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Pi2 Magnetic Pulsations, Auroral Break-ups, and the Substorm Current Wedge: A Case Study

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Abstract. The two-dimensional distribution of the characteristics of Pi2 magnetic pulsations observed by the Scandinavian Magnetometer Array (SMA) during the passage of a westward travelling surge on 11 November 1976 and during three sucessive auroral break-ups around magnetic midnight on 15 February 1977 have been studied in relation to the position of active aurora and the break-up current system. On both days the greatest Pi2 amplitudes were collocated with the region where the brightest auroras were observed. The sense of polarization of the horizontal disturbance vectors changed along longitudinal and meridional lines. The two-dimensional equivalent current system of the Pi2 pulsations resembled a circular current vortex around the location of the localized upward field-aligned currents and changed its direction from counterclockwise to clockwise and back to counterclockwise again within one Pi2 cycle. Our observations indicate that the generation of Pi2 pulsations is not directly connected to periodic fluctuations of the complete current system at substorm onset, but that the upward directed field-aligned currents at the western edge of this system play the most important role for the Pi2 generation.

Key words: Pi2 magnetic pulsations – Auroral break-up – Substorm current wedge.

Introduction

There is now a great deal of evidence for a one-to-one correspondence of the magnetic Pi2 pulsation train to the substorm expansion phase (Saito, 1961; Rostoker, 1967; Koshelevsky et al., 1972; Sakurai and Saito, 1976). Different investigators consider different phenomena occurring during the auroral break-up to be the source of this type of pulsation.

Maltsev et al. (1974), for example, proposed that Pi2 pulsations are the results of an Alfvén impulse transferred to and reflected from the ionosphere of the opposite hemisphere. The original impulse is generated in the ionosphere at the moment of auroral brightening. Mallinckrodt and Carlson (1978) and later Nishida (1979) extended this model to impulsive changes generated in the magnetosphere. Rostoker and Samson (1981) pointed out that a Pi2 train in the midnight and evening sector may be caused by an impulsive release of energy in a longitudinally localized portion of the Harang discontinuity. Rostoker and Samson (1981) further showed that there is a relationship between a sudden increase of the upward field-aligned current flow at the equatorward edge of the westward electrojet and the associated Pi2. By introducing a special three-dimensional current system related to the Pi2, Samson (in press 1982) is able to show that the net Hall current in the ionosphere is phase shifted by 90° relative to the net field-aligned current and certain experimental results (for example, the elliptical polarization of Pi2's) can be explained by Samson's model.

A close morphological connection of PiB magnetic pulsations (whose low-frequency part is observed as Pi2 pulsations) with field-aligned currents has been pointed out by Heacock and Hunsucker (1981) and Bösinger et al. (1981). There is also some evidence that Pi2 pulsations can be generated by fluctuations of the complete current system associated with the substorm (Boström, 1972; 1974; Chao and Heacock, 1980).

This work is a case study of the relationship between the Pi2 characteristics and the local three-dimensional current system associated with the break-up of aurora and substorm onset and to give some experimental outline of a Pi2 model that may explain our two-dimensional observations.

Data and Data Analysis

The present work is based on magnetic field data from the Scandinavian Magnetometer Array (SMA; see Küppers et al., 1979; Maurer and Theile, 1978) and data from the Finnish all-sky camera chain for events on 11 November 1976 and 15 February 1977. The ground based observations on 11 November 1976 have already been analysed by Yahnin et al. (in press 1982) and Pellinen et al. (1982). The unfiltered magnetic data and information on the Finnish all-sky cameras operated during this event may be found in these publications. The data obtained on 15 February 1977 between 2100 and 2130 UT have been described in detail by Baumjohann et al. (1981), who constructed a three-dimensional model for the break-up current system, i.e. the substorm current wedge, based on all-sky camera, STARE radar (Greenwald et al., 1978), and SMA data. In Baumjohann et al. (1981) a map with station names, profile numbers etc. can also be found.

The Pi2 pulsations have been separated from the back-

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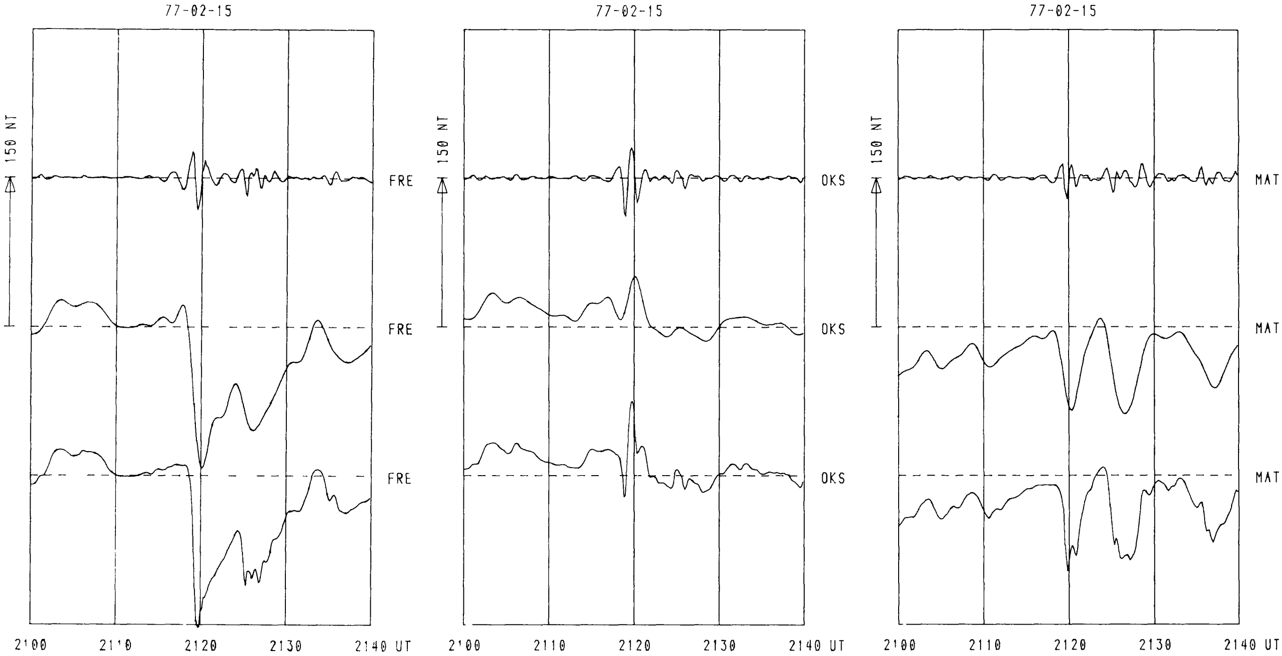

Fig. 1. High-pass filtered (periods less than 150 s; *upper traces*), low-pass filtered (*middle traces*) and original (*lower traces*) magnetograms of the horizontal *A* component (roughly directed to geomagnetic north) at the stations FRE, OKS and MAT observed on 15 February 1977

ground magnetic field by applying a high-pass filter with a cut-off period of 150 s to both horizontal magnetic disturbance components (*A* component: roughly geomagnetic north; *B* component: roughly geomagnetic east; see Küppers et al., 1979). Such a filtering process is not without problems. Inspection of Fig. 1 shows that one may identify the Pi2 on 15 February 1977 as a dPi pulsation, a classification introduced by Stuart (1972). This means that, in addition to the Pi2 pulsation, there occurs a simultaneous background variation of the magnetic field which has a time constant similar to the Pi2 itself. Because of the rapid switch-on of the background field the filtered data will be heavily influenced by the impulse response function of the filter used. The influence of the response function will be strongest for a magnetogram of the type shown in the left part of Fig. 1. This is about the worst case we found in our data while a recording of the type shown in the middle part of Fig. 1 does not cause much trouble. In this latter case the Pi2 is clear in the unfiltered data. The right panel of Fig. 1 shows data from a station with a moderate degree of confidence. To give an idea of how realistic the filtered waveforms are, an artificial signal (Fig. 2), similar to that in the left part of Figure 1 but without an additional Pi2-like signal, has been constructed and filtered in the same way as the real data. The result (lower part of Fig. 2) is a signal with an amplitude of about one third of the value of the offset in the unfiltered signal. This shows that data like those shown in the left panel of Fig. 1 are heavily contaminated by the influence of the filter used.

Although this technique is far from perfect, it is adequate for the job in hand. Such sophisticated methods as the complex demodulation used by Beamish et al. (1979) and Lester and Orr (1981) suffer from the same difficulty. The polarization filters developed by Samson and Olson (1981) are probably the best method presently available for separating a Pi2 signal from the background variation,

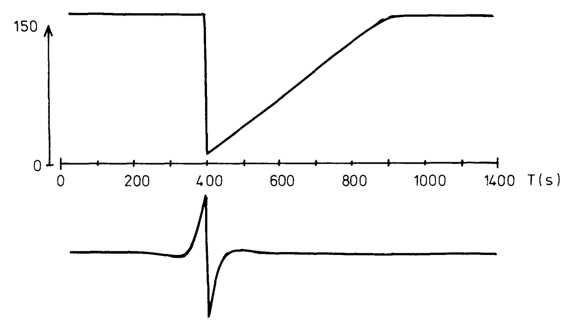

Fig. 2. An artificial signal representing the trend in the magnetic data shown in Fig. 1 together with its high-pass filtered (T < 150 s) signal (*lower part*). The amplitude is given in arbitrary units

but to our knowledge the perfect technique does not yet exist.

Figure 3 shows raw power spectra of the unfiltered time series shown in Fig. 1. All the spectra have a peak near a period of 90s which confirms that a filter cut-off at 150s is suitable for this event.

Following the criteria given by Samson (in press 1982), to distinguish a real Pi2 from Pi2-band electrojet noise, we looked at the mid-latitude magnetograms at Borok (USSR) and Göttingen (FRG) where one can see clear Pi2 activity during the time of the events analysed. For the 15 February 1977 event, Bösinger et al. (1981) also report strong PiB activity.

One of the most important Pi2 characteristics we wished to analyse was polarization, along with it's variation in space and time. Therefore, to get information about these parameters, hodograms of the horizontal disturbance vectors were constructed (Fig. 4). From such hodograms the amplitude of the major axis of the hoirzontal polarization ellipse and the sense of rotation of the Pi2 disturbance

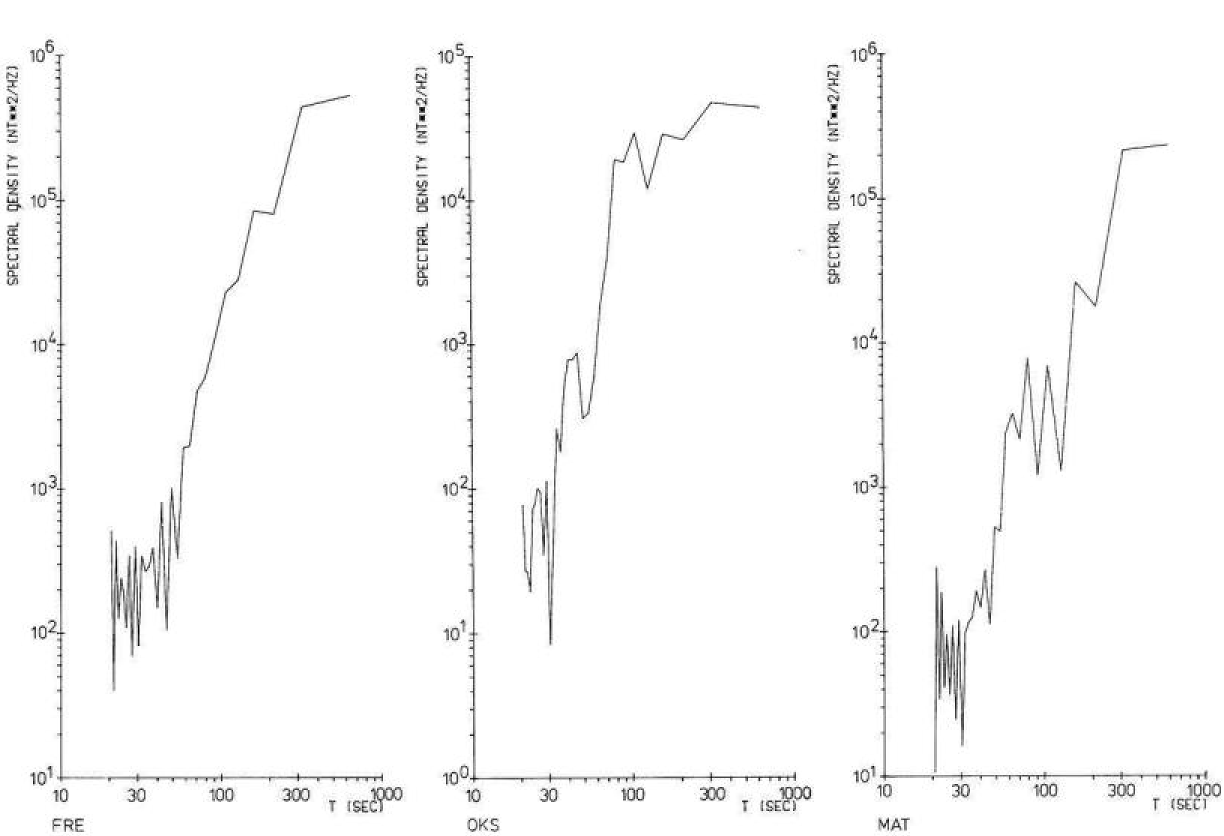

Fig. 3. Raw power spectra of the *A* components at the stations FRE (*left*), OKS (*middle*) and MAT (*right*) between 2115 and 2125 UT on 15 February 1977

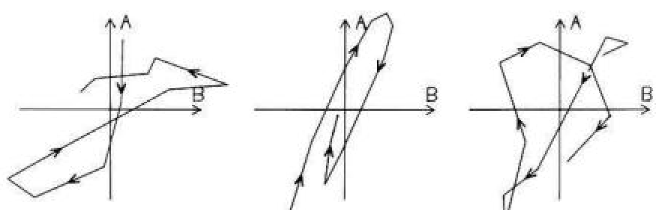

Fig. 4. Examples of hodograms of the horizontal disturbance vectors at the stations FRE, OKS and MAT. The hodograms start at 2119 UT and are plotted for 120 s. The sense of rotation is indicated by *small arrows*

vector can be determined within about one cycle. In some cases an unambigous determination of the sense of rotation was not possible (see station FRE in Fig. 4). This will be indicated in further figures. In the following discussion it will become apparent that the highest possible temporal resolution of the Pi2 characteristics is needed, since they change drastically with spatial and temporal changes in the active aurora.

Observations

11 November 1976

Most stations of the SMA recorded data during this event. The development of the disturbances was characterized by an intensive growth phase (the magnetic field due to the westward electrojet over Scandinavia reached values of about −300 nT) that lasted for about 30 min, and a weak auroral break-up (the poleward expansion amounted to about 2° only). The disturbances during the event on 11 November 1976 were described in detail by Yahnin et al. (in press 1982) and Pellinen et al. (1982). Highpass filtered magnetograms ($T < 150$ s) from the stations located on the meridional profile 4 are shown for this event in Fig. 5. During the break-up (2102–2107 UT) the bright aurora was in the field of view of the Finnish all-sky cameras.

At 2103 UT a bright arc was observed and until 2104 UT the poleward border of the bright aurora remained at the same latitude but the western edge moved to the west. The location of bright aurora at 2103 UT and isolines of the amplitudes of the major axes of the horizontal polarization ellipses (as determined from the hodograms) for the interval 2102:30–2104:00 UT are drawn in the left upper panel of Fig. 6. The region of the greatest amplitudes coincides well with the region occupied by the auroral bulge. Though there are no magnetograms available from the stations ROS and MIE on profiles 3 and 4 the overall pattern of the amplitude distribution does not depend critically on this data gap. The distribution of the sense of rotation of the horizontal disturbance vectors for the same time interval is shown in the upper right panel of Fig. 6. Along profile 4 there is a clear change of the sense of rotation of the horizontal vectors near the bright arc. The sense of rotation at the stations of the meridional profiles 2 and 3 is uncertain. This may be due to the high speed of the bulge's western edge (1.5 km/s) when crossing the profiles 2 and

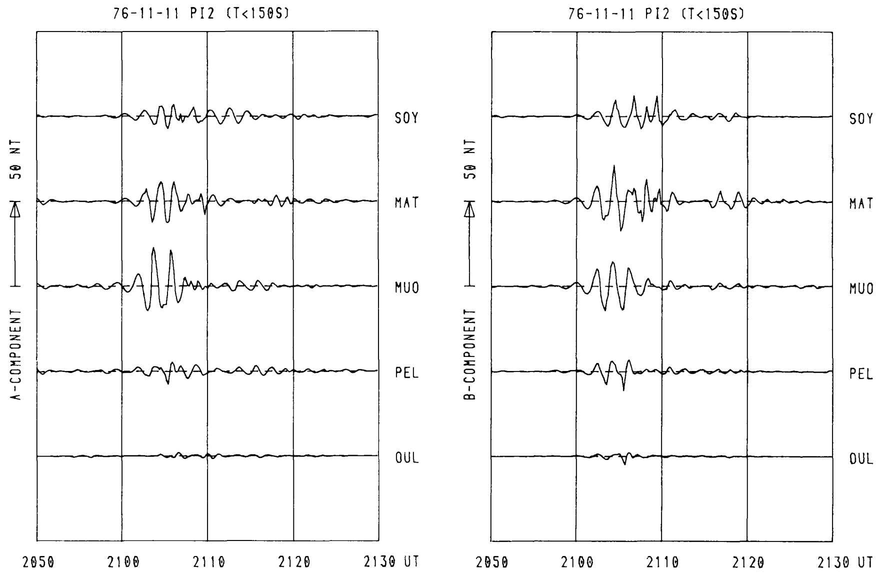

Fig. 5. High-pass filtered magnetograms of the horizontal A (roughly directed to geomagnetic north) and B (roughly directed to geomagnetic east) components observed on 11 November 1976, along the meridional profile 4 of the SMA, SOY is the northern-most station

3. There is some indication in Fig. 6 that the sense of rotation also changes while crossing the auroral bulge's western edge.

A new arc brightened at 2105 UT poleward of the auroral bulge and the auroral bulge region expanded westward. Auroral structures at 2106 UT and isolines of the amplitudes of the major axes of the Pi2 for the interval 2105–2107 UT are plotted in the lower left panel of Fig. 6. Unfortunately an unambiguous determination of the location of the maximum amplitude region is not possible due to missing data at the stations ROS and MIE. But there is a clear change of the sense of rotation of the horizontal disturbance vector (as compared to the time of the first intensification) at the stations on profiles 2 and 3 (Fig. 6, lower right panel). As in the time interval 2102:30–2104:00 UT along profile 4 there is now along profile 2 a clear change of the sense of rotation near the bright arc. Such a change is not observed along profile 3. It is also evident that during the interval 2105–2107 UT stations on profiles 3 and 4 show clockwise rotation south of the aurora.

This may be interpreted as a westward propagation of the region of clockwise rotation that was observed at the stations of profile 4 between 2102:30 and 2104 UT. Accordingly one may regard the spatial distribution of the sense of rotation of the horizontal disturbance vector as being fixed in the bulge's moving frame of reference.

It is not possible to give exact numerical values for confidence intervals for the amplitude and polarization parameters given in Fig. 6. One can only state subjectively, on the basis of unfiltered magnetograms like in Fig. 1, that the data from the stations MIK and SOY have the worst, data from stations KVI, RIJ, KIR, NAT, MUO and VAD have a moderate degree of confidence and the data from all other stations are of the type with the highest degree of confidence as shown in Fig. 1.

15 February 1977

On 15 February 1977 between 2100 and 2130 UT three consecutive localized auroral activations were observed over Scandinavia. The first activation was recorded at 2109 UT between MUO and MIE. The second one occurred at 2119 UT slightly northwest of the first and was followed by the third activation. Each of these had break-up signatures (Baumjohann et al., 1981) and was accompanied by a Pi2 train. Figure 7 shows the temporal development of the A component of the magnetic pulsations (periods less than 150 s) for this time interval at the stations on the meridional profiles 1 and 4 of the SMA. Pulsations of a prominent amplitude are observed only at the stations MIE and MUO during the first weak break-up. The second and the third Pi2 trains are seen at all the stations of the SMA. Distinct auroral structures and isolines of the amplitudes of the major axes of the horizontal polarization ellipses of the Pi2 pulsations for the three auroral break-ups are shown in Fig. 8. As on 11 November 1976, the greatest Pi2 amplitudes occur in the region where the aurora is brighest and forms a bulge- or surge-like structure. The isolines of amplitude are more or less elongated in the longitudinal direction, gradients of the amplitude are more significant along meridional profiles. Again, to get some idea of the degree of confidence for the results in Fig. 8, all data have bee classified subjectively as belonging to one of the three cases shown in Fig. 1.

Stations FRE, HAS, AND, EVE, RIT, ROS, KIR, MUO, BER, VAD and SKO belong to the worst, stations GLO, KVI, MIK, PIT, MAT, PEL and all stations of profile 5 to the moderate and all other stations to the case with a high degree of confidence.

There is a clear change of the sense of rotation along profile 4 and 5 near the active aurora and the region of maximum major axis amplitude. No change of the sense of polarization in the east-west direction is observable which may be due to the fact that at 2109:30 UT the surge-like structure is very localised and Pi2 pulsations, as far as they can be recorded by the SMA magnetometers, are present only at the stations situated near this region.

During the second break-up (around 2120 UT) a clear change of the sense of rotation in the east-west direction occurs between profile 4 and 5 near the eastern edge of the bright aurora forming the surge-like structure (see middle part of Fig. 8) but well away from the amplitude maximum at FRE. A meridional change of rotation as ob-

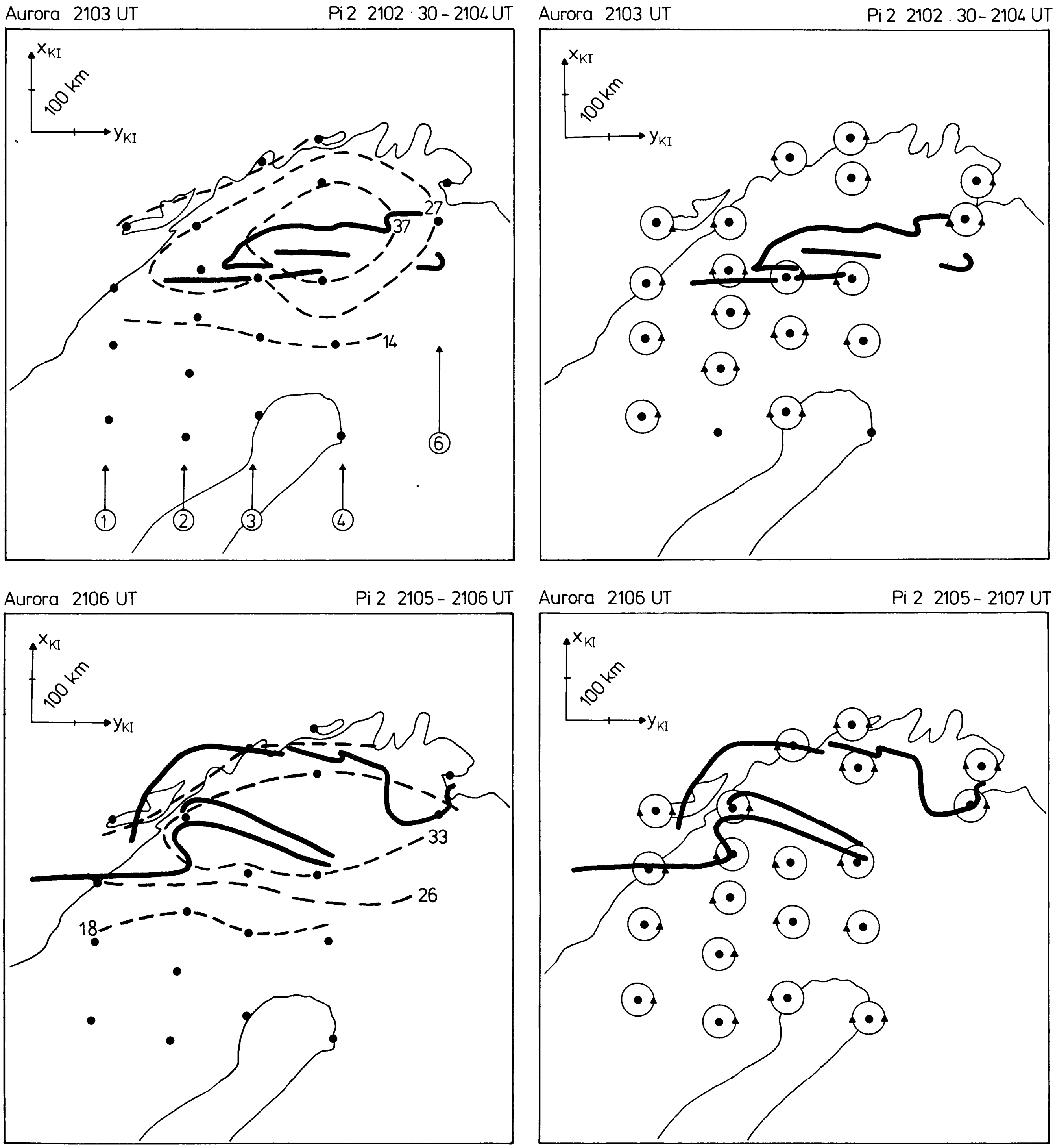

Fig. 6. Contours of the amplitudes of the main axes of the Pi2 horizontal polarization ellipses and spatial distribution of the sense of polarization for the time intervals 2102:30–2104 UT (*upper part*) and 2105–2107 UT (lower part) together with the auroral structures at 2103 and 2106 UT, respectively. Numbers on the contours give the corresponding amplitude values in nT *Circles with one arrow* denote elliptic polarization with the sense of rotation given by the arrow. *Two arrowheads* indicate that the sense of rotation is ambiguous. The locations of the SMA stations are indicated by the *dots, encircled numbers* are profile numbers. The coordinate system in the *upper* left corner of each picture shows the directions of the x_{KI} and y_{KI} axes in the Kiruna system (see Küppers et al. 1979)

served during the first break-up, and on 11 November 1976, is not clearly visible. However, there is a change of rotation between SKA and KUN on profile 5 and most of the coastal stations show an ambigous sense of rotation which may indicate a change. It should be noted that in the middle part of Fig. 8 the auroral picture at 2119 is shown. One minute later a bright arc (new or poleward expanding) is seen near the northern coast of Scandinavia (Baumjohann et al., 1981).

During the third break-up (around 2125 UT) a surge-

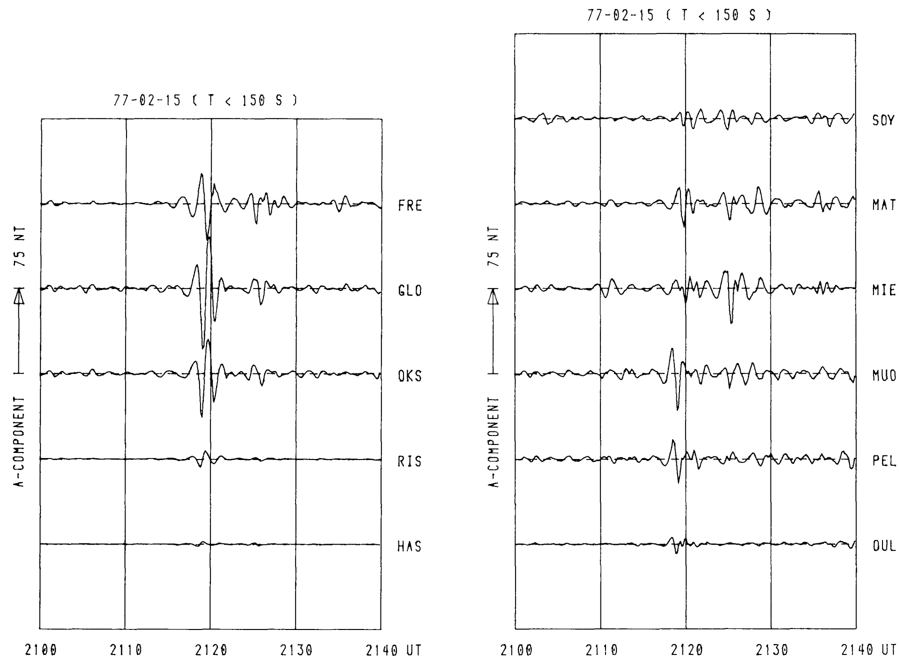

Fig. 7. High-pass filtered (periods less than 150 s) magnetograms of the horizontal *A* components (roughly directed to geomagnetic north) observed on 15 February 1977 along the meridional profiles 1 (FRE-HAS) and 4 (SOY-OUL)

like structure appears at the northern border of the SMA. Changes of the Pi2 horizontal vector rotation are similar to those in the previous break-ups, e.g. there are changes around the region of maximum major axis amplitude.

The equivalent current system associated with the second, most prominent break-up appears immediately after the auroral activation and is very localized (Fig. 9). Numerical modelling of the real current system based on observations of magnetic variations and ionospheric electric fields (Baumjohann et al., 1981) indicate that at 2119 UT highly localized and intense upward field-aligned currents flow at the western edge of the active region and less intense and more wide-spread downward currents flow at the eastern edge. These field-aligned currents are connected by a westward Cowling current which completes the substorm current wedge. Figure 10 shows isolines of the Pi2 major axis amplitude together with the modelled distribution of field-aligned currents. The greatest Pi2 amplitudes correspond to the maximum in the upward field-aligned current density. Since the upward field-aligned current was located at the north-western edge of the SMA it is not possible to decide clearly whether there are changes of the sense of rotation around the region of the upward field-aligned current or, equivalently, the region of maximum major axis amplitude as has been seen before (Figs. 6 and 8). It may only be noted that at the station FRE, slightly north-east of the strong upward field-aligned currents, the sense of rotation of the horizontal disturbance vector is not clearly defined, which could indicate a change of rotation just outside our network. Another interesting feature which shows the importance of the upward field-aligned currents for the generation of Pi2 pulsations can be seen in pictures of the equivalent current system of the Pi2 (Fig. 11). During the second break-up on 15 February 1977 there is a clear circular current vortex with its center somewhere at the western coast of Scandinavia e.g. just in the region where strong and localized upward field-aligned currents flow (cf. Fig. 10). At 2118 UT the equivalent current flows counterclockwise just as a Hall current associated with an upward field-aligned current in a uniform ionosphere. About half a period later at 2119 UT the current flows clockwise and has again changed its sense of rotation at 2120 UT.

It appears from Figs. 10 and 11 (see also Baumjohann et al., 1981) that the equivalent current system associated with the break-up differs substantially from the Pi2 equivalent current system which shows that the Pi2 equivalent current system is not caused simply by a periodic fluctuation of the whole break-up system.

Discussion

The two most important results of the previous analysis are the close relationship between the Pi2 equivalent current system and the location of intense upward flowing field-aligned currents and the fact that the sense of rotation of the horizontal polarization ellipse may change in the north-south as well as in the east-west direction, around the location of the active aurora and the amplitude maximum.

Maltsev et al. (1974) suggested a theory for the generation of Pi2 pulsations which allows the prediction of polarization parameters observed at the ground. In their model Maltsev and coworkers assume that during auroral brightening the ionospheric conductivity will be increased. Therefore, in this region the ionospheric electric field decreases. The equivalent current system of the generating impulse is that of a two-dimensional dipole (Maltsev et al., 1974). The theory further predicts that the field-aligned current system flows at the periphery of the enhanced conductivity region. The generating impulse is transferred along magnetic field lines and reflected from the ionosphere of the opposite hemisphere thus forming a standing Alfvén wave. If the region of enhanced conductivity has a circular form, polarization will be counterclockwise under that region and clockwise at some distance away. Therefore it is extremely difficult to explain the polarization peculiarities found in the present study using this model alone. The theory of Maltsev et al. (1974) has been extended to magnetospheric

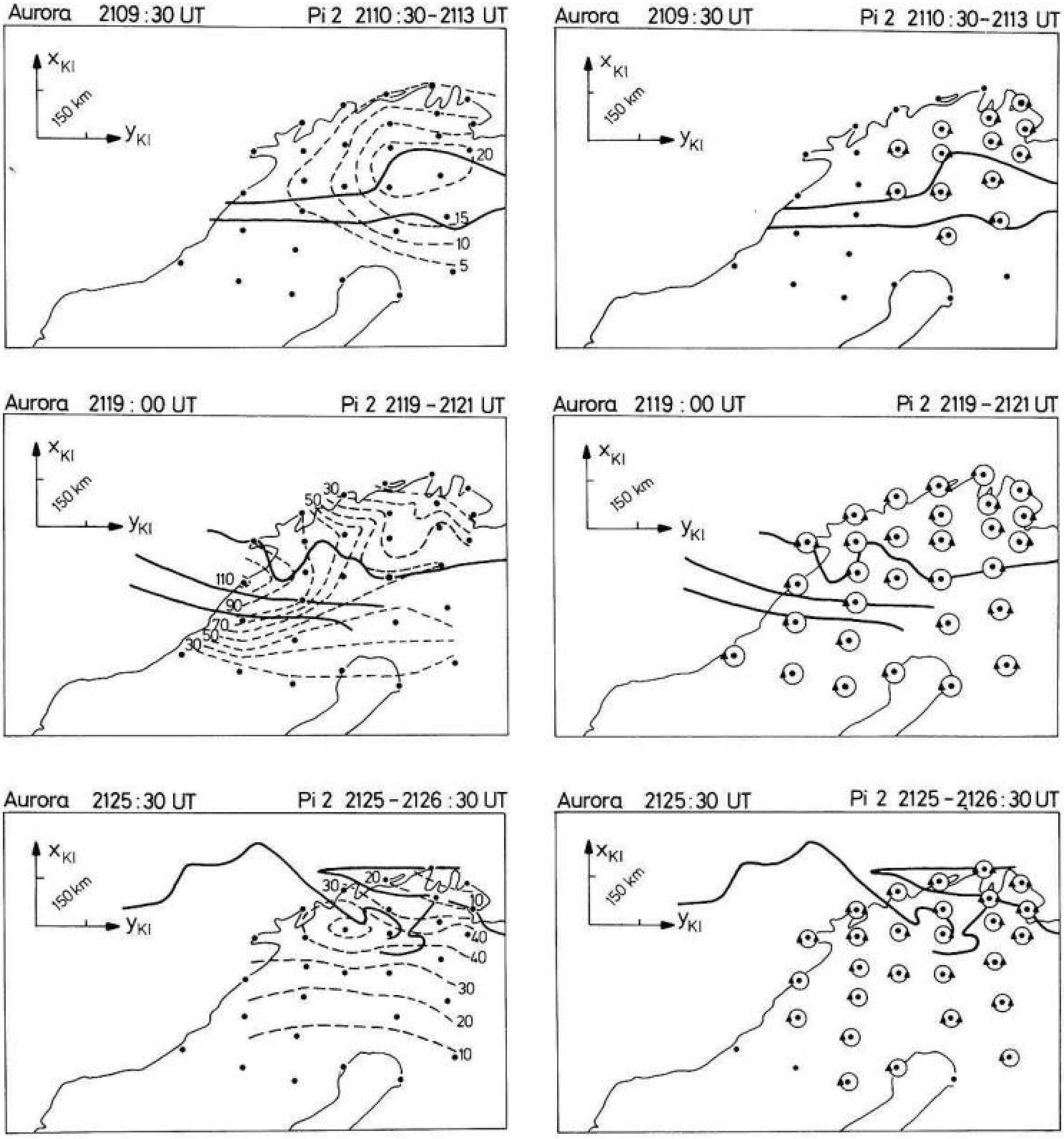

Fig. 8. Same as Fig. 6, but for the time intervals 2110:30–2113 UT (Pi2) and 2109:30 UT (aurora) (*upper part*), 2119–2121 UT (Pi2) and 2119 UT (aurora) (*middle part*) and 2125–2126:30 UT (Pi2) and 2125:30 UT (aurora) (*lower part*) on 15 February 1977

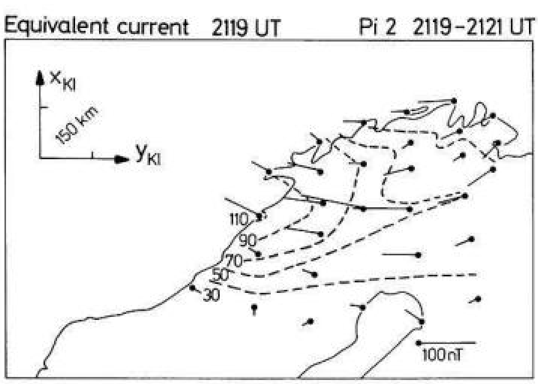

Fig. 9. Contours of the amplitudes of the main axes of the Pi2 horizontal polarization ellipses between 2119 and 2121 UT and spatial distribution of unfiltered equivalent current vectors constructed from the total magnetic field disturbance observed at the SMA stations on 15 February 1977

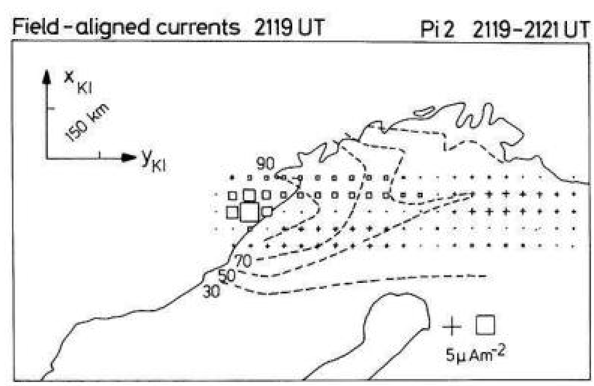

Fig. 10. Contours of the amplitudes of the main axes of the Pi2 horizontal polarization ellipses between 2119 and 2121 UT and spatial distribution of field-aligned current densities modelled by Baumjohann et al. (1981)

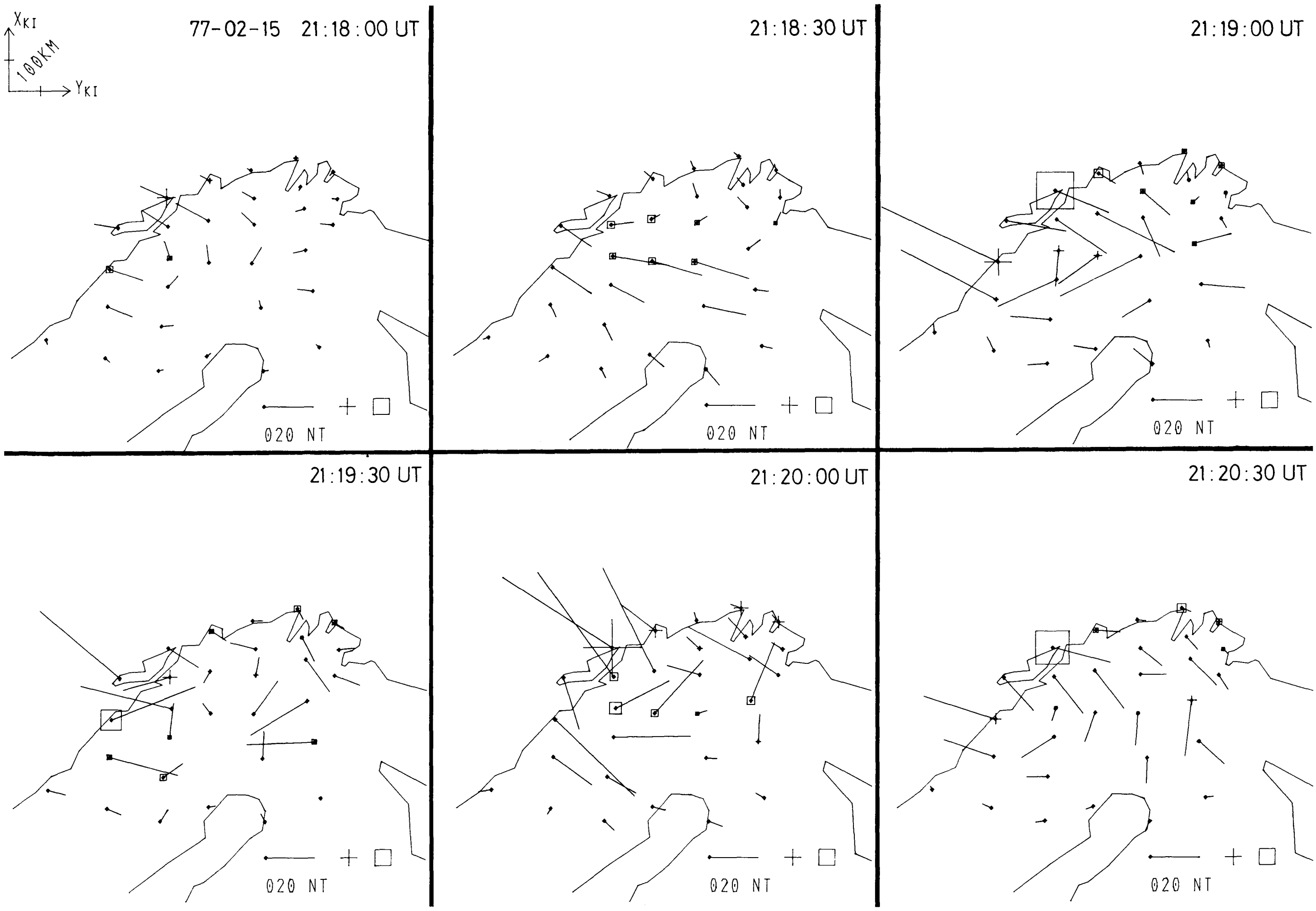

Fig. 11. Spatial distribution of equivalent current vectors of the high-pass filtered records for six successive times on 15 February 1977. The current vectors have their origin where the corresponding magnetic disturbances have been recorded; *squares* and *crosses* denote negative and positive Z perturbations, respectively

sources of the Alfvén-impulse by Mallinckrodt and Carlson (1978) and Nishida (1979). Nishida (1979) assumes the generation of a transient dusk-to-dawn electric field from ionospheric channelling of the dawn-to-dusk tail current. Once such an electric impulse has been generated it will be reflected at the ionosphere and will bounce between the two hemispheres. For a detailed comparison with our observations Nishida's (1979) model must be extended to three dimensions.

One may also try to explain the polarization of the ground-magnetic horizontal vector in terms of the evolution of the equivalent current system of the rather impulsively swiched-on substorm current. Boström (1972 , 1974) indicated that the three-dimensional current system associated with auroral break-ups, i.e. the substorm current wedge, can resonate in the Pi2 frequency range after it has been switched on. From this model of oscillations of the whole substorm current wedge one should expect that the location of the amplitude maximum of the Pi2 pulsations coincides with the location of the intensity maximum of the unfiltered equivalent current system. However, the result of our investigations show that this is not the case (cf. Fig. 10 and Fig. 11). The Pi2 equivalent current system exhibits a clear circular structure with alternating sense of rotation. Because the center of the current loop is closely connected to the location of the upward field-aligned currents one may regard the electric field generated in the ionosphere by the periodic fluctuations of the particle precipitation as a radial electric field. The fluctuating particle precipitation can also generate a periodic change in the ionospheric conductivity distribution with gradients in radial directions only. This means that the equivalent current system observable at the ground will be due to the ionospheric Hall currents (if there are not other conductivity gradients perpendicular to the electric field). The Pedersen currents will close by downward field-aligned currents possibly also radially distributed around the highly localized upward field-aligned currents. However, at the beginning of the break-up the oscillating field-aligned current should increase the total field-aligned current density while after half a cycle it will decrease the total density. The high-pass filtered current density therefore will show alternating up- and down-flowing currents which, to a first approximation will generate counterclockwise and clockwise flowing Hall currents, respectively. This is in excellent agreement with our observations. Periodic modulation of the intensity of precipitating electrons has been reported, for example, by Namgaladze et al. (1967) and Stuart et al. (1977).

The observation that the Pi2 current system is closely connected to the location of the upward field-aligned

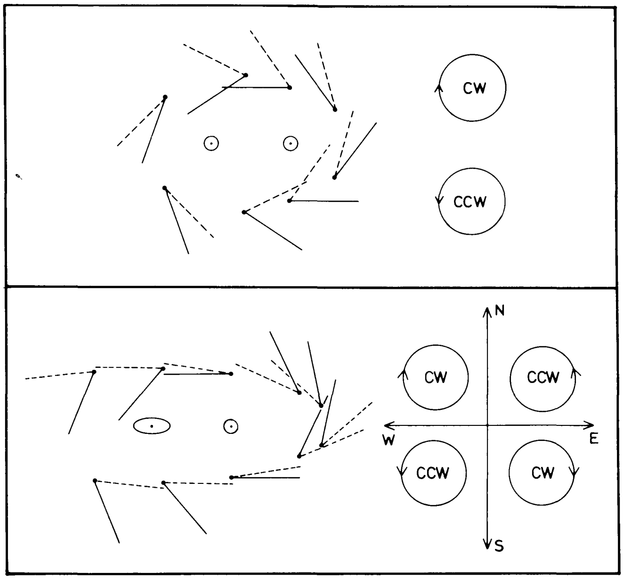

Fig. 12. Two cases of current distributions separated in space and time producing different polarization features. *Upper part:* current vectors associated with circular current systems. *Lower part:* current vectors associated with a circular and an elliptic current distribution. The current centers are indicated by a *small circle* or ellipse *with a dot*. Only the directions of the vectors are given correctly, not the length. Current vectors at the earlier time are represented by *solid lines;* those at the later time are shown by *dashed lines*. The right part of the figure shows schematically the polarization pattern around the center line if during the westward movement the current strength changes periodically with time

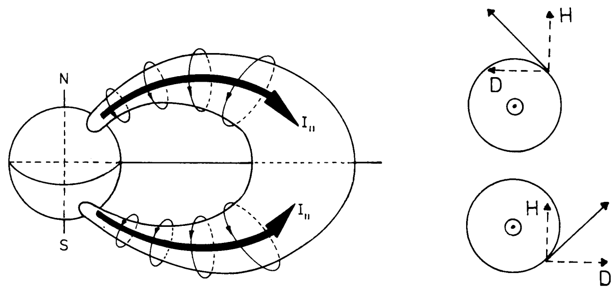

Fig. 13. Schematic view of the generation of odd-mode standing oscillations in the magnetospheric magnetic field by line-type upward field-aligned currents. In the *right part* the magnetic field generated in the magnetosphere by an upward field-aligned current in the northern and southern hemisphere is shown schematically (after Raspopov, 1976)

current may also be used to explain partly the observed polarization characteristics. Assuming as above, that in a first order approximation the equivalent current system accompanied by the oscillating upward field-aligned current is a Hall current and that the location of this current loop is fixed relative to our network one would expect linear polarization to be observed on the ground. But as may be seen from Baumjohann et al. (1981) the region of the highly localized field-aligned currents moves rapidly to the west and also changes its shape. This has an important influence on the polarization characteristics. Due to the westward movement of the region of intense upward field-aligned current and of the associated Pi2 equivalent current system regions of different sense of rotation will be generated as may be seen from Fig. 12. To simulate the situation we have choosen two different cases. In the first one (upper part of Fig. 12) we consider a circular equivalent current distribution which moved to the west during the course of the Pi2 and changes its strength periodically with time. One can clearly see that north of the current distribution a clockwise sense of rotation may be observed while to the south the opposite is the case. This is in good agreement with the results of Rostoker and Samson (1981) and Samson (in press 1982) but appears to contradict those of Kuwashima (1978). For the second case we have chosen the streamlines of the equivalent currents to have a circular shape at the beginning of the Pi2. This system moves to the west and the streamlines change their form to become of elliptical shape (lower part of Fig. 12). How such current distributions may be generated depends strongly on the ionospheric electric field and the inhomogeneous ionospheric conductivity distribution. Now, in this second case, four quadrants with different sense of rotation appear. For current systems with other than elliptical or circular shapes the polarization pattern observable on the ground will be more complicated. In general one may say that a situation as in the upper part of Fig. 12, i.e. a change of the sense of polarization along a meridional line, occurs if there is a westward movement of the current region. This is in good agreement with the observations shown in Figs. 6 and 8. The second case is not always possible and depends strongly the ellipticity of the streamlines and the westward velocity of the current region. However, a detailed comparision with the observations requires a more detailed modelling of the Pi2 equivalent current system.

One has to take into account that a periodic change of the field-aligned current density (e.g. fluctuation of electron precipitation) is accompanied by an Alfvén-wave so that reflection of wave energy will occur at the ionosphere and the electric field will therefore depend strongly on the ionospheric conductivity distribution. Due to the fluctuations of the electron precipitation the conductivity distribution will also change with time (Chao and Heacock, 1980). Some ideas on the physical processes which might occur in such a case may be found in Maltsev et al. (1974) or Mallinckrodt and Carlson (1978). Though we have not as yet been able to make a more detailed model of the Pi2 current system, we believe that the westward movement of the region of upward field-aligned current plays an important role in generating the observed polarization features. Samson (in press 1982) points out another possible mechanism which could generate elliptical polarization on the ground. He assumes field-aligned current sheets to be related to the Pi2 and to vary periodically in the azimuthal direction. Under special conditions it is then possible to show that the net Hall current in the ionosphere is 90° phase-shifted relative to the net field-aligned current thus producing phase shifts in the magnetic field observable at the ground.

Noting the clear connection between the location of the upward field-aligned currents and the Pi2 equivalent current system, as found in the present analysis, it may be possible to explain another important feature of Pi2 pulsations. Raspopov (1976) pointed out that field-aligned currents associated with the break-up could generate standing hydromagnetic waves in the odd-mode. Figure 13 shows the magnetic disturbance transverse to the background field as produced by field-aligned currents. In the equatorial plane the transverse magnetic component will be very small, as at the node of a standing wave. At two conjugate points in the northern and southern hemispheres the *H*-components will be in phase as Fig. 13 shows. Such a feature coincides with the oddmode of standing wave in the magnetosphere and has been observed, for example, by Raspopov et al. (1967) and Lanzerotti and Fukunishi (1974). Therefore, a fluctuating field-aligned current as shown in Fig. 13 and a spatially localised hydromagnetic wave are essentially the same thing and previous observations of an odd-mode characteristic for Pi2 magnetic pulsations agree with our observation of a fluctuating field-aligned current.

Summary and Conclusions

From the experimental results presented above the following conclusions can be drawn:

– The Pi2 equivalent current system as seen on the ground is closely connected to the location of intense upward field-aligned currents.

– The Pi2 equivalent current system is not directly connected to periodic fluctuations of the *whole* substorm current system.

– Because an oscillating field-aligned current as shown in Fig. 13 and a transverse standing wave in the odd-mode are essentially the same thing, part of our observations (see above) are supported by the earlier results of Raspopov et al. (1967) and Lanzerotti and Fukunishi (1974).

– If the location of the Pi2 equivalent current system, possibly caused by oscillating field-aligned currents, is fixed relative to the earth one would expect linear polarization. However, because of the westward motion and changes in the shape of the field-aligned current region, elliptically polarized horizontal disturbance vectors will be generated on the ground and the sense of rotation will change in the north-south as well as in the east-west direction, in agreement with our observations.

As has been discussed above high-pass filtering of the magnetic data to separate the Pi2 disturbances from the background variations present some difficulties. Some new method should be developed to perform this separation in a more reliable way than has been possible in the present study.

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