J. Geophys. 44, 415–426, 1978

Journal of Geophysics

Parameters of the Auroral Electrojet From Magnetic Variations Along a Meridian

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Abstract. The parameters of the auroral electrojet are described by using an ionospheric sheet current model. Data from a line of magnetometers between 62 and 67 degrees magnetic latitude are the input for the computation of the parameters during electrojet activity. The parameters are depicted in the parameter-time diagram which furnishes mainly the following information:
1. Applicability of the two dimensional current model.
2. Latitudinal extent of the electrojets as a function of time.
3. Location of centre of the current as a function of time.
4. Current flow direction.

Two case studies are carried out. The first comprises DMSP (*D*efense *M*eteorological *S*atellite *P*rogram) data, the second makes use of data collected simultaneously by the *S*candinavian *T*win *A*uroral *R*adar *E*xperiment (STARE). The results of the parameter-time diagram and the DMSP as well as the STARE data are in good agreement.

Key words: Substorm – Auroral electrojet – Ionospheric currents – Magnetic field observation – IMS.

1. Introduction

Six magnetometer stations are installed in Finland and Norway between 66 and 71 degrees northern geographic latitude in order to measure the magnetic variations of auroral electrojet activity. The proper locations of the stations are shown in Figure 1. The project is carried out as part of the *I*nternational *M*agnetospheric *S*tudy (IMS). The european magnetometer network is dedicated to the IMS. It consists of the Braunschweig magnetometer chain on which is reported here only, and the Münster network (Küppers et al., 1978). Table 1 contains the geographical and geomagnetic coordinates of our line of stations.

The auroral electrojet has to be regarded as the ionospheric component of a dynamical magnetospheric process called the magnetospheric substorm (Akasofu, 1968). Thus the quantitative knowledge of the electrojet's properties

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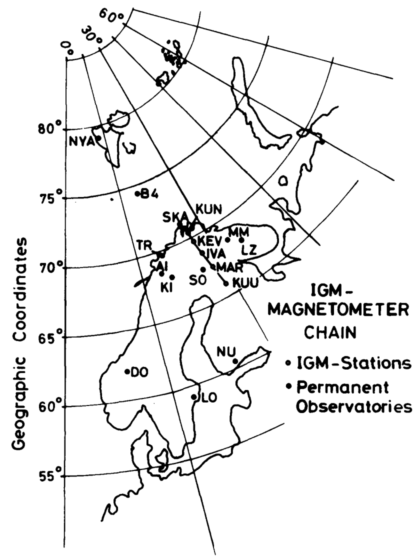

Fig. 1. The IMS-Magnetometer Chain in Scandinavia of the Technical University Braunschweig. Observatories are indicated by two-letter codes

Table 1. Coordinates of the magnetometer stations used in this study

Name	Code	Geographic coordinates		Geomagnetic coordinates[a]		CGM[b]
		Latitude [Deg]	Longitude [Deg]	Latitude [Deg]	Longitude [Deg]	[UT]
Skårsvag	SKA	71.11 N	25.83 E	67.61 N	111.04 E	21:17
Kunes	KUN	70.35 N	26.51 E	66.84 N	110.79 E	21:18
Kevo	KEV	69.75 N	27.03 E	66.23 N	110.61 E	21:19
Ivalo	IVA	68.60 N	27.47 E	65.05 N	109.94 E	21:22
Martti	MAR	67.47 N	28.28 E	63.90 N	109.76 E	21:23
Kuusamo	KUU	65.91 N	29.05 E	62.37 N	109.24 E	21:25

[a] Revised corrected geomagnetic coordinates calculated after Gustafsson (1970)

[b] *C*orrected *G*eomagnetic *M*idnight calculated for January 19, 1977 (Montbriand, 1970)

is a prerequisite for the understanding of the physics of the substorm. The observation along a meridian enables us to resolve temporal and spatial variations along the profile. Heinrich et al. (1970) and Hanser et al. (1973) used north-south magnetometer lines to determine parameters of the auroral electrojet in conjunction with sounding rocket launches. Czechowsky (1970) calculated equivalent E-region currents from four magnetic ground recordings for comparison with VHF backscatter data. Significant advances were achieved by the North American line of Rostoker and his coworkers. Kisabeth and Rostoker (1971) were the first to publish data collected from their meridian line of magnetometers in North America. In a series of papers (Kisabeth and Rostoker, 1973; Rostoker and Kisabeth, 1973; Kisabeth and Rostoker, 1974; Rostoker et al., 1975; Wiens and

Rostoker, 1975) they analysed the structural and temporal behaviour of auroral electrojets.

The purpose of this paper is to show how the data of the magnetometer chain can be used to obtain a synoptic survey of the electrojet activity along a meridian. It is shown how the simultaneous observation by six stations can be converted into a concise representation for subsequent physical interpretation. The temporal and spatial behaviour of the electrojet can be studied by means of a parameter-time diagram. This diagram is based on a method of data presentation first published by Zaitzev and Boström (1970). Two examples demonstrate under what circumstances the data from the magnetometer chain can be used to give quantitative information on the electrojet. For instance, if the current flow becomes too complex, it is difficult to interpret the magnetic field data using the technique presented in this paper.

2. Data Collection

The six stations are of identical design: A three component flux gate magnetometer measures the variation of the horizontal component H, of the magnetic east component D and of the vertical component Z of the earth's magnetic field. Each component may vary within $\pm 1000\, nT$ with respect to the baseline value. The analogue magnetometer output signal is digitised by a 12 bit analogue to digital converter (ADC) with an accuracy of $0.5\, nT$. A quartz controlled time base generator provides the time code and controls data recording on a magnetic tape compatible with a digital computer. The normal sampling rate is 10 s, aliasing filters suppress frequencies above the Nyquist frequency in the original signal. The subsequent data processing procedure includes error detection routines and conversion of the field components from the magnetic system H-D-Z into the geographic system X (=North), Y (=East) and Z (=Down). By this the geographic north direction is used as directional reference rather than the magnetic declination which varies from one location to another.

3. Parameters of the Electrojet

Simultaneous observations by backscatter techniques and magnetometers show that the auroral electrojet can be described in terms of a sheet current flowing in 115 km altitude (Brekke et al., 1974; Greenwald et al., 1977). We will use x, y, and z to denote the geographic directions north, east and down. The corresponding magnetic field components are X, Y, and Z. Figure 2 shows the resulting X and Z field components at the earth's surface for a model westward flowing sheet current with infinite extent in the east-west direction, positioned at a height of 115 km. The north-south extent of the sheet is 4 degrees centered at 68 degrees with a uniform surface current density of $1.5\, \mathrm{Am}^{-1}$.

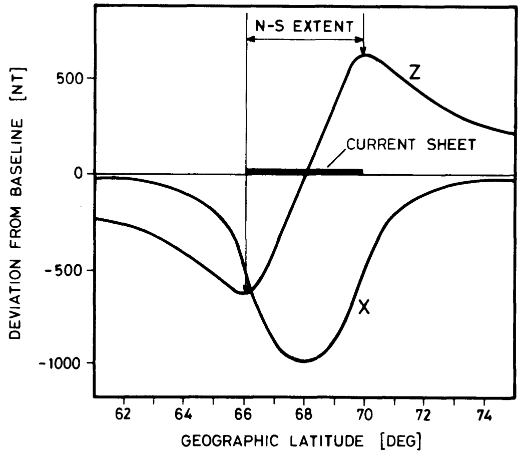

Fig. 2. Sheet current model for the auroral electrojet and resulting magnetic field components measured on the ground

This figure also may illustrate the parameters we use for the description of the current (cf. Figs. 6 and 9):

X_{min} or X_{max} = indicates latitude where the centre of the current is located, from minimum or maximum in X

Z_{zero} = indicates same latitude from $Z=0$

Z_{min}, Z_{max} = indicates latitudes of the Z extrema as a measure of the north-south extent of the current flow

X_a = X value at the latitude indicated by X_{min} or X_{max} as a measure of the current density and the flow direction (west or east)

Z_g = gives the gradient of Z at the latitude where $Z=0$.

If the latitudes indicated by the symbols Z_{zero} and X_{min}, X_{max}, derived from measurements along our station line, coincide, the actual current can be approximated using this model.

The gradient Z_g together with the amplitude value X_a will be used to compute the north-south extent of the current for those cases where the extrema of Z (cf. Fig. 2) are outside the range of the magnetometer chain.

As shown by Kertz (1954) the magnetic field of a line current I at height h_l can be expressed in terms of an infinitely broad sheet current at height $h<h_l$ with the current density:

$$j_H(x)=\frac{I}{\pi}\frac{h_l-h}{x^2+(h_l-h)^2} \qquad 0\leqq h<h_l \tag{1}$$

h_l = height of the line current
h = height of the sheet current
I = line current strength.

For a line current of infinite east-west extent, flowing at the height h_l above the earth's surface in east-west direction we have the well known equations:

$$X(x) = \frac{\mu_o}{2\pi} \frac{I \cdot h_l}{x^2 + h_l^2}$$

$$Y(x) = 0 \tag{2}$$

$$Z(x) = \frac{-\mu_o}{2\pi} \frac{I \cdot x}{x^2 + h_l^2}.$$

Assuming that the measured magnetic field variations at the earth's surface are due to a line current we obtain expressions for the current I and the height h_l in terms of the measured quantities Z_g and X_a:

$$I = \frac{2\pi}{\mu_o} \frac{X_a^2}{Z_g}$$

$$h_l = \frac{X_a}{Z_g}. \tag{3}$$

With the result of (3) and the assumption that the ionospheric sheet current flows at 115 km altitude ($h = 115\,\mathrm{km} < h_l$) we can determine the current distribution by using Equation (1). This in turn allows us to determine the north-south extent of the electrojet which is chosen to be the half width of the current distribution. In Section 4.1 a comparison is made between the directly measured extrema of Z and the indirectly computed north-south extent. These show good agreement.

This simple model cannot account for east-west fields. The Y-component may be due to field-aligned currents first reported by Zmuda et al. (1966) and/or an x-component of the ionospheric current (cf. Brekke et al., 1974).

Earth induction effects are neglected. Investigations using simplifying assumptions for the conductivity within the earth and the temporal behaviour of the current are previously reported in the pioneering work by McNish (1938) and Forbush and Casaverde (1961). Recent results are given by Boström (1971) and Mareschal (1976). The result is an increase of the magnetic field amplitude by the earth-induced current which in turn means that current densities derived from ground-based magnetic recordings may appear to be larger than they are in nature.

If we plot the latitudes X_{min} or X_{max} as well as the Z_{zero} as a function of time, we are able to judge how well this model describes the actual current. The current flow is symmetrical relative to our station line and satisfies also the model assumptions as long as the X_{min}, X_{max}, and Z_{zero} are measured simultaneously at the same latitude.

4. Case Studies

4.1. January 19, 1977

Figure 3 shows the magnetic field components as recorded by the six stations between 18:00 and 21:00 UT. Upper, middle and lower panel contain X, Y, and Z

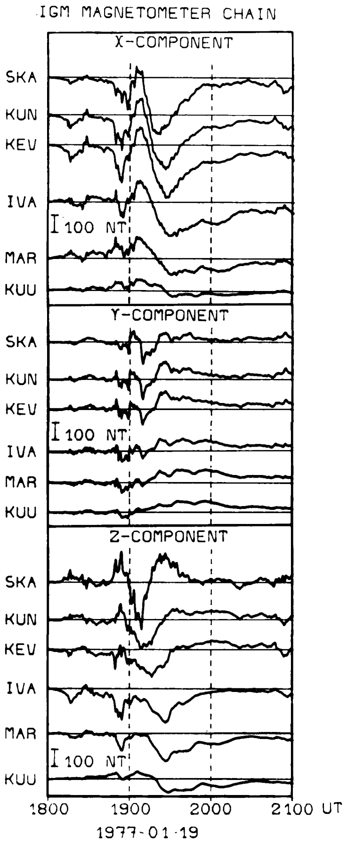

Fig. 3. Traces of magnetic field components recorded along a north-south line. For station codes refer to Table 1. Corrected geomagnetic midnight occurs at 21:18 UT. Upper panel: X or Northward Component, middle panel: Y or Eastward Component, lower panel: Z or Downward Component

respectively. The magnetic field was very quiet until 18:00 UT. Therefore the magnitudes of the field components as measured before 18:00 UT were chosen as baselines. Corrected geomagnetic midnight (Montbriand, 1970) occurs between 21:17 UT and 21:25 UT at the different station latitudes (cf. Table 1). Each trace in Figure 3 reflects temporal and spatial variations of the ionospheric current. We seperate temporal and spatial effects by computing latitude profiles from our station line for selected times. The profiles are obtained by joining the six field values given at the six station latitudes by means of a Spline interpolation. The result is shown in Figure 4 with the time increasing from bottom to top.

Until about 19:20 UT X is positive in the south and negative in the north. From this we conclude that there is an eastward current in the south and at the same time a westward electrojet north of it. After this time there is a well developed negative X, this means a westward electrojet.

Hughes and Rostoker (1977) as well as Yasuhara et al. (1975) have shown that field-aligned currents may be observed on the ground by changes of the east-west component of the magnetic field. As Y (Fig. 4) is just slightly positive and fairly constant after 19:20 UT, we assume that there is no strong field-aligned current flow during that time along our line.

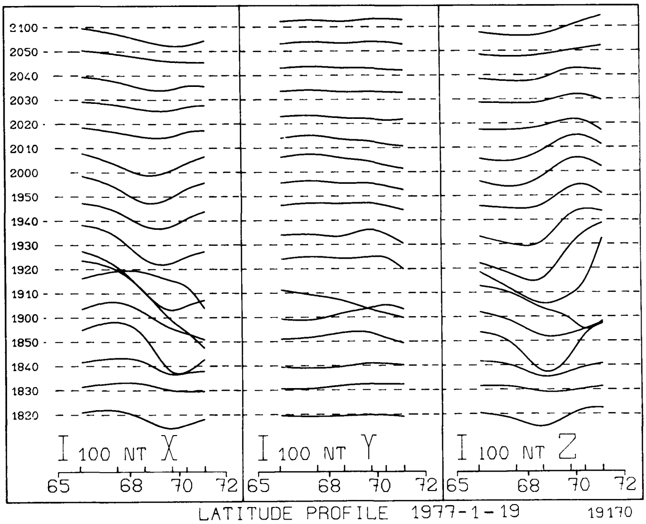

Fig. 4. Latitude profile of magnetic field variations on January 19, 1977 between 18:20 and 21:00 UT. The six ticks on the abscissas indicate the station latitudes. Refer to text for further explanation. $Kp = 3-$

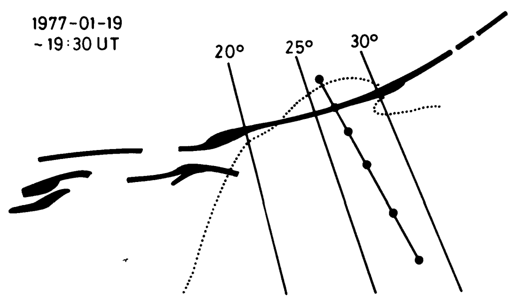

Fig. 5. Auroral emissions taken by a DMSP satellite. The dotted line indicates the scandinavian coastline. The magnetometer chain is between the 25° and 30° meridians

After 19:30 UT both extrema of Z are within the range of the chain. The actual locations of the maximum and the minimum (i.e., the north-south extent) coincides with the values obtained by computation using Equations (1) through (3).

Figure 5 shows auroral structures photographed by a DMSP satellite (*D*efense *M*eteorological *S*atellite *P*rogram). The Scandinavian coast is indicated by a dotted line, the station line is between 25 and 30 degrees geographic longitude. The picture was taken at about 19:30 UT corresponding to 22:11 corrected geomagnetic time. The aurora is located over Kunes. The latitude profile (Fig. 4) indicates a westward electrojet to the south of Kunes.

A comprehensive description of the development between 18:00 and 21:00 UT is given in the parameter-time diagram (Fig. 6). The upper panel shows the latitude variations of the parameters Z_{zero}, Z_{max}, Z_{min}, X_{max}, X_{min} versus time. The middle panel shows – as far as it can be calculated by the method described in Chapter 3 – the north-south extent of the current versus time. The lower panel gives the direc-

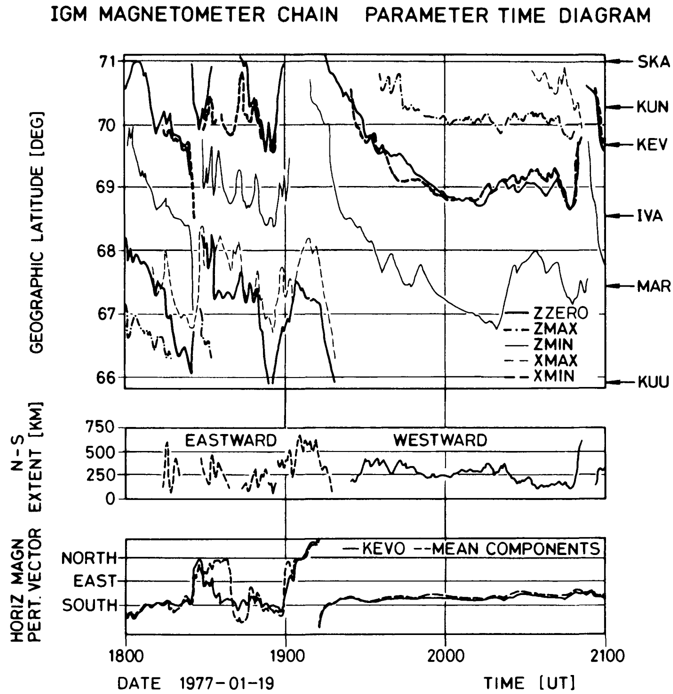

Fig. 6. Parameter-time diagram for January 19, 1977. The upper panel contains information on the location of the current flow, the middle panel shows the prevailing flow direction and north-south extent. The direction of the horizontal magnetic field is plotted in the lower panel. More explanations are given in the text

tion of the horizontal magnetic perturbation vector. The dashed curve was computed from the means of all X and Y values taken over all six stations for a given time, the solid curve shows the behaviour of the vector in Kevo. By comparing the curve for Kevo with the mean direction curve, one can easily see the homogeneity of the current flow.

An inspection of the upper panel shows that there is a very complex current flow until about 19:20 UT. The two Z_{zero}-traces are an indicator for two currents, the corresponding X_{max} and X_{min} curves shows that the currents are flowing antiparallel – as we know already from Figure 4. The strong irregularities in the parameters indicate strong variations of the current strength and direction. We cannot apply a simple sheet current model. If we reinspect Figure 5 we realize a multiple arc structured aurora west of 14 degrees longitude. It is likely that this structure moved over the chain in westward direction. However due to cloud cover no all-sky recordings are available to back this assumption. The transition from a complex current system to a "simple" auroral electrojet at the magnetometer chain longitude occurs at 19:20 UT. From that time on the current can be modelled using a sheet current model. The Z_{zero} and X_{min} location coincide very well. The current system moves southward until 20:00 UT as indicated by the northward (Z_{max}) and southward (Z_{min}) edge of the system. After 21:00 UT

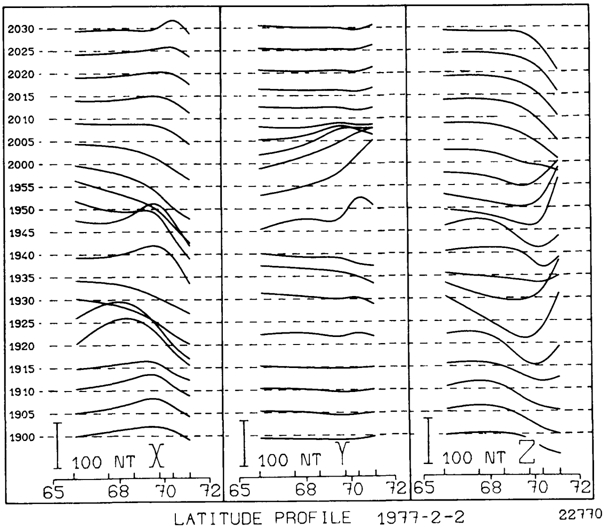

Fig. 7. Latitude profile of magnetic field variations on February 2, 1977 between 19:00 and 21:00 UT. $Kp = 3-$. Refer to Figure 4 and text for explanation

the centre of the current is at 69 degrees geographical latitude. The horizontal field is rather homogeneous and directed mainly to the south with as slight deviation to the east as one can see in the lower panel of Figure 6.

The parameter-time diagram allows the following summary: Between 18:00 and 19:20 UT we find strongly varying currents which cannot be explained by a simple model. After 19:20 UT until about 21:00 UT the current becomes a westward sheet current. The counterflowing currents before 19:20 UT indicate that a Harang discontinuity (Heppner, 1972) moved over the magnetometer line. The substorm onset occurred at about 18:45 UT followed by the main phase and recovery phase.

4.2. February 2, 1977

Figure 7 shows the three magnetic components in a latitude profile plot for the time between 19:00 and 20:30 UT. The X-component shows an eastward electrojet at 19:00 UT. Later on, from 19:15 UT onwards X becomes negative in the north, which means that a westward current develops in the north. After some time the eastward current in the south disappears. The variations in the Y-component from 19:40 UT onwards suggest either field-aligned currents or a north-south component in the ionospheric current.

Figure 8 depicts four selected STARE (*S*candinavian *T*win *A*uroral *R*adar *E*xperiment) observations (courtesy of R.A. Greenwald). STARE measures the horizontal Hall-currents in the ionosphere. At 19:05 UT STARE shows an eastward electrojet between 69 and 70 degrees geographic latitude (panel a in Fig. 8). The parameter-time diagram for the same time interval is shown in Figure 9.

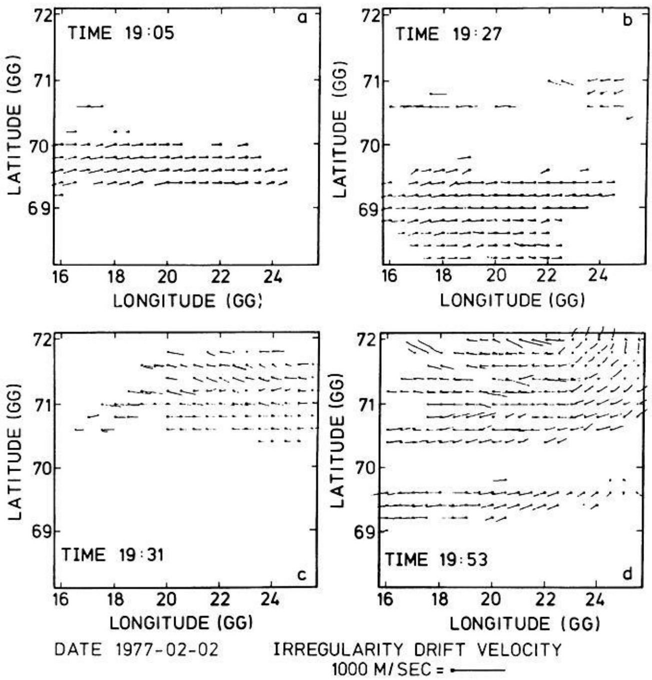

Fig. 8. Current flow measured by the STARE on February 2, 1977. The current is opposite to the drift velocity and shows only the Hall current. (Courtesy of R.A. Greenwald)

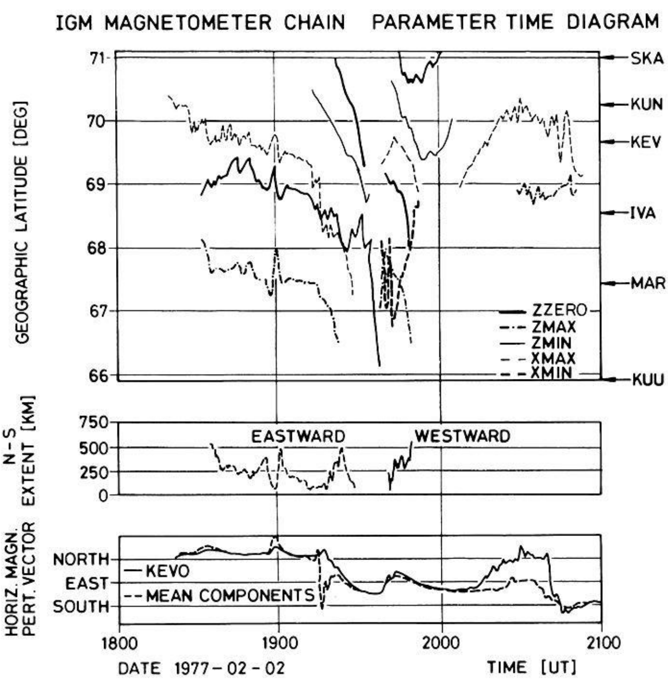

Fig. 9. Parameter-time diagram for February 2, 1977. Until about 19:30 UT an eastward electrojet centered at 69° latitude dominates. After that time there are at least two currents of opposite direction

The X_{max} curve in the parameter-time diagram indicates the same position of the electrojet as well. X_{max} and Z_{zero} do not coincide too well, but the locations are not more than 40 km apart. The next STARE observation at 19:27 UT (panel b in Fig. 8) shows an eastward current between 68 and 69.5 degrees and a westward current between 70.5 and 71 degrees latitude. For this time we find two Z_{zero} curves in the parameter-time diagram indicating the proper locations of the current flow. A few minutes later, at 19:31 UT (panel c in Fig. 8) the current in the south has vanished, only a westward flow between 71 and 72 degrees latitude is observed. The parameter-time diagram shows rather confusing patterns. This is due to two effects: 1. The STARE observation shows the high temporal variability of the current, which results in highly variable magnetic fields. 2. There are currents of opposite direction. The superposed magnetic fields lead to erroneous results in the parameter-time diagram.

The last STARE observation at 19:53 UT (panel d in Fig. 8) shows a westward electrojet with a southward component north of 70 degrees latitude. Only 100 km to the south there is an eastward current. It appears quite natural that this current flow cannot be derived from the parameter-time diagram. The latitude profile of the Y-component in Figure 7 becomes positive in the northern part after 19:40 UT. By comparison with the STARE data we can explain this by the southward current (panel d in Fig. 9).

5. Conclusions

Magnetic field observations can only be interpreted in terms of electric currents when some geometrical properties of the currents are known. By means of an ionospheric sheet current model the parameters Z_{zero}, Z_{min}, Z_{max}, X_{min}, and X_{max} are computed and plotted in the parameter-time diagram. As long as the electrojet behaves as assumed in the model, the parameter-time diagram is a good tool to study the behaviour of the current. Magnetic data and auroral emissions as well as auroral radar data are consistent. As soon as the ionospheric current flow becomes so complex that the model assumption is strongly violated, the parameter-time diagram becomes a confusing line pattern, telling us that the situation cannot be analysed only by magnetic observations along the profile. Simultaneous measurements by auroral radar technique and the ground based magnetometer chains show how difficult it is to solve complex current structures by ground based measurements. However, it is considered to be an important result of the parameter-time diagram that it immediately delivers information on the simplicity or complexity of the prevailing ionospheric current at a certain time.

Acknowledgements. The authors are indebted to Professor Dr. W. Kertz for the steady support of this project. We greatly acknowledge the help of Drs. Sucksdorff, Helsinki and Boström, Uppsala, through which the observation in Scandinavia became possible. Mr. Kataja and Mr. Mustonen from the Geophysical Observatory in Sodankylä supported greatly the operation of the chain, as well as Mr. Berger in Tromsö. We appreciate the valuable software and hardware contribution by Mr. Hähnsen and Mr. Stoll. We are indebted to Drs. Greenwald and Nielsen, MPAe Lindau, for relaying DMSP data and supplying us with STARE data. The authors are grateful to the DFG who financed the project.

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Received February 10, 1978 / Revised Version May 16, 1978