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A Case Study of the Response of the Magnetosphere to Changes in the Interplanetary Medium

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Abstract. The general response of the magnetosphere to the various solar wind parameters is now generally understood. However, the many deviations found for individual cases via à vis the norm show an incomplete knowledge of the relative role of each of the solar wind parameters presently thought to be of importance in predicting the level of the solar-terrestrial interaction. This study presents a detailed analysis of world-wide ground based magnetometer data together with information on the plasma and magnetic field properties of the interplanetary medium and magnetosheath obtained from the ISEE 1 and 2 and IMP 8 spacecraft. The event in question featured an interval of relatively stable southward IMF followed by a sharp northward turning. During the interval of southward IMF there were occasional transient northward turnings with significant substorm expansive phase activity appearing to be triggered by these transient northward turnings. The final northward turning of the IMF was associated with an episode of strong magnetospheric substorm expansive phase activity after which the level of high latitude magnetic activity decayed to a low level. Evidence is presented that the driven system auroral electrojets begin to decay at the time of the northward turning of the IMF even as the substorm expansive phase activity is initiated in the midnight sector. The collapse of the substorm current wedge during the final decay of high latitude activity is traced in some detail and it is shown that this collapse occurs progressively from east to west in a series of impulsive episodes. The results reported above are discussed in the context of energy dissipation in the magnetosphere-ionosphere system through direct input of solar wind energy and through unloading of the magnetotail.

Key words: Substorm – Electrojet – Interplanetary Fields

Introduction

Over the past decade, a considerable amount of research has been carried out in an effort to understand better the way in which energy from the interplanetary medium enters the earth's magnetosphere and the way in which the magnetosphere is coupled to the ionosphere where the energy is eventually degraded to heat. The work of Axford and Hines (1961) and Dungey (1961) provided a theoretical basis which caused researchers to investigate some correlation between the solar wind parameters and the interplanetary magnetic field and the level of geomagnetic activity in the high latitude regions (which was the indicator of the amount of energy being dissipated in the ionosphere). Fairfield and Cahill (1966) and Rostoker and Fälthammar (1967) were the first to find positive correlations between the interplanetary magnetic field (IMF) and interplanetary electric field (respectively) and the level of geomagnetic activity. Both studies indicated that when the interplanetary magnetic field had a southward component, energy transfer between the solar wind and the magnetosphere took place more efficiently than when the IMF had a northward component. Since these early studies, it has become clear that the coordinate system in which the IMF is ordered is of importance with the GSM (geocentric solar magnetospheric) coordinate system being a more physically reasonable one in which to organize the IMF data than the GSE (geocentric solar ecliptic) system in which the original IMF data were analysed. Furthermore, it is now recognized that the azimuthal B_y component of the IMF has some impact on the modulation of the high latitude cleft (DPY) current system which in turn influences the rate at which energy can be dissipated in the sunlit high latitude ionosphere. At the present time, more comprehensive indices are being developed which give a physically meaningful parameter with which to describe the amount of energy entering the magnetosphere from the solar wind. The two parameters most frequently utilized at the present time are ε (Perreault and Akasofu, 1978) and V_sB_z (V_s being the solar wind velocity and B_z the component of the IMF antiparallel to the earth's dipole field lines in the magnetospheric equatorial plane).

A major question at the present time is how the energy deposited in the magnetosphere from the solar wind is stored and dissipated. In particular, there is a considerable body of evidence (cf. Caan et al., 1977; Pellinen et al., 1982; Rostoker et al., 1982) which suggests that a significant amount of energy stored in the magnetotail during an episode of southward IMF may be released suddenly into the ionosphere at the time when the IMF experiences a northward turning of either a transient or a more long-lived nature. Thus, while some portion of the energy entering the magnetosphere from the solar wind is dissipated directly in the ionosphere (i.e. the driven system of Akasofu, 1981), there is also a significant amount of energy stored in the magnetotail which can continue to drive the auroral electrojeet system even after the energy entering the magnetosphere has been cut off through a reconfiguration of the IMF. Rostoker et al. (1982) have dealt with this problem and have suggested that when the IMF experiences a southward turning, the magnetotail must store some of the increased energy flowing into the magnetosphere. In this way the magnetotail can come into equilibrium with the changed plasma and field properties of the magnetosheath in which it is immersed. Correspondingly when, after a period of southward IMF, the interplanetary magnetic field experiences a northward turning, the magnetotail must reconfigure and give up energy so as to again come into equilibrium with the surrounding magnetosheath environment. In this paper we shall examine in some detail the response of high latitude current systems, on a global basis, to a well defined northward turning of the IMF.

Rostoker and Fälthammar (1967) first pointed out that the product of the solar wind velocity V_s and the north-south component of the IMF B_z (viz. the azimuthal component of the interplanetary electric field) was the relevant parameter to consider when trying to evaluate the amount of energy entering the magnetosphere from the interplanetary medium. (The point here is that, if the velocity of the solar wind is zero, no magnetic field is brought up to the front of the magnetosphere and therefore no merging of IMF and earth magnetic field lines can take place.) However, most researchers studying the solar-terrestrial interaction usually present only the IMF when attempting to establish the level of flow energy into the magnetosphere. One might expect that the flow of energy into the magnetosphere might be regulated, on occasion, purely by changes in solar wind velocity. That this should be the case is evident from the presence of the product of V_sB_z in both the interplanetary electric field parameter favored by some researchers (e.g. Baker et al., 1981) and the ε parameter favored by others (e.g. Akasofu, 1979, 1981). While, as pointed out above, reductions in this energy flow may act to trigger substorm expansive phases, we are able to show in this paper, using ISEE plasma and magnetic field data, that expansive phases may be initiated at times of little apparent change in either V_s or B_z.

Finally we note that the recovery of the magnetosphere from an episode of substorm activity yields an excellent opportunity to study the time constants of the magnetosphere as a whole. There has been a tendency in the past to involve the entire magnetosphere in each substorm perturbation. (For example, one school of thought contends that each substorm involves a neutral line which extends across the entire width of the tail resulting in large sections of the plasma sheet disappearing downstream after the formation of a near-earth neutral point (cf. Nishida and Nagayama (1973) and Hones (1979).) Certainly it appears that, at ionospheric levels, the substorm expansive phase occurs as the development of discrete filaments localized in both latitude and longitude which appear further and further to the west during the course of a substorm. This implies that each element of a substorm has a relatively small scale-size compared to the overall dimensions of the magnetotail and that different regions of the magnetotail can be activated at different times during the course of a substorm disturbance (cf. Rostoker and Camidge, 1971; Sergeev, 1974; Wiens and Rostoker, 1975; Baumjohann et al., 1981). The question then arises as to whether this structured behaviour of the magnetosphere during the substorm expansive phase is also evident during the recovery phase of the disturbance. In this paper we shall present, in detail, a global picture of the decay of the substorm current wedge after the final northward turning of the IMF alluded to earlier in the text. We shall show that the recovery phase can, in fact, proceed in a structured fashion and not as the smooth decay of all the relevant current systems on a global basis.

The Event of 12 December 1977: the Data and their Interpretation

This interval is part of a data set which was first studied at CDAW 1 in late 1978 and for which the data acquisition and distribution was organized by the Steering Committee for the IMS. The period of time we shall present is 0000–0800 on 12 December 1977. (All times given in this paper are in UT unless otherwise specified.) For this period, data from three satellites were available to describe conditions in the interplanetary medium and in the magnetosheath. These were the IMP 8 spacecraft and the ISEE 1 and 2 satellites, both equipped with plasma detectors and fluxgate magnetometers. At the time of the final northward turning IMP 8 was approximately 26 R_E in front of the earth and 17 R_E on the dusk side of the sun-earth line. At the start of the interval under study, ISEE 1 and 2 were inside the magnetopause, however by $\sim$0300 they entered the boundary layer and by $\sim$0345 they crossed the dawnside magnetopause and began to monitor the magnetosheath. ISEE 1 and 2 acted as magnetosheath monitors for the balance of the interval under study. Figure 1 shows the magnetic field data for IMP 8, Fig. 2 shows the magnetic field data from ISEE 1 and Fig. 3 shows the plasma data for ISEE 1 (which, at the time, was separated from ISEE 2 by less than 0.2 R_E). We shall refer back to these Figures as we proceed to identify the responses of the electric current systems to changes in the interplanetary medium. However, it is worthwhile at this point to identify some of the important features of the interplanetary particle and field parameters over the period of interest.

From the IMP 8 data, it is clear that the IMF was dominantly southward for the period 0000–0500 UT after which it was completely northward. During this interval, there were three well separated brief northward turnings of the IMF at $\sim$0030, 0130, and 0220. The separation time between these turnings is, in each case, greater than the approximate L/R time constant of $\sim$50 min for the magnetotail currents associated with the driven system (Rostoker and Boström, 1976) so that for each of these cases, if a substorm had been excited it would have had time to have substantively decayed. Apart from a brief excursion towards the north (although the IMF retained its southward direction throughout) the IMF B_z at IMP 8 reached a steady magnitude of $\sim$10 nT which it maintained for slightly over one hour before the northward turning of 0500 alluded to earlier took place. The total IMF strength over the interval 0000–0500 showed an irregular increase from $\sim$5 nT to $\sim$15 nT, with each of the short-lived northward turnings referred to above being accompanied by a drop in total field strength. The final northward turning at 0500 was also accompanied by a decrease in the total field strength of the IMF.

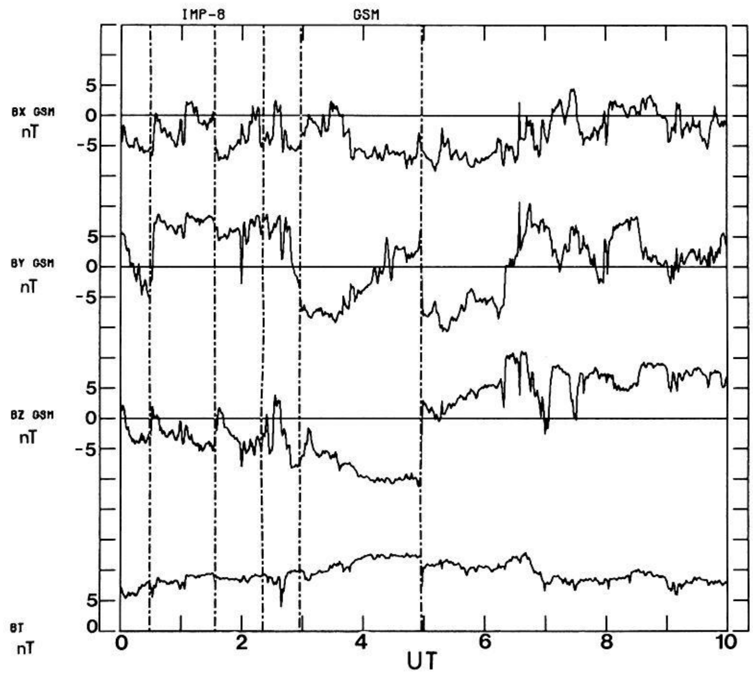

Fig. 1. The components of the interplanetary magnetic field plotted in solar magnetospheric coordinates together with the total field strength as measured by the IMP 8 spacecraft. At the start of the interval under study the satellite was 27 R_E in front of the earth and 17 R_E on the dusk side of the sun-earth line. The reader's attention is drawn to the transient northward turnings of the IMF at ~0030, ~0130, ~0230, ~0300 and the final northward turning at ~0458

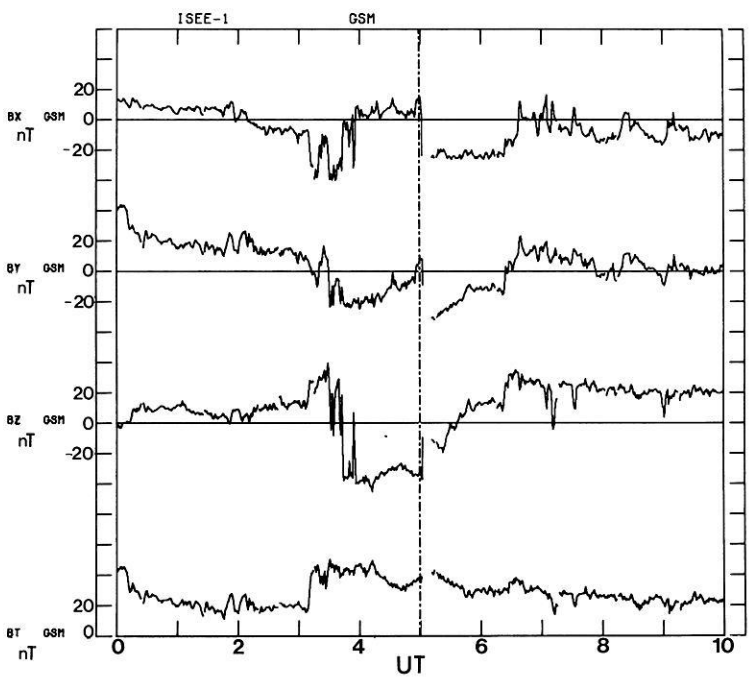

Fig. 2. The components of the magnetic field plotted in solar magnetospheric coordinates together with the total field strength as measured by the ISEE 1 spacecraft (see Russell (1978) for details of the ISEE fluxgate magnetometers). Until shortly after 0300 the satellite is in the magnetosphere. At that time the satellite enters the boundary layer near the dawn meridian and it emerges into the magnetosheath slightly before 0400. The reader is directed to the northward turning of the magnetosheath field just prior to 0500 at approximately the same time as the northward turning detected by IMP 8

The ISEE 1 and 2 satellites were in the magnetosphere until ~0345, after which they were in the magnetosheath. From the time they left the magnetosphere to the time of the 0500 northward turning of the IMF, the ISEE 1 satellite detected a steady southward IMF B_z component with a magnitude of ~30 nT (about a factor of 3 greater than the southward B_z measured at IMP 8 over the same period of time). Of great interest is the fact that the 0500 northward turning at ISEE 1 had a somewhat different structure than that observed at IMP 8. In particular, the IMF B_z component at IMP 8 became northward over a period of less than 5 min. In contrast, at ISEE 1 the B_z component went from about −35 nT of −10 nT at 0500 but did not become completely northward until the time of a second sharp northward turning at ~0520. The fact that the two satellites did not observe the same fine structure in the 0500 northward turning should serve as a warning to researchers trying to use data from a single satellite to correlate with terrestrial activity.

One final point of interest in the IMF data relates to the interval of time starting shortly after 0400, at which time the strength of the magnetosheath magnetic field (Fig. 2) and the velocity of the magnetosheath plasma appeared to decline noticeably (Fig. 3). During this interval

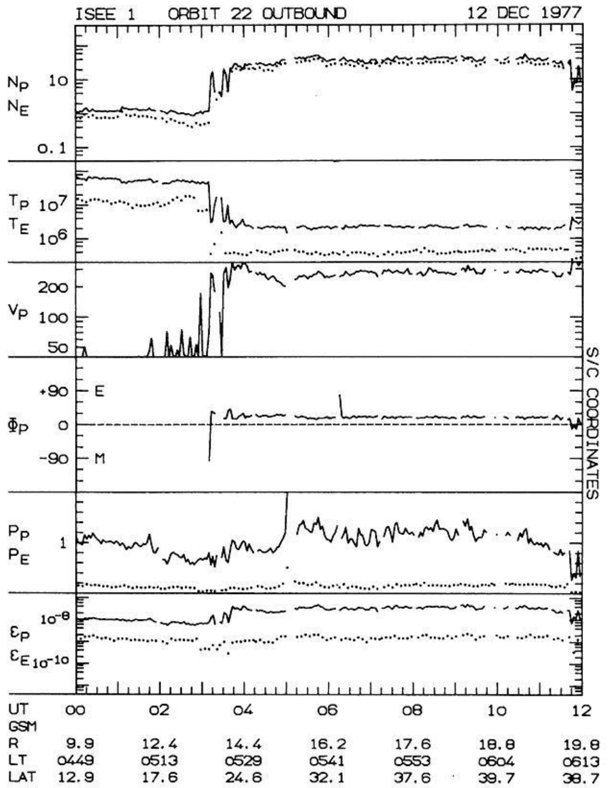

Fig. 3. Plasma parameters measured by the ISEE 1 spacecraft. N_e and N_p are the electron and proton number densities (cm^{-3}) respectively; T_e and T_p are the electron and proton temperatures (K) respectively; V_p is the proton bulk speed ($km \cdot s^{-1}$) and ϕ_p the azimuth direction of that bulk flow (0° being the sunward direction); p_e and p_p are the electron and proton thermal pressures (10^{-8} $dynes \cdot cm^{-2}$) respectively; ε_e and ε_p are the electron and proton energy densities ($ergs \cdot cm^{-3}$) respectively. The reader's attention is drawn to the magnetosheath bulk velocity which is ~350 km s^{-1} at 0400 and which drops steadily over the following hour reaching ~240 km s^{-1} by the time of the final northward turning of the magnetic field at ~0500

the strength and direction of the IMF, as measured in the interplanetary medium by IMP 8, was not changing significantly. The changing plasma and magnetic field in the magnetosheath suggested that there must have been a change in solar wind velocity at the IMP 8 orbital position, however this was found not to be the case. The apparent discrepancy between the IMP 8 and ISEE data will be discussed later in the text.

We now proceed to present the changes in magnetospheric and ionospheric current systems occurring over the time interval 0000–0700 UT for which the interplanetary and magnetosheath conditions were described above. Our data will be presented in the form of individual magnetograms, stackplots of array data where such were available and latitutde and longitude profiles of magnetometer array data where some useful information could be effectively displayed using this latter format. We shall attempt to build up a complete picture of the various types of global activity occurring over the interval of time in question and in the following discussion section we shall interpret the various correlations in terms of the physics of the solar-terrestrial interaction.

The interval of five hours leading up to the start of the UT day 12 December 1977 featured continual activity which had subsided somewhat in the hour 2300–2400. Around 0030 on 12 December a substorm onset was detected in the Scandinavian sector (Fig. 4) – this substorm onset coincided with the northward turning of the IMF noted earlier (Fig. 1). A major episode of substorm activity was activated at ~0130 in the Atlantic Ocean sector (Fig. 5) as was clearly observed at Leirvogur (Iceland) and at Narssarssuaq (Greenland). Again this substorm onset coincided with a northward turning of the IMF (described earlier) which took place after an interval of about one hour of rather strong (~3–5 nT) southward IMF. After some recovery had taken place following this latter event, a further substorm intensification occurred near 0230 (best seen at Narssarssuaq). This was relatively close in time to the third northward turning of the IMF referred to earlier. A further northward turning of the IMF shortly after 0300 is clearly associated with a further substorm intensification best observed at Leirvogur (Fig. 5). All this activity took place while ISEE 1 and 2 were in the magnetosphere, and it is with this last substorm development shortly after 0300 that these two satellites entered the boundary layer of the magnetosphere. Inspection of low latitude magnetograms for these first few hours of 12 December reveals that only the 0130 substorm could be classified as being of global impact. Figure 6 clearly shows a marked enhancement of the asymmetric ring current over the longitude range stretching from Kakioka to Tuscon across the afternoon sector. Further to the east, San Juan detects the classical positive H-component increase associated with the growth of the substorm current wedge for both the 0130 and ~0300 substorm expansive phases. In summary, the interval of time from 0000–0400 more or less confirms the typical characteristics of the response of the magnetosphere to the changes in the north-south component of the IMF identified by Caan et al. (1977), Rostoker et al. (1982) and Pellinen et al. (1982); namely, after some reasonable amount of southward IMF is brought up to the front of the magnetosphere, a northward turning of the IMF leads to the onset of a magnetospheric substorm expansive phase.

The period of time from 0400–0500 also features an onset of substorm expansive phase activity, but in this case the IMF both outside the bow shock (IMP 8) and in the magnetosheath (ISEE 1 and 2) is relatively stable and strongly southward. The substorm expansive phase activity initiated around 0420, while not being particularly large, is typical in its character both on the local and global scale. The onset is most clearly identifiable in the Atlantic and Scandinavian sectors and there is a clear growth in asymmetric ring current stretching westward from San Juan to Kakioka. The sharpness of the electrojet onset seen in the Scandinavian sector (Fig. 4a) strongly suggests that the negative H-component bays are associated with an explosive increase in current strength rather than simply an increase in the strength of the driven system. This particular expansive phase onset is of interest because there is no identifiable change in the strength of the north-south component of the IMF with which to associate it. There are no particular significant fluctuations of the solar wind velocity or number density over the interval 0400–0500 as measured by IMP 8 (Table 1) so that the incoming solar wind momentum flux and electromagnetic field do not exhibit any fluctations which might be claimed to trigger the observed expan-

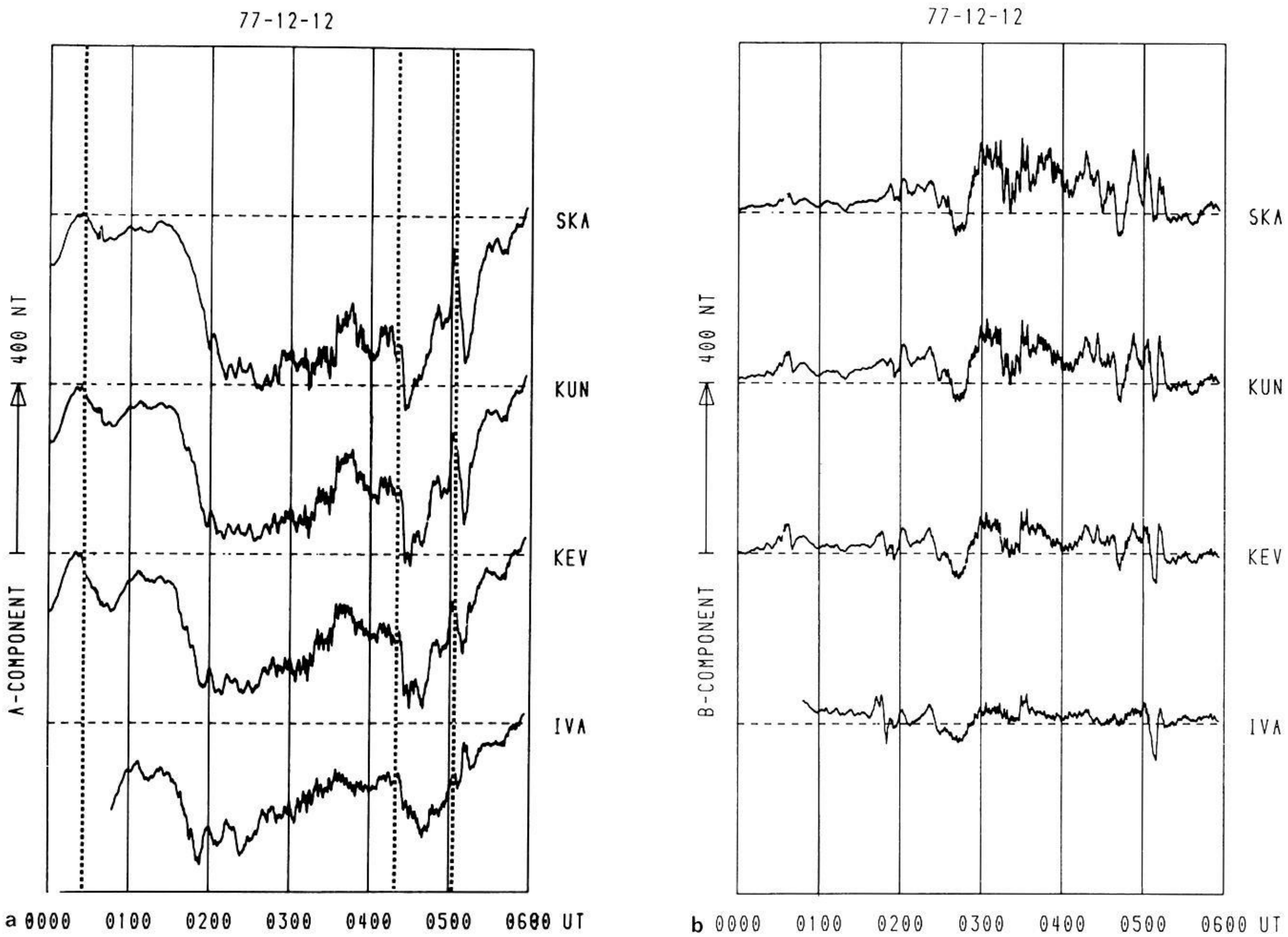

Fig. 4a and b. Stackplot of magnetograms form a meridian line of magnetometers located in eastern Scandinavia. **a** The north-south component of the perturbation field. **b** The east-west component of the perturbation field. The coordinates and code names of the stations are given in Appendix A

sive phase onset. The only possible interplanetary parameter which shows any unusual behaviour around the time of the expansive phase onset is the B_y component of the IMF which reverses polarity from negative to positive (Fig. 1). The behaviour of the magnetosheath plasma during the interval 0400–0520 is rather interesting although somewhat difficult to understand. The components of the plasma bulk velocity shown in Table 2 have been provided through the courtesy of Dr. C. Huang (University of Iowa). Perhaps the most significant feature here is the marked decrease in the *Z*-component of the magnetosheath bulk flow velocity around the time of the onset of the substorm expansive phase. The change in this component of the flow velocity coincides with the switch in polarity of the B_y component of the IMF from negative to positive. The return of B_y to negative values is accompanied by the return of the *Z*-component of the magnetosheath bulk flow to its previously high values prior to 0420. One further point of interest is that the spectrograms from the University of Iowa LEPEDEA indicate that after $\sim$0420 there is a steady increase in the flux of sunward streaming particles in the magnetosheath. The presence of these sunward streaming particles influences the calculation of the bulk velocity of the magnetosheath plasma making the anti-sunward flow of plasma appear to be at a lower velocity than it really is (C. Huang, priv. comm.). It is difficult, at this time, to decide whether the change in the character of the magnetosheath plasma is influential in triggering the observed substorm activity or whether, on the other hand, it is stochastically triggered substorm activity which causes a reconfiguration of the magnetosphere leading to changes in the magnetosheath flow. Finally, it cannot be ruled out that the substorm onset observed at $\sim$0420 was triggered internally and that the changes in the magnetosheath flow properties were completely unrelated to the substorm activity. Our observations do, however, suggest that further studies should be undertaken to establish if there are normally responses of magnetosheath flow to substorm onsets in the magnetosphere.

We now come to the northward turning at 0500 which is associated with the largest substorm expansive phase effect recorded over the interval studied in this paper. There are several points which we wish to bring to the attention of the reader regarding the morphology of this event. The first point relates to the interpretation of positive *H*-component disturbances in the auroral oval. On first sight, the positive movement of *H*-component at the auroral oval station of Leirvogur at 0500 (Fig. 5) would appear to indicate that the northward turning of the IMF at that time had initiated recovery of the magnetosphere. This would be exactly the wrong interpretation, as the sub-auroral stations of Ottawa, Whiteshell and Victoria (Fig. 8) clearly indicate

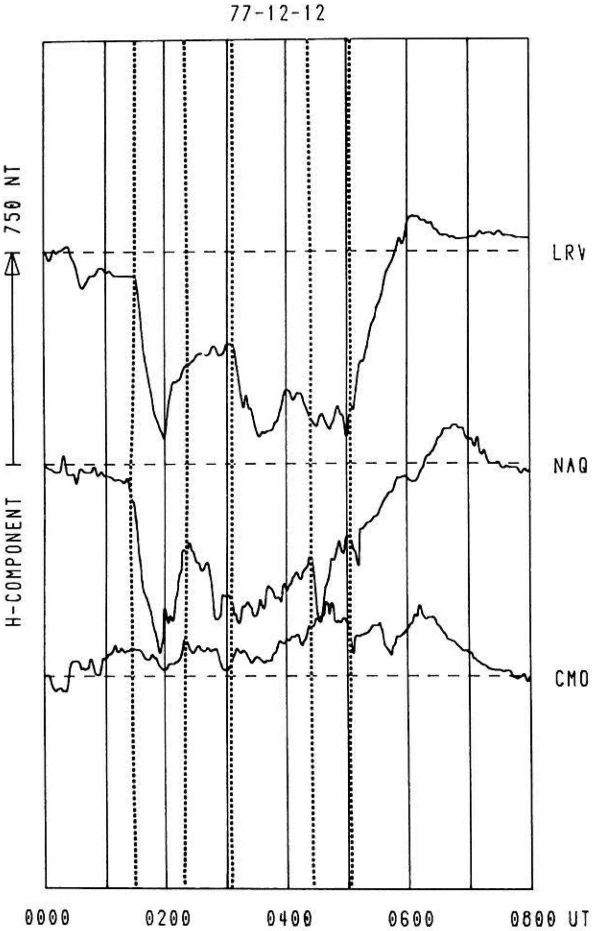

Fig. 5. *H*-component magnetograms from the auroral zone stations of Leirvogur, Narssarssuaq and College for the interval 0000–0800 on 12 December 1977. The coordinates and code names of the stations are given in Appendix A

Table 1. 5 min average values of the interplanetary plasma and magnetic field[a] parameters for the interval 0400–0520 on 12 December 1977

Time (UT)	B_x (nT)	B_y (nT)	B_z (nT)	V_s ($km \cdot s^{-1}$)	n_s (cm^{-3})
0400	−6.6	−3.5	−9.7	462	11.7
0405	−6.7	−2.5	−10.1	461	11.7
0410	−6.0	−1.2	−10.2	467	12.1
0415	−6.9	−0.8	−10.2	462	11.8
0420	−5.5	2.9	−10.1	485	11.5
0425	−6.1	−0.6	−10.5	468	12.0
0430	−6.2	2.9	−10.3	483	10.0
0435	−6.3	3.0	−10.1	470	10.1
0440	−7.3	2.1	−9.7	464	9.1
0445	−7.1	1.8	−9.7	460	9.3
0450	−6.2	2.4	−10.2	469	13.1
0455	−4.9	0.0	−5.0	469	11.5
0500	−6.7	−8.0	2.0	464	14.1
0505	−7.7	−7.3	1.4	463	12.2
0510	−8.3	−6.8	0.0	455	12.6
0515	−4.4	−10.0	9.0	477	15.1
0520	−4.5	−10.3	1.5	478	15.0

[a] Field magnitudes given in the GSM coordinate system

Table 2. Components of magnetosheath plasma bulk velocity[a] obtained from the ISEE-1 LEPEDEA for the interval 0400–0520 on 12 December 1977

Time (UT)	V_x $km \cdot s^{-1}$	V_y $km \cdot s^{-1}$	V_z $km \cdot s^{-1}$	V $km \cdot s^{-1}$
0400	−358	−96	175	410
0402	−337	−87	166	386
0404	−323	−78	138	360
0406	−311	−85	110	341
0409	−314	−98	117	349
0411	−305	−95	132	346
0413	−273	−79	94	299
0415	−296	−105	97	329
0417	−307	−88	102	335
0419	−310	−88	116	342
0422	−304	−82	99	330
0424	−315	−84	81	336
0426	−295	−88	74	317
0428	−292	−90	69	313
0430	−292	−88	71	313
0432	−286	−88	72	308
0434	−293	−79	74	312
0437	−297	−85	82	320
0439	−291	−87	72	312
0441	−274	−83	64	293
0443	−278	−93	68	301
0445	−272	−106	62	298
0447	−269	−98	66	294
0449	−257	−96	53	279
0451	−263	−104	59	289
0454	−259	−102	58	284
0456	−254	−101	52	278
0458	−243	−86	63	265
0510	−267	−56	132	303
0512	−265	−59	145	308
0515	−262	−57	144	304
0517	−266	−59	141	307
0519	−266	−53	135	303

[a] Velocity components given in the GSM Coordinate System

the development of a large substorm expansive phase at ~0505 as do the Alberta array stations further to the north (Fig. 7). The large negative *D*-component perturbation at Ottawa indicates that the western edge of the substorm current wedge is well to the west of Ottawa, while the positive *D*-component and rather weak response in the *H*-component at both Victoria and Newport (magnetogram not shown here) show the western edge of the wedge to be east of the Alberta array at the time of onset. The extremely large negative *Z*-component perturbation at Whiteshell associated with the substorm expansive phase effect in question strongly suggests that this station is near the equatorward edge of a substorm westward electrojet whose peak intensity is ~500 nT a few degrees further north. Note that, based on the above observations, one would conclude that the AE (or AL) index, which would be dominated by the Leirvogur contribution at ~0500, would decrease markedly after that time completely masking the fact that a major substorm expansive phase effect had taken place.

The question then arises as to why the westward electrojet near dawn (as reflected in the Leirvogur data) decreases in strength at the same time as the substorm current wedge is activated in the midnight sector. An answer to this question can be found in the results of Rostoker et al. (1982)

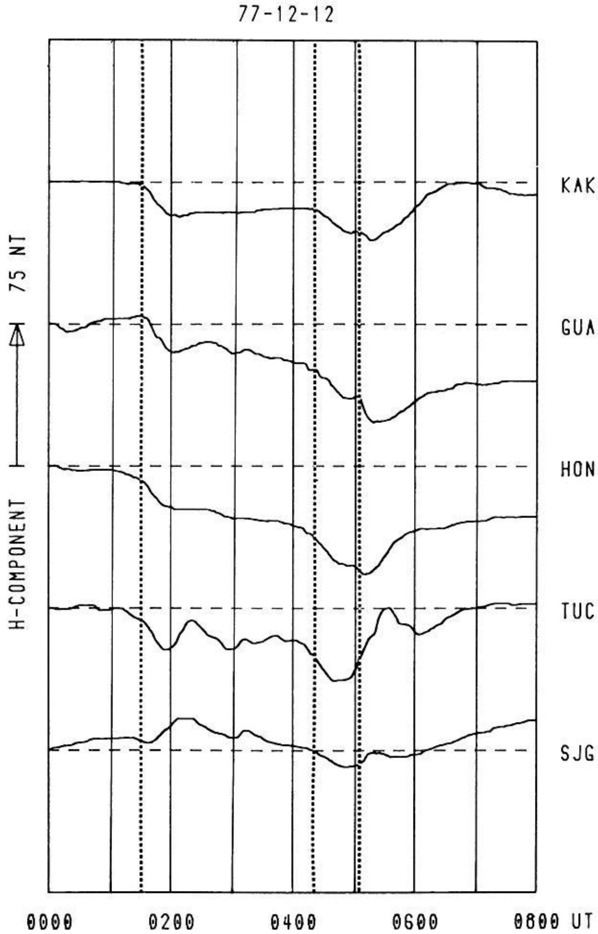

Fig. 6. *H*-component magnetograms from selected low latitude stations ranging from Kakioka in the west to San Juan in the east. The coordinates and code names of the stations are given in Appendix A

who suggested that, in conjunction with a northward turning of the IMF, a significant amount of magnetotail current (which is closing along the high latitude magnetotail boundary) is rerouted – some into the outer ring current belt (of which the cross-tail plasma sheet current is a component) and some directly into the ionosphere forming the substorm current wedge. In this way, some of the energy stored in the magnetotail magnetic field is deposited in the ionosphere where it is dissipated through Joule heating and through collisions of primary auroral particles with atmospheric constituents. The outer ring current belt is coupled to the auroral electrojets of the driven system (Akasofu, 1979, 1981) by field-aligned currents flowing into the auroral oval ionosphere across the noon sector and out of the ionosphere around the region of the Harang discontinuity in the pre-midnight quadrant (Hughes and Rostoker, 1977, 1979). The magnetic perturbations associated with this driven system produce the signature of the asymmetric or partial ring current (Cummings, 1966; Fukushima and Kamide, 1973). The ionospheric electrojets of the driven system and of the substorm current wedge are maximal at quite different local times with the driven system westward electrojet peaking late in the dawn sector (Allen and Kroehl, 1975) and the substorm current wedge peaking near midnight. Based on these considerations, we would suggest that the recovery of the negative *H*-component bay at Leirvogur signals the decline of the strength of the driven system due to the substantial decrease in solar wind energy entering the magnetosphere marked by the northward turning of the IMF. The substorm current wedge, on the other hand, responds to the release of magnetotail energy triggered by the northward turning of the IMF by markedly intensifying. It is quite clear that the maximum auroral electrojet strength associated with the substorm current wedge is attained near 0530 (see Whiteshell in Fig. 8) well after the entry of solar wind energy had been strongly reduced. We would contend that the energy powering the substorm current wedge is derived from the magnetotail during the expansive phase activity after 0500. The portion of the tail current rerouted into the ionosphere is clearly evident in the magnetic effects of the substorm current wedge. The low latitude stations (Fig. 6) show a strengthening of the asymmetric ring current (see e.g. the negative *H*-component perturbations at Guam and Kakioka in comparison to the response at San Juan) marking the temporary storage of the remainder of the tail energy which was redistributed through the rerouting of the magnetotail closure current of the magnetotail boundary. (See Fig. 17 of Rostoker et al. (1982) for a complete presentation of the current configuration in the magnetotail.)

The remaining points which we wish to discuss regarding the 0500 northward turning of the IMF and the ensuing change in magnetospheric substorm activity pertain to the manner in which the magnetosphere recovers to the ground state. Since the northward direction of the IMF persists for several hours after the 0500 northward turning, this would appear to be an excellent opportunity to study the recovery characteristics of the magnetosphere from a state of relatively strong activity.

The first point we wish to note is that the expansive phase breakup activity initiated at 0505 did not terminate immediately but carried on for approximately one hour with intermittent intensifications (as can be seen from the fact that the eastward electrojet in the College sector did not begin to decay until after ~0610). Since the IMF was clearly northward during this period of time, we conclude that the energy for these substorm intensifications continues to be derived from the magnetotail through the release of stored energy. Even during the substorm current wedge intensifications, the driven system electrojets continue to decay as reflected by the decay of the negative *H*-component bays recorded at Leirvogur and Narssarssuaq (Fig. 5) and the eastward electrojet strength as detected in the evening sector by Sitka (Fig. 8). The decaying driven system electrojets result from the reduction of the velocity of plasma convection in the magnetosphere, with the kinetic drift energy of the plasma being converted through MHD generator mechanisms to the electrical energy needed to account for the dissipation of energy in the ionosphere through Joule heating (Rostoker and Boström, 1976).

A second point which we find very striking is the rapidity with which the ionospheric electrojet currents associated with the substorm current wedge can decay in a given region of space. We see this most clearly in the Alberta array magnetograms (Fig. 7) where, just prior to 0600, the *H*-component of the auroral zone east-west line magnetograms recovers to pre-substorm values within ~15 min. This is a factor of ~8 less than the time constant of the driven system as evaluated by Clauer et al. (in press 1983)

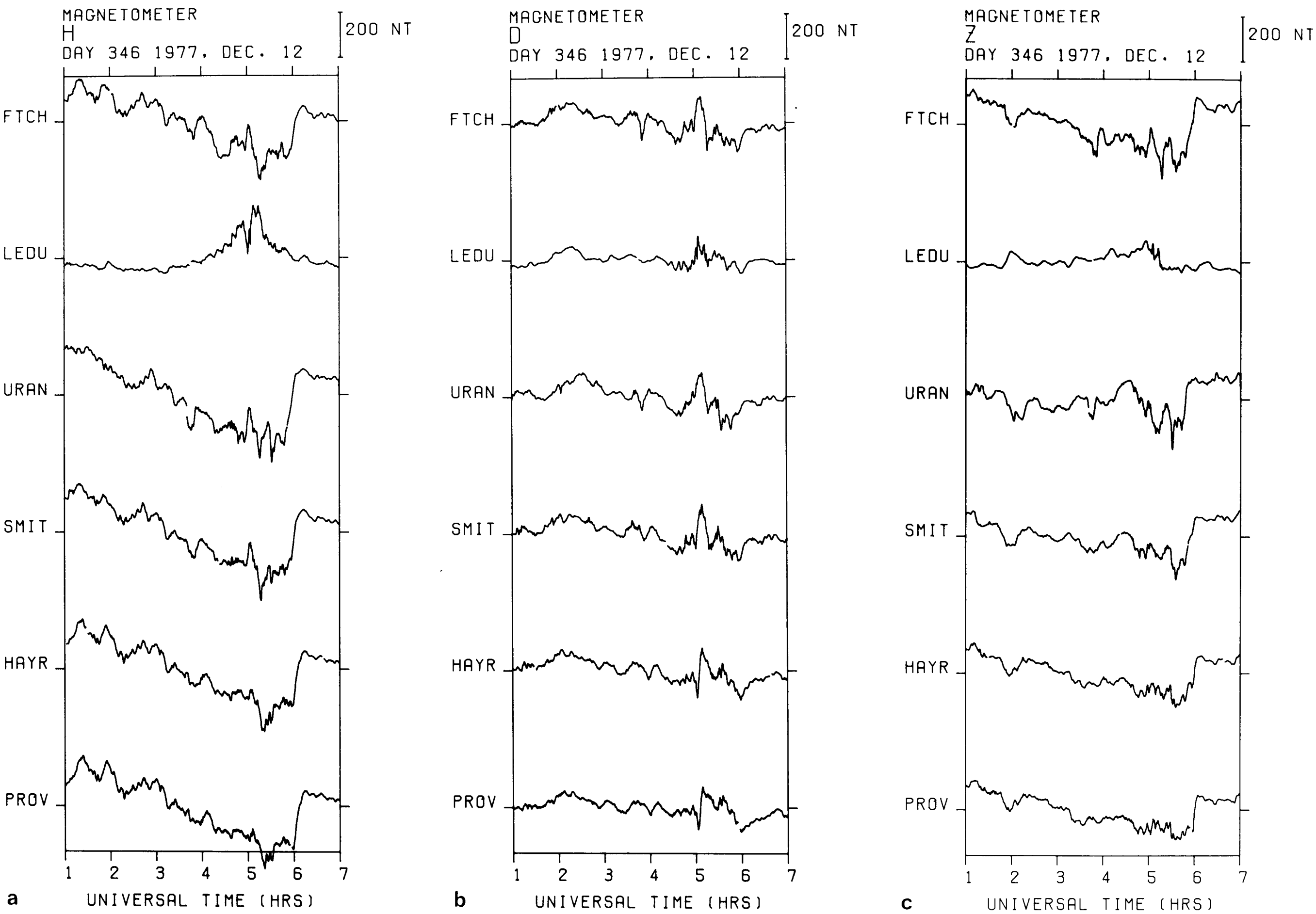

Fig. 7a–c. Stackplot of magentograms from the Alberta array, **a** the *H*-component, **b** the *D*-component, **c** the *Z*-component. The coordinates and code names of the stations are given in Appendix A. The stations URAN, SMIT, HAYR and PROV lie along a common line of geomagnetic latitude over a longitudinal range of ~12° at 67.3° N. The southernmost station of LEDU is dominated by the eastward electrojet associated with the driven system while the stations further north are strongly influenced by the substorm current wedge

and demands that the scale size of the substorm current wedge be considerably smaller than that of the driven system. Furthermore, since the convective drift velocity of the magnetotail plasma varies on the time scale of the driven system, this suggests that the sharp reduction in ionospheric electrojet current flow must be due to a reduction in ionospheric conductivity as suggested some time ago by Gurnett and Akasofu (1974). The effects of the driven system are also seen in the Alberta sector as reflected in the behaviour of the eastward electrojet most easily seen in the *H*-component magnetogram from the lowest latitude station of Leduc. Aside from a brief positive spike in the *H*-component which is associated with the passage of the westward travelling surge over the Alberta array shortly after 0500, the recording provides a measure of the decay of the eastward electrojet (which has a time constant of the order of that expected for the driven system).

The final point which we wish to deal with relates to the details of the decay of the substorm current wedge which had built up from the time that the IMF turned northward shortly before 0500. On the time scale of Fig. 7, the decay of the current wedge appears to be simultaneous at all the Alberta array auroral zone stations. However, when we expand the time scale for these data (Fig. 9) we find that the recovery is quite structured with sudden episodes of decay occurring at approximately 10–15 min intervals. What is most interesting is that the decay is observed first at the easternmost edge of our overall IMS array (LYN) and last at the westernmost edge (NOW). It appears to be the case that the substorm current wedge collapses from east to west across our array. Our earlier observation that the decay of the substorm current wedge occurs as a consequence of a reduction in ionospheric conductivity can now be understood in the context of the following picture of the lifetime of a substorm electrojet system.

Earlier studies of multiple onset substorms (Wiens and Rostoker, 1975; Pytte et al., 1976; Baumjohann et al., 1981) suggested that the typical development of such a disturbance involved the sequential onset of several substorm electrojet elements, each one further to the north and often west of the previous one. The ensemble of these current elements makes up the substorm current wedge and each element can co-exist with the elements formed earlier and later in the sequence. If each element has roughly the same characteristic lifetime, one would expect the first element in the sequence (namely the most eastern one) to decay

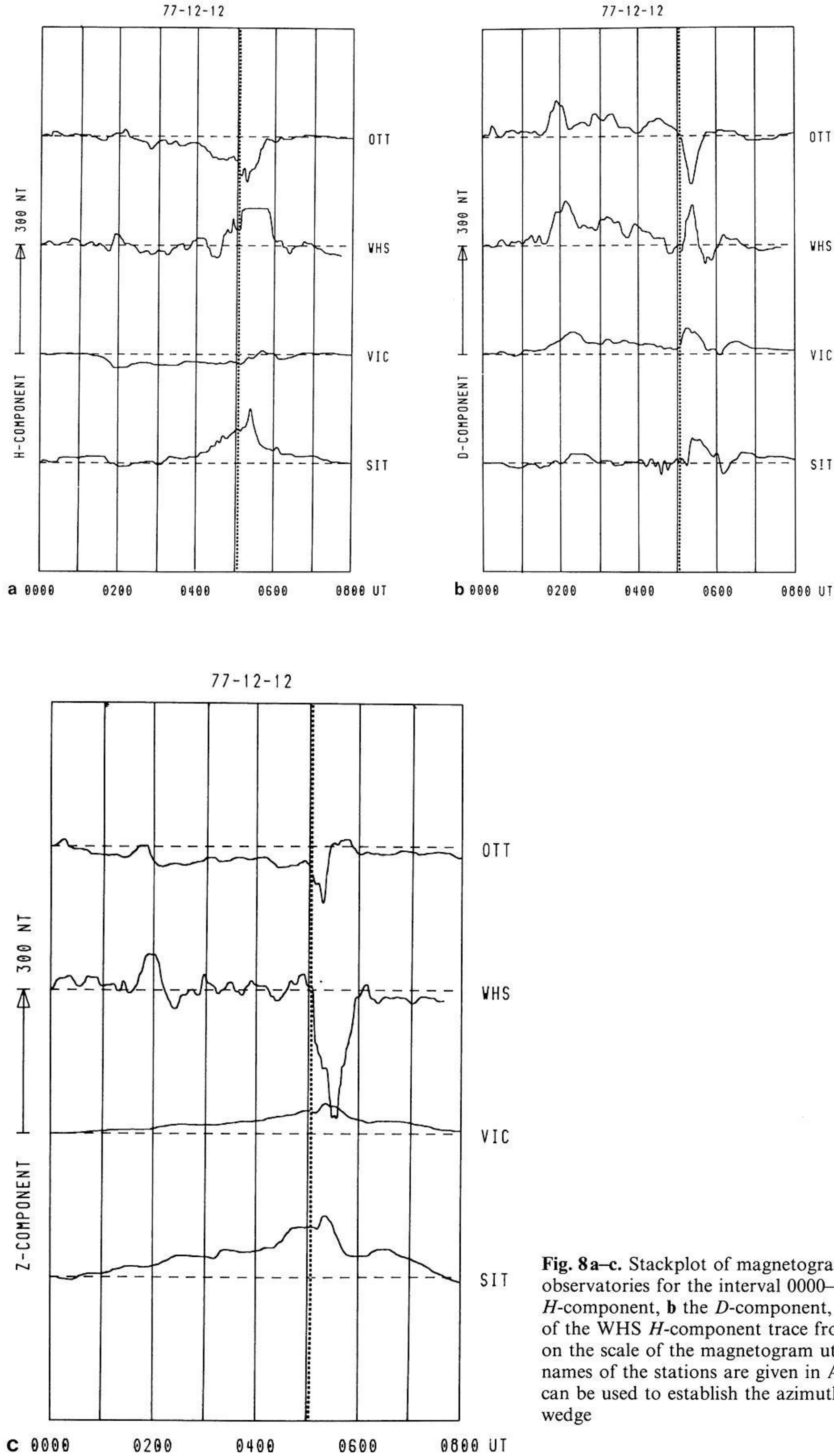

Fig. 8a–c. Stackplot of magnetograms from selected sub-auroral observatories for the interval 0000–0800 on 12 December 1977. **a** The *H*-component, **b** the *D*-component, **c** the *Z*-component. The flat portion of the WHS *H*-component trace from ~0510–0550 indicates saturation on the scale of the magnetogram utilized. The coordinates and code names of the stations are given in Appendix A. The data shown here can be used to establish the azimuthal extent of the substorm current wedge

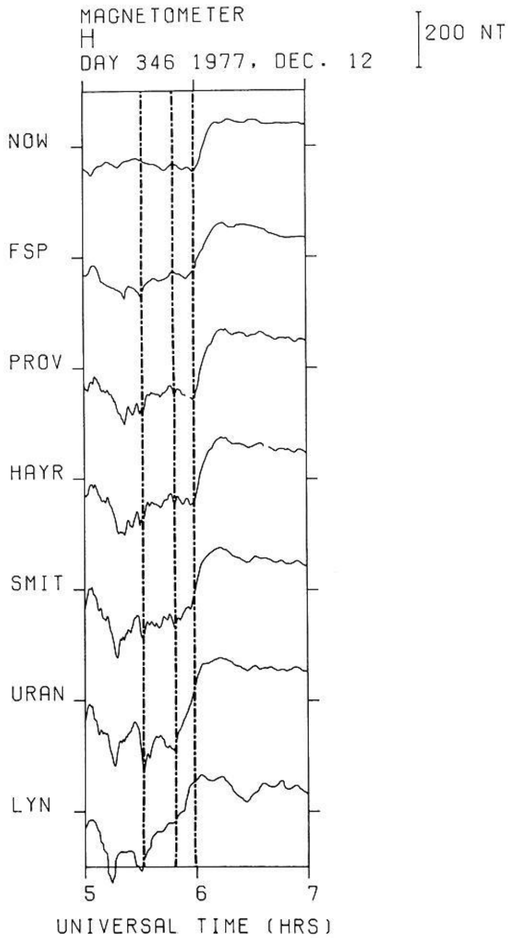

Fig. 9. *H*-component data for the interval 0500–0630 recorded at several stations lying along the auroral oval in the North American sector from LYN in the east to NOW in the west. The coordinates and code names of the stations are given in Appendix A. Note the impulsive character of the substorm recovery with LYN recovering well in advance of the recovery at NOW

first. In this framework we can now understand why the substorm current wedge collapses from east to west across our array. Insofar as the physical processes leading to the development of an electrojet element are concerned, we associated the onset with the sudden activation of the acceleration region at ~ 1 R_E altitude due to the growth of field-aligned current densities to above $\sim 10^{-6}$ A m^{-2} (see Akasofu, 1981 and Pellinen et al., 1982 among others). The crossing of this current density threshold accounts for the sudden precipitation of keV electrons into the ionosphere characteristic of the development of discrete auroral forms at the onset of an auroral breakup. Equally, we believe that when the current density of the field-aligned current drops below $\sim 10^{-6}$A m^{-2}, the acceleration can terminate as suddenly as it turned on. This would happen sequentially with the electrojet element which began the sequence being the first to suddenly disappear. In this manner, we can understand both the east-to-west collapse of the substorm current wedge and the rapidity which the decay of each electrojet element exhibits.

Summary of Results

The International Magnetospheric Study involved the cooperative acquisition of ground based and satellite data using an array of instrumentation which was far superior to anything available in the past for the study of global processes in the magnetosphere. Our study has taken advantage of the availability of this superior data base to deal with the problem of the development and decay of magnetospheric substorm activity on both a global and a local scale. Our major findings are as follows:

(1) We provide further evidence that northward turnings of the IMF, after periods of southward IMF have allowed energy to be stored in the magnetotail, can trigger significant substorm expansive phase activity, the energy for which is derived from the magnetotail. Although there has been evidence presented in the past for such an influence of the IMF on substorm activity, there have been some doubts expressed as to the strength of the correlations presented. Even for the case of isolated substorms, where the correlation has been presented recently by Rostoker (in press, 1983), the question has arisen as to whether or not isolated substorms have the same characteristic behaviour as more typical substorms which occur during intervals of more turbulent IMF when the field is never northward or southward for more than a few minutes at a time. In this study we have presented three instances where the IMF fluctuated northward after sustained intervals of southward directed field. These three instances occurred in an interval of less than four hours, and in each case we were able to point to their correlation with the onset of enhanced expansive phase activity. Thus, even for our more complex event, which certainly cannot be thought of as an isolated substorm, the effect of northward turnings of the IMF as a trigger for substorm expansive phase activity seems clear. In addition, we have noted that substorms can be triggered even under conditions when the north-south component of the IMF is relatively constant and the solar wind velocity and number density are unchanging (as typified by the 0420 substorm expansive phase onset). While the possibility of changes in the B_y component of the IMF triggering substorms such as the 0420 event are not ruled out, it appears that there may be substorm onsets which are triggered internally within the magnetosphere rather than externally. Further studies are needed to provide a clearer picture of the influence of fluctuations in the interplanetary medium plasma and field as a trigger for magnetospheric substorm expansive phases.

(2) We have studied in detail the behaviour of the magnetosphere-inosphere current systems in response to a sharp northward turning of the IMF followed by a period of sustained northward field of the order of a few hours. In this case we have provided convincing evidence that at least some substorm expansive phase activity can be driven by the unloading of magnetotail energy stored during the growth of the driven system. Our case study has shown the great danger in using *AE* or *AL* to define the presence or absence of substorm expansive phase activity, since these indices are very often dominated by the effects of the driven system rather than the substorm current wedge.

(3) We have shown that, following the reduction of energy flow from the solar wind into the magnetosphere, the substorm current wedge can grow at the same time as the driven system is decaying. This demonstrates the need to take great care in correlating increases and decreases in auroral current systems with changes in the level of the solar-terrestrial interaction.

(4) We have shown that the decay of the substorm cur-

rent wedge occurs as the sequential sudden collapse of segments of the ionospheric electrojet. The decay starts at the most eastern edge of the wedge and proceeds westward until the entire electrojet has disappeared. We have pointed to a threshold effect in the current denstiy of upward field-aligned current as a possible explanation of the sudden turning on of the electrojet elements which constitute the substorm current wedge and the equally sudden turning off of these electrojet elements.

We conclude by noting that a great deal of data (i.e. from an adequate array of ground stations and suitably equipped satellites) must be analysed in order to be able to minimize the ambiguity in the interpretation of the behaviour of the magnetosphere-ionosphere current systems in response to changes in the interplanetary medium. Many studies of the kind we have reported here must be carried out in the future for different interplanetary plasma and field environments before most of the suggestions made in this paper can be placed on a firm basis. The data base acquired during the International Magnetospheric Study is now available for these much needed detailed studies of the various ways in which the magnetosphere can respond to changes in the interplanetary medium.

Appendix A. Geomagnetic coordinates and code names of stations used in this study

Station Name	Code Name	Geomagnetic	
		Latitude (°N)	Longitude (°E)
Alberta Array			
Leduc	LEDU	60.6	302.9
Fort Chipewyan	FTCH	66.3	303.1
Uranium City	URAN	67.4	304.3
Fort Smith	SMIT	67.3	300.0
Hay River	HAYR	67.3	294.3
Fort Providence	PROV	67.5	292.0
Scandinavian Array[a]			
Ivalo	IVA	65.0	109.9
Kevo	KEV	66.2	110.6
Kunes	KUN	66.8	110.8
Skarsvag	SKA	67.6	111.0
Additional High Latitude Stations			
Leirvogur	LRV	70.2	71.0
Narssarssuaq	NAQ	71.0	37.0
Lynn Lake	LYN	66.0	315.6
Norman Wells	NOW	69.2	278.8
College	CMO	64.6	256.5
Fort Simpson	FSP	67.2	287.2
Sub-Auroral Stations			
Ottawa	OTT	54.6	247.1
Whiteshell	WHS	58.6	323.1
Victoria	VIC	54.2	293.0
Sitka	SIT	60.0	275.3
Low Latitude Stations			
Kakioka	KAK	26.0	206.0
Guam	GUA	4.0	212.9
Honolulu	HON	21.1	266.5
Tucson	TUC	40.4	312.2
San Juan	SJG	29.6	3.1

[a] Coordinates of the Scandinavian stations are given in revised geomagnetic coordinate system

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