Wiens and Rostoker, 1975) and Pi2 pulsations (Saito et al., 1976) will be analyzed to study the global features of these substorms. According to Rostoker et al. (1980) these data give information about both strong and weak expansions occurring in any local time sector. Local features will be studied by investigating in detail the auroral zone data recorded in the Scandinavian sector. The discrete events observed during the expansion phases are summarized in Table 2.

Time Interval 1730–1800 UT

Global features. In general, between 1200–1900 UT the level of magnetic activity in the auroral zone is rather high as can be deduced from Fig. 1. However, between 1630–1730 the Pi2 activity is low at Lovozero, Borok and Kaliningrad (data not shown here) and there are no sharp magnetic

Table 1. Permanent or temporary stations from which data have been used in the present study

Station	Symbol	Geogr. Coord.		Corr. geom. coord.[a]		Type of instrument
Alma-ata	AAA	43°15′N	76°55′E			M
Apatity	APA	67 33	33 20			M
Borok	BOX	58 02	38 20	53.5°N	113.8°E	M(2) P
Boulder	BOU	40 08	254 46	49.2	316.1	M
Dixon	DIK	73 33	80 34			M
Evenes	EVE	68 31	16 46			M
Fredericksburg	FRD	38 12	282 37	50.3	355.7	M
Honolulu	HON	21 19	202 00	21.7	267.8	M
Irkutsk	IRT	52 10	104 27	46.9	176.0	M
Ivalo	IVA	68 36	27 29			AR
Kaliningrad	KNG	54 48	20 30			M(2)P
Kevo	KEV	69 45	27 01			APR
Kiruna	KIR	67 50	20 25			AM
Lovozero	LOZ	67 58	30 05			M(2)P
Mattisdalen	MAT	69 51	22 55			M
Mikkelvik	MIK	70 04	19 01			M
Minsk	MNK	54 30	27 53	49.3	103.2	M
Muonio	MUO	68 02	23 34			AM
Nattavaara	NAT	66 45	21 00			M
Novosibirsk	NVS	54 51	83 15	50.6	153.1	M
Nurmijärvi	NUR	60 31	24 39			P
Odessa	ODE	46 47	30 53			M
Oulu	OUL	65 06	25 29			PR
Petropavlovsk	PET	52 58	158 15	45.4	225.2	M
Ritsemjokk	RIJ	67 42	17 30			M
Rovaniemi	ROV	66 33	25 50			R
San Juan	SJG	18 07	293 51	31.0	6.6	M
Sodankylä	SOD	67 22	26 38			MPR
Sverdlovsk	SVD	56 44	61 04	52.0	133.6	M
Tixie	TIK	71 35	129 00			M
Vadsö	VAD	17 06	29 39			M
Valentia	VAL	51 56	349 45	51.3	72.2	M
Vladivostok	VLA	43 41	132 10	36.8	203.3	M

A = all-sky camera, M = magnetometer, M (2) = normal and rapid-run magnetometers, P = induction magnetometer, R = riometer

[a] Corrected geomagnetic coordinates for 1980.0 epoch geomagnetic field after Tsyganenko (1979) are given for the stations in Figs. 2 and 3

bays at mid-latitudes (see Fig. 1). The mid-latitude magnetic H and D variations (quiet level from 5–6 November 1976 subtracted) shown in Fig. 2, upper panel, resemble the conditions of intense stationary magnetospheric convection reported by Sergeev (1977).

Figure 1 shows that there are two pronounced magnetic bays starting at mid-latitudes at 1730 and 1748 UT. Also Fig. 7a indicates that these bays are associated with two separate Pi2 trains recorded at Borok and Kaliningrad. The mid-latitude magnetic H and D variations given in Fig. 3 are typical for an intense substorm expansion phase (McPherron et al., 1973; Akasofu, 1977) and for successive separate microsubstorms (Sergeev, 1974; Pytte et al., 1976a). According to Sergeev (1978) the positions of the positive and negative maxima in the ΔD curve correspond to the longitudes of the western and eastern edges of the auroral bulge. Hence, the auroral bulge in the first expansion is within 100–150° corrected geomagnetic longitude and in the second expansion within 70–200°. The shape of the ΔD curve in the second case indicates that two new current wedges appear both eastwards and westwards of the first expansion region. The interplanetary magnetic field data (Fig. 4), show strong fluctuations between 1700–1800 UT, B_z being southwards (<0) during periods of auroral activity. The second auroral activation in particular, which starts at 1748 UT, seems to coincide within one minute with the sharp southward turning of the IMF.

Auroral zone phenomena. All-sky pictures from the first substorm are shown in Fig. 5a. The lower borders of distinct auroral structures have been digitized and replotted on geographical maps in Fig. 5b (Kaila, 1981). The shaded ovals on the maps give the effective antenna beams (at auroral altitudes) of the Finnish riometer chain from which the data are displayed in Fig. 6. Figure 7a presents the recordings of low-frequency magnetic pulsations from both the auroral zone (LOZ) and the mid-latitudes (BOX and KNG), while Fig. 7b shows a sonagram of the high-frequency pulsation component recorded in the auroral zone (KEV).

The first substorm can be divided into two microsubstorms starting at 1730 and 1748 UT (for details see Table 2). The first microsubstorm is preceded by typical preonset features like enhanced absorption (Pytte et al., 1976d; Ranta, 1978; Ranta et al., 1981) (Fig. 6) and auroral structures moving southwards with an average speed of 180 m/s. The absorption maximum reaches Rovaniemi at 1720 UT where the poleward boundary of diffuse aurora is also located by that time.

At 1729:30 UT a Pi2 onset is recorded at mid-latitudes

Table 2. Timing of events in different phenomena appearing during substorm expansion phases

No.	Time UT	Relation to substorm phases	Mid-latitude magnetic bay	Mid-latitude Pi2	Auroral development in Scandinavia	Cosmic noise absorption and X-rays	Appearance of PiB's
1	1730	Onset of first microsubstorm	Sharp bay onset	Onset at 1729:30 UT	Rapidly westward traveling "auroral horn" appears in the south-eastern sky, altitude 92±2 km	Absorption starts to increase at 1732 UT in ROV under the "auroral horn"	No PiB
2	1735	The micro-substorm continues	The bay continues to develop	Intensification and phase change occur at 1734:30 UT	Brightening of the "horn", appearance of ripples	Onset of slow rise in absorption in SOD	PiB at 1734 UT, most distinctly at OUL
3	1738	The micro-substorm continues	The bay continues to develop	Distinct intensification at 1737 UT	WTS appears in the eastern horizon, altitude 86±3 km	Onset in IVA and KEV	PiB after 1737 UT
4	1745	The micro-substorm continues	The bay continues to develop	Onset of weak pulsations	Formation of a new faint discrete arc on the poleward edge of auroral bulge, altitude 97±2 km	Weak onset in SOD	PiB at 1745 UT only at KEV
5	1748	Onset of second micro-substorm	Sharp change in bay pattern	No intensification, change in phase at 1747:30 UT	Brightening of the poleward edge of auroral bulge, altitude 85±5 km	Onsets in IVA and KEV (sharp)	PiB at 1748 UT
6	1750	The micro-substorm continues	The bay continues to develop	Intensification	Formation of new bright discrete arcs (altitudes 73±2 and 83±2 km) on the poleward edge of auroral bulge	Intensification in absorption in KEV	PiB at 1750 UT
7	1752	The micro-substorm continues	The bay continues to develop	Intensification	Intensification in luminosity in the north (altitudes between 79±2 and 90±4 km) and decrease in the zenith as seen from MUO	Absorption in KEV reaches a maximum (6 dB)	PiB at 1752 UT
8	2102	Onset of a small microsubstorm	–	–	Brightening and activation of discrete arc, altitude 105±3 km	X-ray enhancement starts at 2101:30 UT	PiB's appear in KEV, SOD
9	2103	The micro-substorm continues	–	Onset of Pi2 at 2102:30 UT	Formation of a bright discrete arc, altitude 98±2 km	X-ray spikes detected by balloons 1 and 2	PiB's appear in KEV, SOD
10	2105	The micro-substorm continues	–	Intensification at 2105 UT	Formation of a bright discrete arc (at 2106 UT) altitude 103±3 km	X-ray enhancement starts at balloon 3 at 2104. Enhancement starts at all balloons at 2105 UT	PiB's appear in KEV, SOD

(Fig. 7a). At Kevo no Pi activity is observed (Fig. 7b) at this moment. A discrete auroral arc propagates from the east along the poleward boundary of the diffuse band south of Muonio (Fig. 5a). This arc, which we call „auroral horn" is located at a considerably lower altitude (92±2 km) than the diffuse band (approximately 105 km).

At 1732 UT the western edge of the horn reaches the Rovaniemi riometer (Fig. 5b), which records an enhancement in absorption (point "1" in Fig. 6). Between 1734 and 1735 UT both Pi2 intensification, phase change, and a small Pi burst (PiB), seen most distinctly at Oulu, are observed (marked as "2" in Figs. 7a and b). These are related to the intensification of the horn brightness (Fig. 5a) and to the minor enhancement in absorption at Sodankylä ("2" in Fig. 6).

The horn is followed by a westward travelling surge (WTS) that appears at 30° E longitude at 1739 UT. The appearance of the surge is related both to a strong intensification of Pi pulsations and to a start of PiB at Kevo (Figs. 7a, b). The altitude of the surge is 86±3 km, which explains the abrupt onset of absorption at Ivalo when the surge moves over ("3" in Fig. 6). The region of energetic

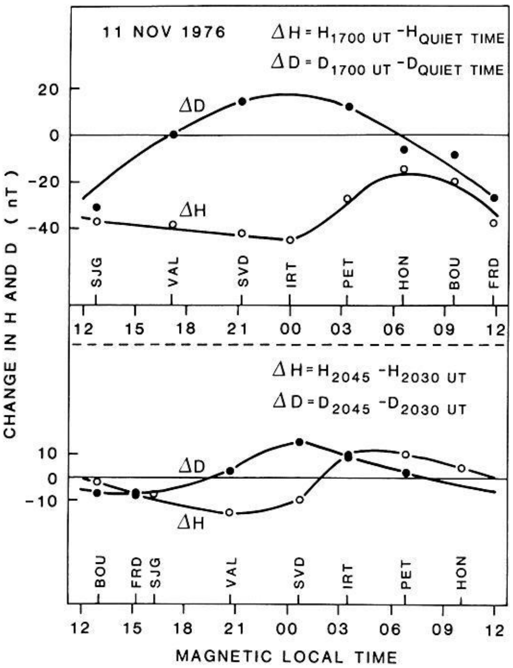

Fig. 2. Longitudinal profiles of mid-latitude magnetic disturbances, showing their patterns during the period of intense worldwide disturbances (top panel) and changes during the convection bay, which started at 2030 UT (bottom panel)

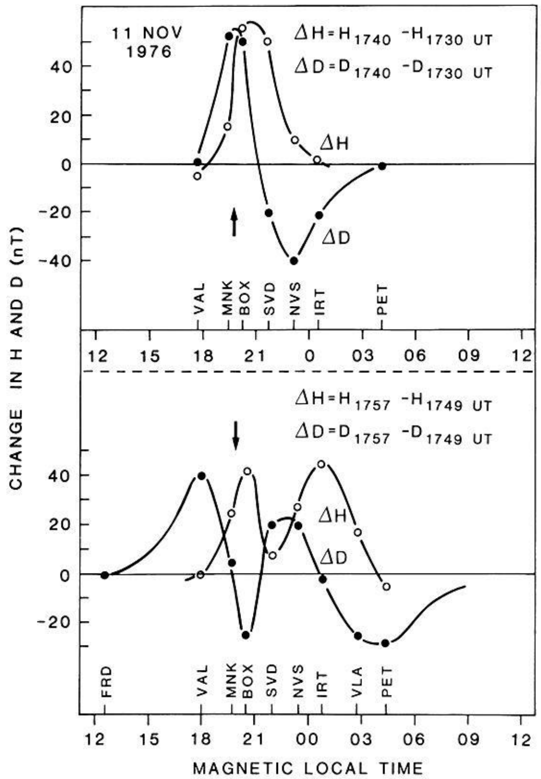

Fig. 3. Longitudinal profiles of mid-latitude bay-like disturbances, related to two intense microsubstorms, started at 1730 and 1748 UT. The arrows denote the meridian of Ivalo

precipitation within the surge seems to be fairly localized since the absorption enhancements at Kevo and Sodankylä remain on moderate levels.

The first microsubstorm ends with the disappearance of the surge. During the passage of the surge the bright auroral arcs that form the auroral bulge propagate some 300 km polewards. Before the second microsubstorm the brightness of the auroras in the bulge region decreases.

At 1745 UT a new faint arc appears polewards of the bulge (Figs. 5a, b). This is associated with a clear onset of a weak Pi2 train at mid-latitudes ("4" in Fig. 7a) and a weak PiB enhancement observed only at Kevo (Fig. 7b). The altitude of the arc is 97 ± 2 km which is of the same order as the altitude of the bulge. Fig. 5b shows that the arc is located between Kevo and Ivalo riometers, which do not record any enhancement in auroral absorption. However, there is a slow absorption enhancement at Sodankylä by this time ("4" in Fig. 6).

The second microsubstorm starts at 1748 UT with a brightening of the poleward edge of the auroral bulge (Fig. 5a). In spite of the abrupt enhancement in auroral intensity there is no change in Pi2 amplitude at mid-latitudes, only the phase seems to change ("5" in Fig. 7a). PiB activity starts at Kevo (Fig. 7b) and the auroral absorption starts to rise both at Ivalo and Kevo (Fig. 6). The poleward edge of the bulge descends to 85 ± 5 km while brightening.

At 1750 UT two new bright arcs (altitudes 73 ± 2 and 83 ± 2 km) appear polewards of the bulge edge (Figs. 5a, b). Since these low-altitude arcs form within the Kevo riometer antenna beam an abrupt absorption enhancement ("6" in Fig. 6) is recorded. At the same time Pi activity intensifies both at mid-latitudes and in the auroral zone (Fig. 7a, b).

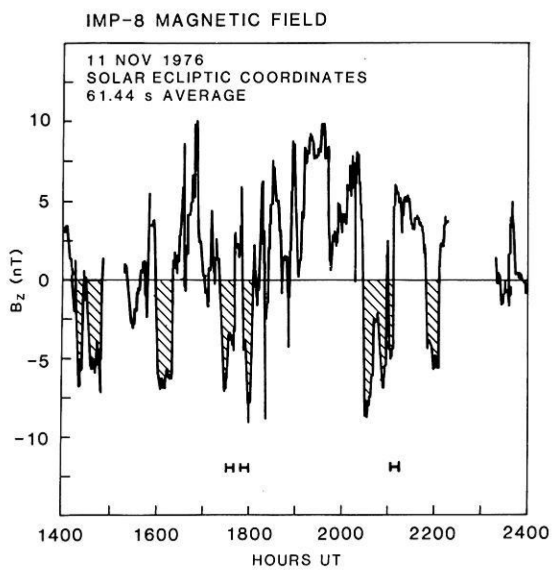

Fig. 4. B_z component of the interplanetary magnetic field in solar-ecliptic coordinates. Southward orientations are indicated by shading. Horizontal bars at the bottom indicate periods of microsubstorms

At 1752 UT a WTS is located to the north-west of Kevo (Fig. 5b). The altitudes of the surge and the arcs over Kevo range between 80 and 90 km (see Table 2). The highest absorption value (6 dB) is recorded at Kevo at this time ("7" in Fig. 6). Also the Pi activity both at mid-latitudes and in the auroral zone reaches a maximum (Figs. 7a, b).

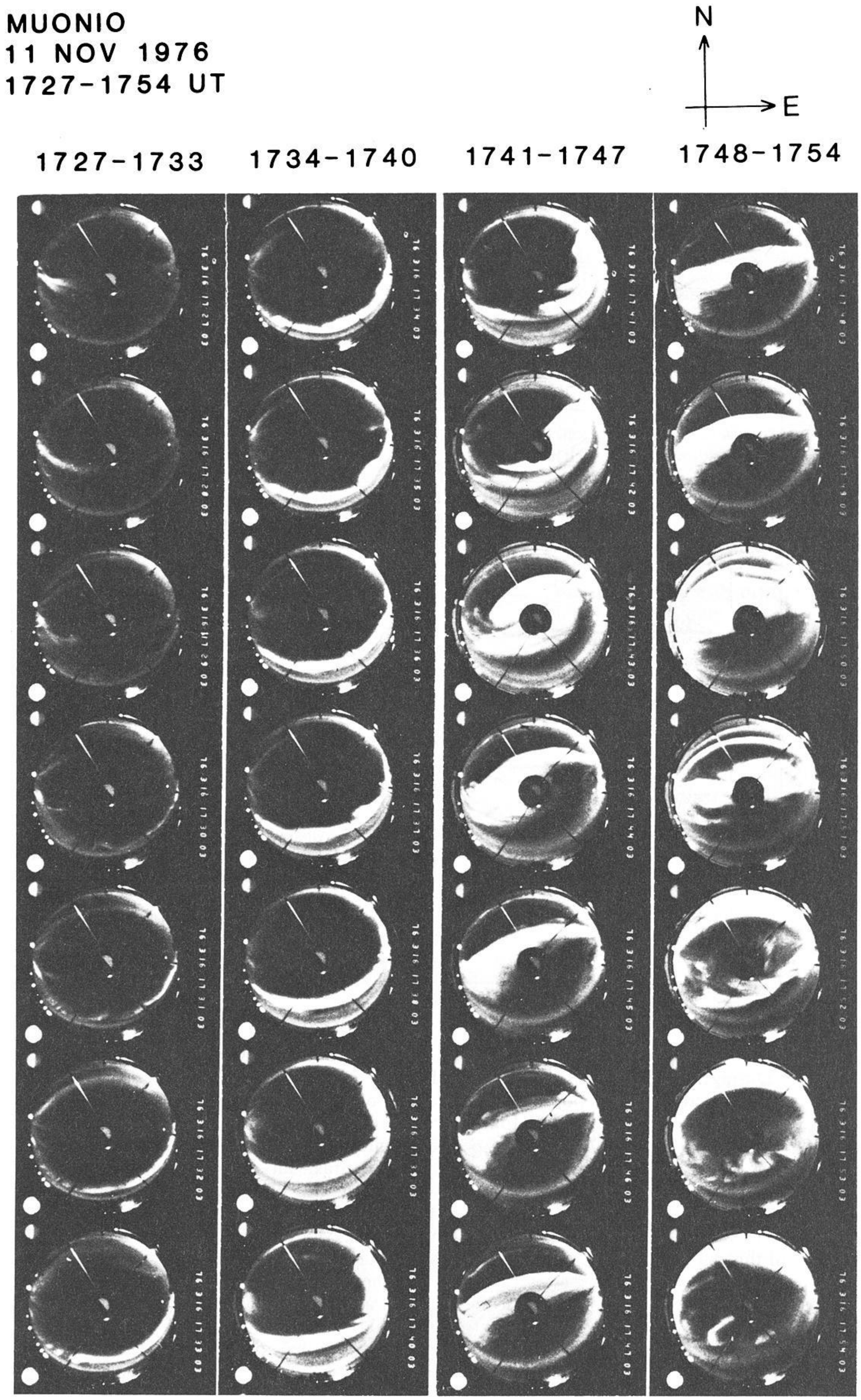
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Fig. 5a

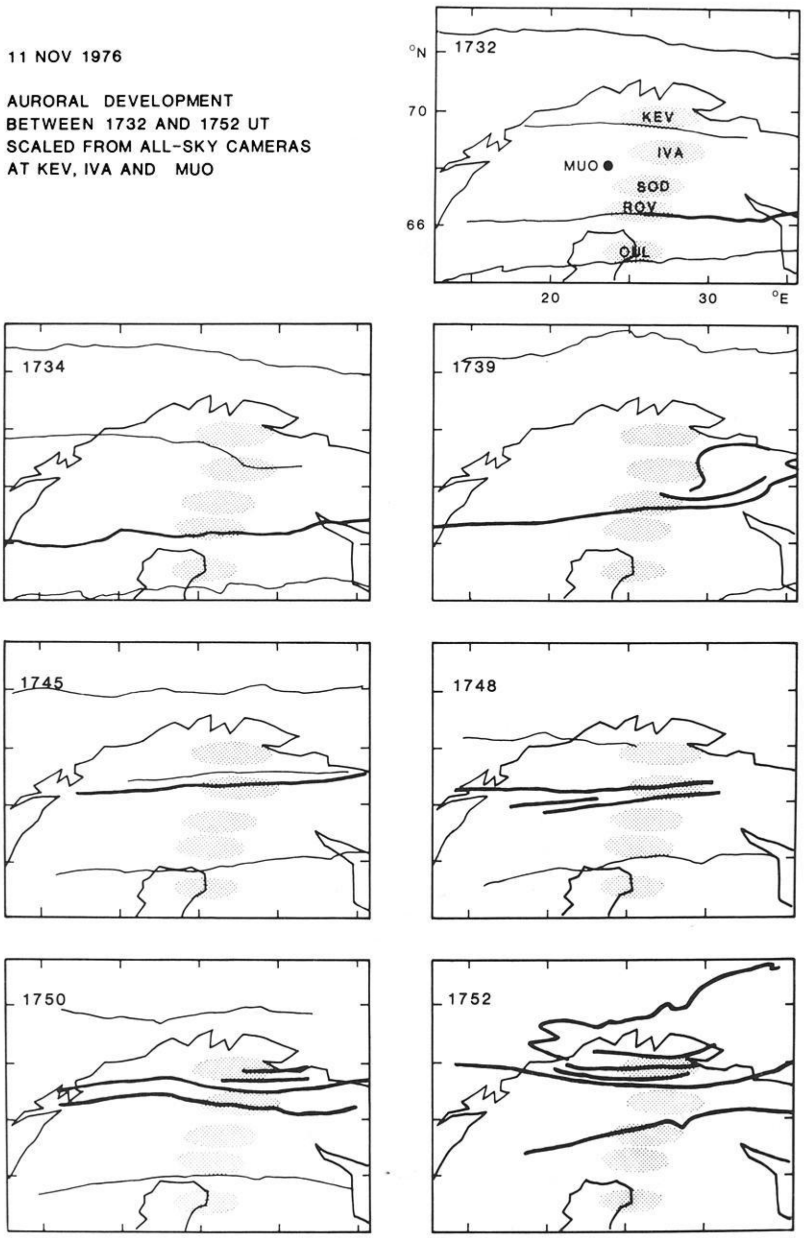


Fig. 5. a All-sky camera pictures recorded at Muonio around the two microsubstorms initiated at 1730 and 1748 UT. **b** Digitized all-sky camera pictures rectified and mapped in geographic coordinates. The lower border altitudes of the arcs are given in the text and Table 2. Shaded ovals indicate effective riometer antenna beams at 100 km altitude

During this second microsubstorm the auroral bulge propagated 600 km polewards. During both microsubstorms faint equatorward drifting arcs were observed polewards of the expanding bulge.

Time Interval 2030–2110 UT

Global features. A thorough description of this event is given in Pellinen et al. (1982), here we will only summarize the results essential to the scope of this paper.

Figure 1 shows a negative magnetic bay starting to develop at the midnight-morning auroral zone stations some half an hour prior to the substorm onset at about 2100 UT. The development is world-wide and associated with a rapid southward turning of the interplanetary magnetic field (Fig. 4). The maximal magnetic disturbance ($AE \sim 500$ nT) is reached at 2045 UT. According to Pellinen et al. (1982) the development observed on the ground is well correlated with variations in the solar wind-magnetosphere energy coupling function ε (Akasofu, 1981).

The pattern of the mid-latitude magnetic variations, as follows from Fig. 2 (lower panel), is similar to the one for the period of intense convection before 1700 UT (Fig. 2, upper panel), but drastically differs from the patterns of substorm expansion, e.g. Fig. 3. During the whole period between 2030 and 2200 UT we are unable to discover any expansion-type behaviour in the mid-latitude data. The only signature is detected in the very sensitive (0.5 nT/mm), rapid-run (90 mm/h) magnetogram (data not shown here) of the Kaliningrad observatory at 2102 UT, but the effect is extremely weak.

During the one and half hour period prior to 2030 UT there are no signatures of mid-latiude Pi2 pulsations both near midnight and in the morning sector. The interplanetary magnetic field is northward directed during the whole period (Fig. 4). A Pi2 onset is detected at 2102 UT, and a weak

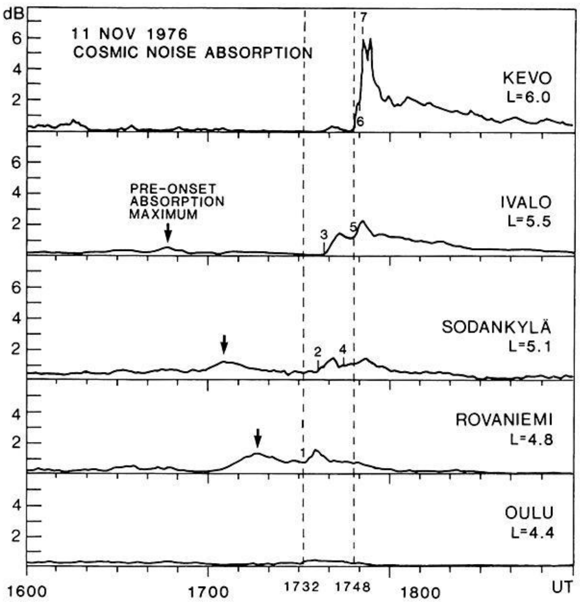
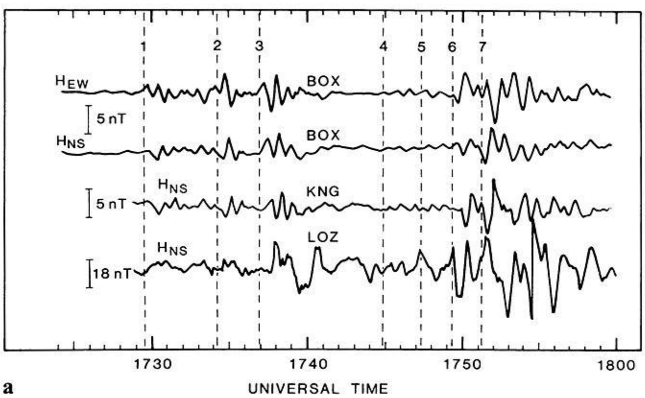


Fig. 6. Data from the Finnish riometer chain during the first expansion event. Numbers, marking the onsets of distinct rises in cosmic noise absorption, correspond to the numbers in Table 2 (see the text for details)



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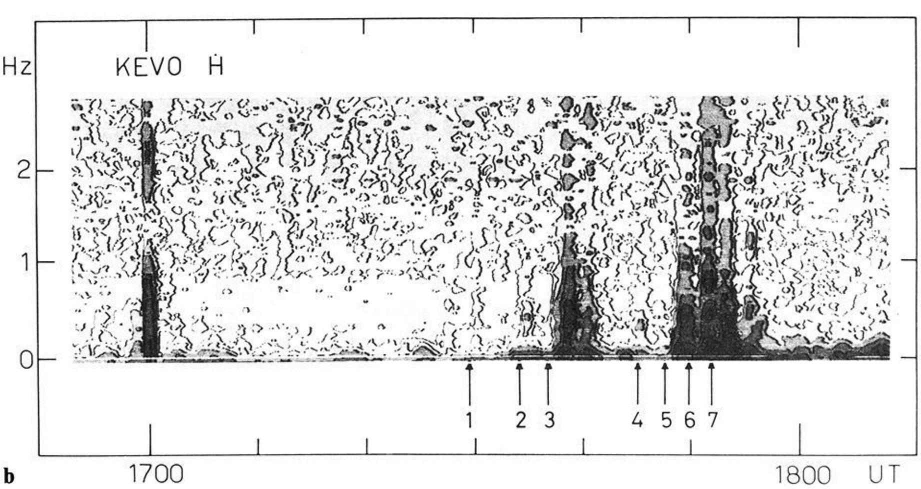


b

Fig. 7. a Mid-latitude and auroral-zone induction magnetograms for the first time interval. **b** Dynamic spectrum of Pi pulsations recorded at Kevo. The numbers 1–7 refer to the same times as in Fig. 7a. The intensity grey-scale is for qualitative purposes only

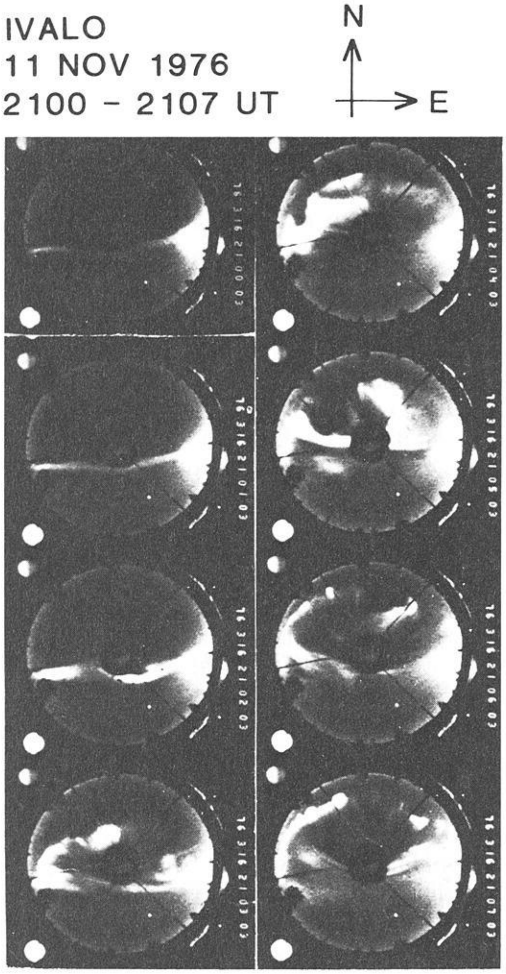
pulsation train appears at 2137 UT. No auroral zone magnetic effects are detected during these two substorm intensifications except at stations within the Scandinavian area (Fig. 9). No enhancement in cosmic noise absorption is detected by the Danish high-latitude riometer network during these events (Stauning and Christiansen, 1978). We shall focus our attention on the earlier one of these two short and weak expansions since it occurs in the Scandinavian sector.

Auroral zone phenomena. During this time interval stations in the Scandinavian region are located in the region of westward electrojet close to magnetic midnight (Pellinen et al., 1982). At 2030 UT, a faint auroral arc appears in the northern sky of Kevo (Fig. 1) and then drifts equatorwards until 2058 UT, when the motion stops between Ivalo and Sodankylä (Figs. 8a and 8b). The average altitude of the arc is 102 ± 3 km both at 2057 and at 2100 UT.

At the onset of the magnetic bay at 2030 UT a small increase in auroral absorption is seen in the Kevo recording (Fig. 9). The subsequent decrease in absorption at Kevo and the simultaneous increase over Ivalo indicates equatorward movement of the absorption region.

Three balloons of the SAMBO-76 campaign drifted over the region between Ivalo and Sodankylä (see Fig. 8b). Their recordings (Fig. 9) show variations in X-ray intensity that are similar to the absorption at Ivalo, but the pre-break-up intensity maximum occurs near 2058 UT, 3 min later than the absorption maximum at Ivalo. The balloon detector aperture is about 100 km wide at 100 km altitude in the ionosphere. The combined riometer and balloon data suggest that the latitudinal width of the energetic electron precipitation region is of the order of 100 km, and the equatorward drift speed is 100 m/s. Comparison of the absorption recordings made at Ivalo and Sodankylä with the X-ray intensity recordings leads to the conclusion that the equatorward motion stops at 2058 UT – 4 min before the break-up, in good correlation with the behaviour of the auroral arc.

The high-frequency component of the Pi pulsations is shown in Fig. 10b by the dynamic spectrum made from the Kevo recordings. No PiB activity appears before 2102 UT. The same holds for all the Finnish stations from Kevo to Nurmijärvi.



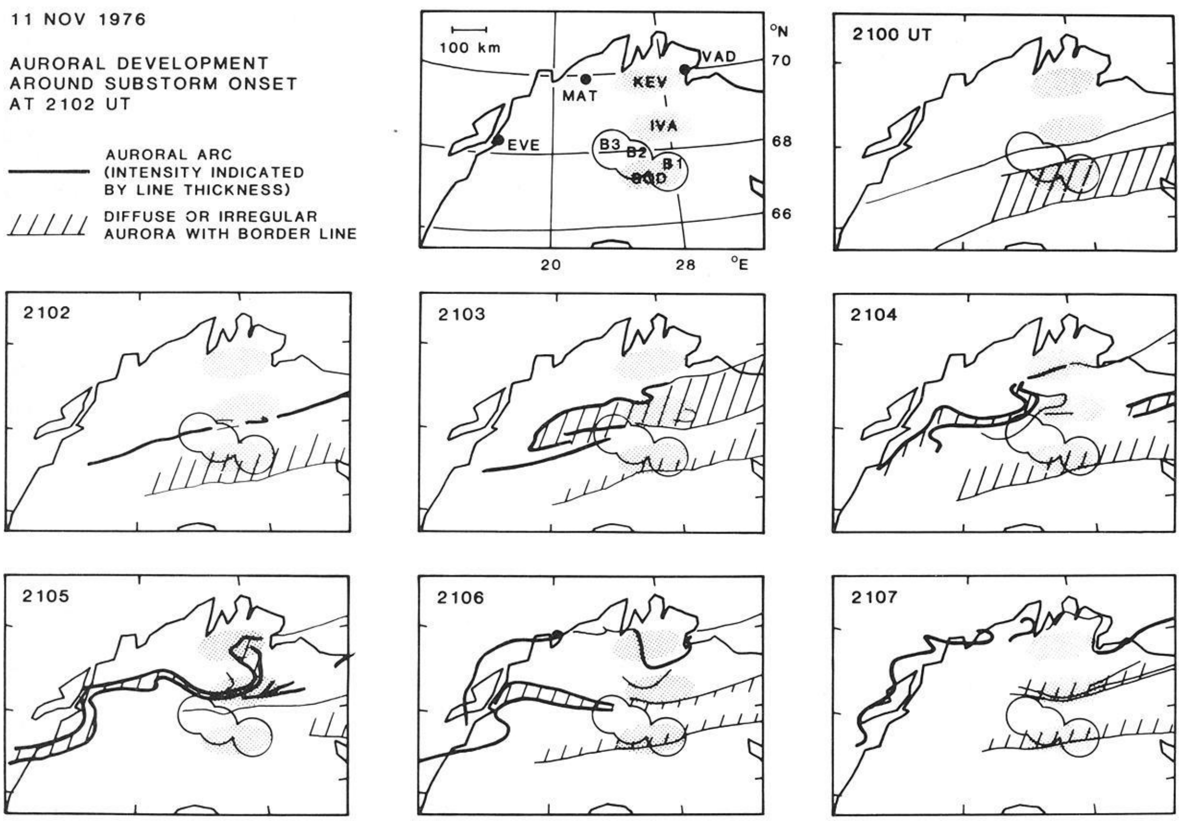
a

At 2102 the arc becomes considerably brighter. In contrast to the substorms between 1730–1800 UT the altitude of the brightening arc seems to ascend at this moment being 105 ± 3 km along the brightest forms. At 2103 UT a new bright arc appears polewards of the previous one, developing a surgelike structure over Kiruna (Figs. 8a and 8b). The average altitude of the surge is 98 ± 2 km. At 2104 and 2105 UT a deformation of the poleward border of the bulge with apparent eastward motion takes place over the observing area. The brightest parts of the eastward travelling surge (possibly a small Ω-band according to Akasofu, 1974) seem to be at an altitude of 103 ± 3 km. Weak glow is visible polewards of the bulge at 2105 UT and one minute later a new distinct bright arc forms in the glow region (altitude about 100 km). At 2106 UT the Ω-band becomes smaller and decreases in intensity. The altitude remains close to 100 km all the time.

The arc located over the Norwegian coast (2107 UT, Fig. 8b) is the last signature of this moderate auroral break-up, which is rather local (about 250 km in poleward expansion) and short in duration (6 min). The longitudinal extent of the auroral expansion is only about 1 h in magnetic local time at 2104–2105 UT.

The auroral break-up at 2102 UT initiates a brief increase in auroral absorption at Ivalo and Kevo (Fig. 9), located by this time near the eastward expanding auroral

Fig. 8. a All-sky photographs from Ivalo during the local break-up, initiated at 2102 UT. **b** Mapped all-sky camera data corresponding to the all-sky pictures presented in Fig. 8a. Shaded ovals indicate riometer antenna beams and the three rings around Sodankylä the effective recording areas (at 100 km altitude) of balloon X-ray counters. The dots at EVE, MAT and VAD give sites of the three magnetometers from which data are presented in Fig. 9



b

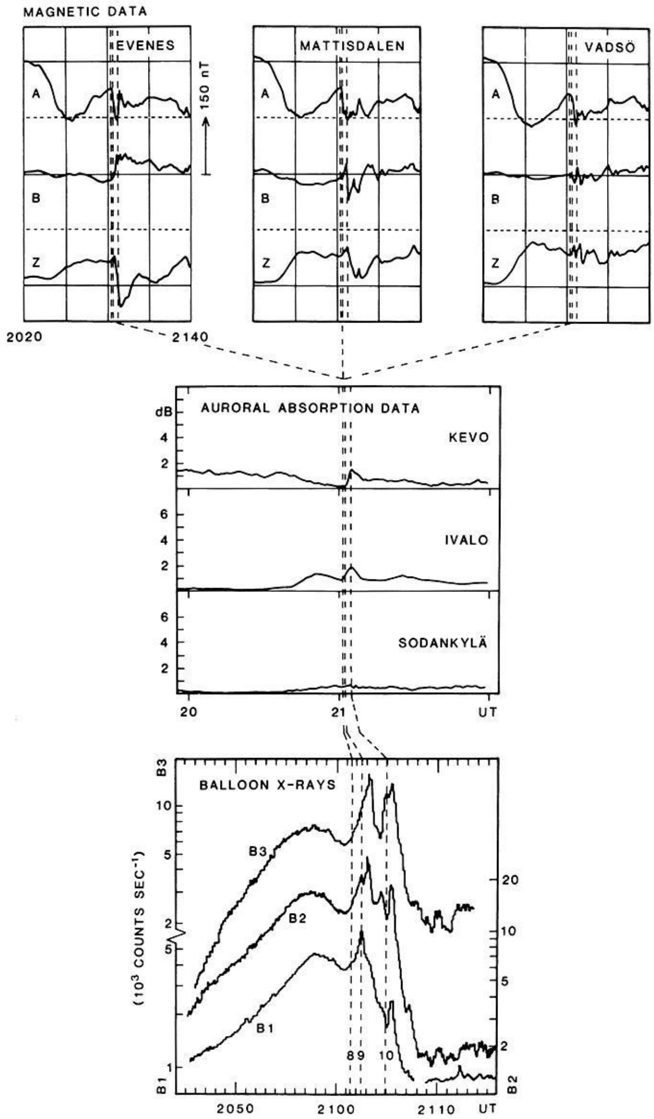


Fig. 9. Magnetic data from Evenes, Mattisdalen and Vadsö (top panels), riometer recordings of the Finnish chain (center) and counting rates of the X-ray detectors at the three balloons shown in Fig. 8b. The X-ray energy ranges are for $B_1 > 25$ keV and for B_2 and B_3 30–40 keV. (data from Melnikov et al. 1978) (bottom panel)

bulge. The impulsive character of the X-ray data recorded in this event is typical for an auroral break-up (Pytte et al., 1976c; Melnikov et al., 1978). The first abrupt onset at 2102 UT (8) is recorded by all three balloons. The first peak at 2102:30 UT is observed only by the two southernmost balloons (B1 and B2) while the second peak at 2103 UT (9) appears over balloons B2 and B3. The first peak obviously corresponds to the auroral activation within the discrete arc and the second peak to the formation of the auroral bulge.

At 2104–2105 UT the Ω-band moves across the poleward sky oof Ivalo. Before it reaches the longitude of Ivalo minor X-ray activity peaking at 2104:30 UT is recorded at balloon 2 and then probably propagates polewards to be recorded by balloon 3 some half a minute later. The exact correlation of this event with aurora is impossible due to the slow recording speed of the all-sky camera. It is possible that local irregularities in the energetic electron precipitation related to Ω-bands cause these impulses (Oksman, 1981). At 2105–2106 UT a new arc forms polewards of the bulge. Impulsive X-ray bursts are recorded at all balloons during this time (10).

A Pi2 onset is detected both at auroral and mid-latitudes between 2102 and 2103 UT ("9" in Fig. 10a). An increase in Pi2 amplitude around 2105 UT (10) is evident at the mid-latitude stations and in the auroral zone (Lovozero) even if the data are more disturbed there. Two PiB's can be identified starting at 2103 (9) and 2105 UT (10) (Fig. 10b). There are no signatures of these pulsations at Oulu and Nurmijärvi.

Again Pi pulsations appear simultaneously with increases in electron precipitation as inferred from the auroral and riometer recordings (see Table 2). A remarkable feature is the total absence of magnetic pulsations during the growth phase before 2102 UT in spite of the clear electron precipitation activity. Similar observations have been reported earlier by Wedeken et al. (1979).

Data from 24 instruments of the SMA (temporal resolution 10 s) are available for this period. Details of the evolution of the current pattern over Scandinavia from 2030 UT to 2100 UT can be found in Pellinen et al. (1982). Gradual changes occur in the westward electrojet intensity during the equatorward movement. Prior to the substorm expansion onset, during the convection bay, the maximal horizontal magnetic disturbance is about 150 nT in contrast to the $\sim$70 nT disturbance being added to the background field during the substorm expansion (see the data in Fig. 9 – top panels).

The pattern of changes in the equivalent currents over Scandinavia from the moment of expansion onset towards its end (Fig. 11) displays a very complex distribution of magnetic disturbances (both in intensity and orientation of the vectors), differing in each part of the magnetometer array. Therefore we analyzed the magnitude of the total horizontal disturbance after the expansion onset by subtracting from it the horizontal magnetic field recorded at 2101 UT in different parts of the expansion current system. Additionally the disturbance amplitude was averaged over a few "typical" stations, as also shown in Fig. 11. In spite of some minor differences, the data consistently show two major increases in disturbance level, starting at 2102:30 UT and between 2104:30 and 2105:00 UT, in good coincidence with the other data mentioned above. In addition we constructed the differential current patterns for each activation, i.e. from 2102:30 till 2104:00 and from 2104:30 till 2106:00. Both of these were found to have a current distribution similar to the summary current system in Fig. 11, but during the second activation the whole current system was displaced polewards in comparison to the first one, being in accordance with the poleward shift of active aurora (data not presented here).

Discussion

The discussion covers three major topics. First we shall discuss the regularities found in the substorm fine structure. As the second question we shall treat the relationships between the different expansion signatures reported above. The third question deals with the problem of whether the global disturbances observed prior to and during the expansion phases are due to external or primarily internally oper-

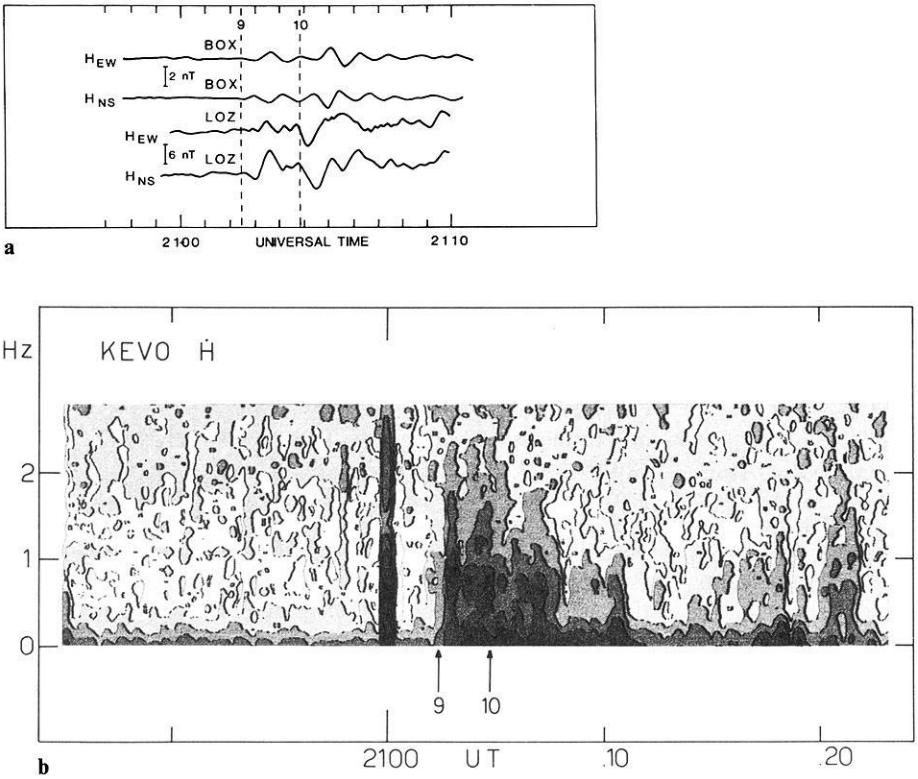


Fig. 10a and b. The same as in Fig. 7a and b for the second substorm event

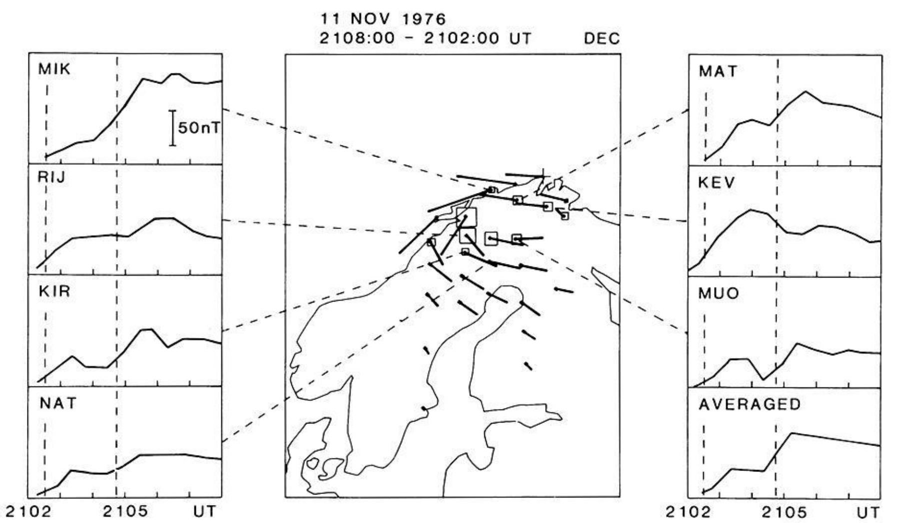


Fig. 11. A change of equivalent current system during the period of local break-up (from 2102 UT to 2108 UT) and the change in magnitude of the horizontal magnetic disturbance at a few stations of the SMA. The averaged data have been taken from the seven other panels framing the map

ating magnetospheric processes. At present the debate on this field is highly controversial (Akasofu, 1981; Fairfield et al., 1981).

Substorm Intensifications: Microsubstorms and Their Fine Structure

Rostoker et al. (1980) defined the substorm expansion phase as "the ensemble of the onset plus all intensifications up to the time of maximum poleward expansion of the substorm-disturbed region". The observations presented in this paper well support this view.

There seem to be two different time scales embeded in the discrete substorm structure. In the first intensive substorm the intervals of auroral expansion last for 5–10 min and they are clearly separated by quiet periods. The active periods are identified by well-separated Pi2 trains and mid-latitude magnetic bay intensifications. In the literature these discrete activations are called microsubstorms (Sergeev, 1974) or multiple onsets (Wiens and Rostoker, 1975; Pytte et al., 1976a, b). Another time scale (repetition interval about 2 min), which we consider as a new element of substorm morphology, appears both in intensive and weak microsubstorms. The most obvious presentation of this type of discrete fine structure can be found in Figs. 7b and 10b where the PiB spikes are repeated approximately in 2 min (see also Table 2). In some earlier studies these spikes were found to be associated with auroral break-ups and intensifications of auroral arcs (Heacock, 1967; Kangas et al., 1979; Bösinger et al., 1981). Our study supports these observations. Each effective brightening of an auroral arc or even a formation of a new faint arc in the vicinity of the auroral bulge is associated with PiB in the auroral zone. At mid-latitudes simultaneous changes in Pi2 characteristics (amplitude, phase, and period) are observed. Each optical activation is also accompanied by a simultanous increase in energetic electron precipitation (monitored by riometers and balloons) and by step-like changes in ionospheric equivalent currents.

The fact that mid-latitude Pi2 recordings are associated with phenomena observed only locally in the auroral zone leads to the conclusion that some large-scale (substorm) mechanisms have to operate in the background, since the responses detected at distances comparable to the dimension of the bulge itself, cannot be caused only by changes in small-scale features within the bulge. This conclusion is supported by Sergeev (1981) who found that simultaneous abrupt changes in Pi2 characteristics at widely spaced (1,000–2,000 km) mid-latitude stations coincided with sharp impulsive variations in the magnetic field of the far tail (30 R_E). Hence, the observed fine structure of microsubstorms must follow from steplike changes in the geometry of the whole auroral bulge (Sergeev an Yahnin, 1979b) and/or from the intensification of the total precipitation in the bulge region. The above results lead to the conclusion that the microsubstorm fine structure is part of the entire substorm mechanism.

Substorm Signatures and Their Relationships

An obvious result of our study is that all expansion signatures, even small details, are strictly grouped in time. However, details in their relations differ, apparently because of the different origin of the phenomena involved. First we shall point out some morphological features. A southward-moving "particle arc" which causes riometer absorption precedes both substorm onsets. The cosmic noise absorption curves from Rovaniemi (Fig. 6) and Ivalo (Fig. 9) look quite similar. The pre-onset absorption maxima are over 1 dB in both cases. Two conclusions can be drawn from these data. First, the strength of the forthcoming substorm seems to be correlated with the location of the southernmost latitude of the pre-onset absorption (lower latitudes lead to more intense expansions). Second, the pre-onset absorption region seems to have a long east-west extension (Ranta et al., 1981) since in our cases the absorption development is independent of whether the substorm is triggered far in the east (first case) or in our immediate environment (second case).

Our results show that after the substorm onset an "auroral horn" propagates with high speed away from the triggering area approximately along the poleward edge of the pre-substorm particle arc. The horn keeps its arc structure while the disturbed auroras that follow are shaped in forms which can be identified as westward travelling surge (Akasofu et al., 1965) and (eastward travelling) Ω-band (Akasofu, 1974). Our observations suggest that the propagation speeds of these large-scale forms are less than the speed of the auroral horn. Supporting examples can be found in the extensive ASC data set collected in Finland during the IMS.

In the present study the following estimates for the lower border altitudes of different auroral structures have been obtained:

Equatorward diffuse band	105–110 km
Faint arcs poleward of the bulge	100–110 km
Auroral horn	90 km
Surge	80– 90 km
Arcs formed near the poleward boundary of bulge	75– 90 km

These numbers show that the auroral horn, westward travelling surge, and the new bright arcs near the poleward boundary of auroral bulge are caused by electrons of higher energy than the discrete and diffuse auroras outside the bulge region. The auroral absorption recordings show that impulsive precipitation of energetic electrons is associated with these low-altitude structures. This conclusion is valid even in the second substorm (mainly for balloon X-rays), where the auroral altitudes are considerably higher ($\sim$100 km – see Table 2).

PiB events seem to be associated with pronounced changes in auroral arcs (Table 2). However, no PiB appears at the onset of mid-latitude Pi2 at 1730 UT. The first PiB event starts at 1734 UT (most distinctly at Oulu, Table 2) when the horn has propagated beyond the Oulu meridian and starts to brighten. This leads to the conclusion that PiB penomena can be observed only in the MLT sector occupied by active aurora but the localization is not as limited as for the burst-like precipitation of energetic electrons. These observations agree with those reported by Parkhomov et al. (1976) who show that a PiB can be observed simultaneously over a longitudinal distance of 30° and it may propagate westward with a speed of 2–10° min^{-1}.

As mentioned above, a significant correlation was found between the times of discrete auroral zone phenomena and the abrupt changes in the intensity (or phase) of Pi2's at mid-latitudes. Details of the response are not the same when comparing, for instance, with the response of PiB pulsations. In particular, Pi2 intensity seems to be influenced much more by the formation of new auroral structures than by brightening of previously existing ones. This can be seen e.g. by comparing points 4 and 5 in Table 2: formation of a faint discrete auroral structure slightly polewards of the bulge causes pulsations of the same amplitude as during the subsequent strong brightening of the bulge's edge. Also point 8 in Table 2 supports the conclusion since auroral brightening does not generate Pi2 pulsations until the formation of a new structure of similar intensity. These results are in accordance with the examples presented by Sergeev et al. (1978) and Sergeev (1981).

Our observation that the mid-latitude Pi2 pulsations and the onset of a magnetic bay occur simultaneously with the appearance of the "auroral horn" in the auroral zone contradicts the results reported by Kawasaki and Rostoker (1979). Based only on auroral zone data from one meridian, they argued that the arc brightening and substorm onset, particularly the onset of Pi2, do not coincide. Pashin et al. (1982) have shown that in the auroral zone there is an intimate connection between the positions of the Pi2 (PiB) maximum and the auroral bulge. Hence, if the auroral bulge develops outside the field of view of the all-sky camera (as in our first event) Pi2 (PiB) pulsations do not appear under the auroral horn, which can also be identified as "arc brightening", until the horn starts to become disturbed. It is also possible that the pulsations associated with the auroral horn have very small amplitude and are confined to the horn area. This feature is supported by the auroral zone data recorded at Lovozero (LOZ in Fig. 7a). Kawasaki and Rostoker (1979) analyzed pulsation data recorded only at one auroral zone station which also may lead to wrong conclusion, e.g. at 1734 UT in our case (Table 2) PiB appears only weakly at Kevo (Fig. 7b) but more distinctly at Oulu.

The mid-latitude magnetic bay seems to be very sensitive to the current intensity and to the longitudinal dimensions of the current wedge. In our second event (around 2100 UT) both the size of the bulge and the total current through it are so small that the disturbance is not distinguishable in a normal mid-latitude magnetogram. According to Pellinen et al. (1982) the current wedge is 2 h wide in MLT and carries a total current of 250 kA which would create about 4 nT maximal disturbance in magnetic H and D components at 40° geomagnetic latitude. This numerical value is below the resolution of standard magnetic data.

Relationship Between IMF Variations, Magnetospheric Convection and Substorms

In spite of the entirely different intensities and scales of the two substorms reported here their general signatures are similar and coincide with those of a "typical substorm". An equatorward moving high-energy precipitation region which, according to Pytte and West (1978), can be regarded as a signature of growth phase, is observed to appear 30–60 min before both expansion phases. The expansion phases develop through brightening an poleward expansion of auroras, abrupt increases in energetic electron precipitation, and appearance of irregular magnetic pulsations both in the auroral zone and at mid-latitudes.

The basic difference in the substorms can be found in the behaviour of magnetospheric convection prior to the onsets. Features of convection can be deduced from worldwide magnetic field recordings. In both cases a two-cell current system (for details see Pellinen et al., 1982) is observed at high latitudes. At mid-latitudes the magnetic disturbance is of partial DR (disturbed ring current) type (Fig. 2, see also Sergeev, 1977). In the first case convection is intense but stable before the onset. The IMF is mainly northwards but fluctuating (Fig. 4). In the second case, an obvious convection intensification prior to the expansion phase is associated with a clear southward turning of the IMF.

The relationship between convection development and substorm processes observed both in the magnetosphere and in the ionosphere appears to be complicated and indirect. In the literature the following examples can be found:

(a) Convection enhancement caused by southward turning of the IMF leads to substorm growth phase and expansion (typical substorm development explored by many authors, see the review by McPherron, 1979).

(b) Strong convection during a stable southward IMF can proceed for a few hours without any significant substorm development (Sergeev, 1977).

(c) Strong expansion preceded by a growth phase can occur within a prolonged period of intense stationary convection and southward IMF (Pytte et al., 1978a).

(d) Strong expansion can be initiated when convection fades at a northward turning of the IMF (Caan et al., 1977).

(e) Substorm expansions may occur without any signatures of convection under northward IMF (substorms along a contracted auroral oval: Akasofu et al., 1973).

An obvious consequence of the complex relationship between convection and substorm is that the use of AE or DR indices, without any further investigation, may lead to wrong conclusions in determining the time of different substorm phases, since they are sensitive to current systems associated both with magnetospheric convection and subsorm expansion. This is well demonstrated in our events. The AE index values recorded during the first expansion phase differ only insignificantly from the values recorded during the growth phase and the several preceding hours (data not presented here). The AE index for the second event reaches a rather intense value (500 nT) during a relatively short interval, about half an hour preceding the subsorm onset. The expansion, strictly confined both in time and space, shows no response at all in the AE index.

The fact that growth phase development is usually associated with enhanced magnetospheric convection (McPherron, 1979) suggests that an external convection electric field is applied to the ionosphere and to the magnetotail. One typical feature of the growth phase, besides the ground-based features described above, is the enhancement of magnetotail current. In rare situations, where the convection is stationary during a stable southward directed IMF (which means no change in external influence) the behaviour of magnetotail current seems to be varying. There may appear growth and expansion-like changes in the tail magnetic field (Pytte et al., 1978a) or, on the contrary, prolonged periods without any changes (Sergeev, 1977). This leads to the conclusion that the relationship between the imposed electric field and the evolution of the tail current intensity is complicated, and that a simple correspondence between enhanced convection and the growth-phase features (classified as "typical" behaviour) can be considered as an exceptional case.

The weakness of the second substorm expansion cannot be explained by the absence of magnetic field energy stored in the magnetotail. The fact that, during the intense large-scale convection prior to the onset, the auroral oval is expanding together with the equatorward moving high-energy particle arc, confirms the idea of growing tail current intensity during the growth phase. Also the estimates of energy balance made by Pellinen et al. (1982) support this view. One possible explanation is that the substorm is triggered by an external influence at the moment when the magnetotail conditions are far from the threshold of a large-scale instability. This may lead to a current instability in a localized region of the plasma sheet but not to a large-scale process in which most of the stored energy is released. Northward turning of the IMF seems to be the reason for the external influence (Fig. 4, see also Pellinen et al. 1982).

Caan et al. (1977) have studied the association of substorm expansions with the northward turning of the IMF. The results obtained by Caan et al. are confirmed in a more detailed study by Dmitrieva and Sergeev (in press 1983) which shows that IMF reversals, brief northward excursions, and fluctuations are effective in substorm triggering. Dmitrieva and Sergeev (1983) also found a class of spontaneous expansions that started without any simultaneous changes in the IMF or in the dynamic pressure of the solar wind. In events triggered by southward turning of the IMF they found a simple quantitative relationship between the duration of growth phase, τ, and VB_s (V = speed of the solar wind, and B_s = magnitude of the southward component of the IMF),

$\tau V B_s \simeq 9 \cdot 10^4$ nT min km s^{-1}.

The constancy of this value can be interpreted as a constant flux of magnetic energy added to the magnetotail, which changes the tail towards the state of marginal instability. In our second substorm $\tau = 30$ min, $V = 500$ km/s, and $B_s =$ 5 nT, which means that $\tau V B_s \simeq 7 \cdot 10^4$ nT min km/s, only slightly below the value given above. In the light of this result the previous explanation for the small scale of the expansion is not completely satisfactory.

In our first event the IMF makes sharp southward turnings around the onset times of the two microsubstorms (1730, 1748 UT) (see Table 2 and Fig. 4). This suggests that external influence may play an important role even in these cases. However, it is impossible to make reliable estimates of the propagation delays of these changes between the satellite and the magnetopause, which makes the treatment of the causal relationship rather vague.

In conclusion of this section we suggest that there is no simple relationship between gross-scale variations of convection intensity and substorm processes in the magnetotail. Furthermore, a transition towards enhanced energy dissipation in the tail (expansion phase) is complicated by the influence of short-term variations in the IMF and solar wind parameters.

Conclusions

1) The conditions of the two substorms analyzed in this work differ from a typical substorm. The first one is associated with a prolonged, stable and intense convection during fluctuating IMF. In the second case a convection enhancement is initiated by a southward turning of the IMF at the beginning of substorm growth phase. Based on these observations we infer that the intensity of convection itself does not define conclusively the state of the magnetotail (steady or non-steady). Therefore the AE and DR indices may be misleading in determing the substorm phases. Our second event supports this view: the substorm expansion that follows after the intense convection during the growth phase, is weak, short-lived and localized.

2) In spite of the uncommon nature of the two substorms clear growth and expansion phase signatures can be distinguished in the ground-based data. Before both onsets, a southward moving absorption band is observed. The strength of the forthcoming substorm seems to be correlated to the southernmost location of the absorption band: lower latitudes lead to more intense expansions.

Substorm onsets are followed by bright auroral arcs ("auroral horns") propagating with high speed along the poleward boundary of the pre-existing diffuse auroral band. These arcs are precursors to the auroral bulges coming into the field of view a few minutes later. The appearance of the auroral horn coincides with the magnetic disturbances (bay, Pi2) starting at mid-latitudes. The PiB's in the auroral zone are delayed until the appearance of the auroral bulge.

The auroral structures appearing within or near the bulge are produced by higher energy particles than the auroras farther away from the bulge.

3) The substorms can be divided into separate microsubstorms that seem to have a systematic fine structure. Microsubstorms last for 5–10 min and are separated by quiet periods. Intensifications (fine structure) in each microsubstorm are repeated approximately each 2 min. Both the microsubstorm onsets and intensifications are observed in the auroral zone and mid-latitude Pi2 pulsation data.The three microsubstorms reported here are all associated with rapid variations in the IMF.

4) Mid-latitude Pi2 pulsations are sensitive to changes in the auroral phenomena. Formation of a weak new auroral structure near the auroral bulge causes pulsations of the same amplitudes as a strong brightening of the bulge edge. Since the pulsation recordings are made at distances comparable to the dimensions of the bulge itself it is concluded that a large-scale substorm mechanism has to be responsible for these observations. In principle, this means that the formation of new auroral structures or the brightening of existing ones has to correspond to impulsive field variations in the distant magnetotail.

5) PiB phenomena can be observed only in the MLT sector occupied by active aurora (auroral bulge). The brightening of the most equatorward arc and onset of PiB need not coincide in the auroral zone at substorm onset but, most obviously, there is a one-to-one correspondence between arc brightening and Pi2 pulsations.

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