AURORAL ELECTROJETS DYNAMICS DURING MAGNETIC STORMS

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ABSTRACT

Effect of the equatorward shift of the eastward and westward electrojets during magnetic storms main phase is analysed based on the meridianal chains of magnetic observatories EISCAT and IMAGE (geomagnetic longitude ~105°). Magnetic disturbances of various Dst index intensity with main phase fall on 10UT - 24UT interval were selected when the observatories chain was located in the afternoon - near midnight sector of LMT. The eastward electrojet center shifts equatorward with Dst increase: when Dst ~ -50 nT the electrojet center is located at Φ ~62° , when Dst ~ -100nT at Φ ~59° , when Dst ~ -300 nT at Φ ~54°. The westward electrojet center during a magnetic storms main phase for intervals between substorms shifts equatorward with Dst increase: at Φ ~62° when Dst ~ -100 nT and Φ ~55° when Dst ~ -300 nT. During substorms the westward electrojet widens poleward covering auroral latitudes. During a magnetic storm main phase it is necessary to take into account subauroral and even middle latitude observatories data for the AE indices calculation. The electrojets location during a magnetic storm main phase and their dynamics in connection with substorms allow to offer a natural interpretation of described in the literature effect of the AE indices saturation in the course of magnetic storms.

1. INTRODUCTION

Geophysical phenomena accompanying appearance of magnetic storms are observed well equatorward of auroral latitudes (Ref. 1). As to the auroral electrojets location, which are intense ionospheric currents with magnitude of up to 10^6A routinely observed at auroral latitudes Φ ~65°, opinion of researches varies. Akasofu (Ref. 2), Weimer et al. (Ref. 3) believe, that the auroral electrojets remain at Φ > 60° during magnetic storms as well and, hence, their shift equatorward is unable to describe observed AE (AL) indices saturation effect for intense Dst or the IMF southward component $B_Z < 0$ leading to the intensive ring current generation. Feldstein et al. (Ref. 4 - 6) on the basis of several magnetic storms showed the existence of the auroral electrojet shift to subauroral latitudes during major magnetic storms main phases. Below we continue investigation of meridional cross-sections ΔX and ΔZ of the geomagnetic disturbances vector component along the IMAGE meridional chain of magnetic observatories operating in full scope since 1994 for disturbances of varous Dst index intensity.

2. AURORAL ELECTROJETS DYNAMICS IN THE INTERVAL OF WEAK MAGNETIC STORM ON MAY 1 -2, 1994

Fig.1 presents variations of northern (X) component of the geomagnetic field along the IMAGE chain during the weak magnetic storm (Dst^{max} ~ -71nT) on May 1-2, 1994. The storm main phase, connected with the onset of decrease of the geomagnetic horizontal component at low-latitudinal observatories, falls on 12 UT May 1. The IMAGE chain during the storm main phase was located at longitudes of the eastward electrojet (evening sector) and then westward (nearmidnight - early morning MLT sector). Vertical dotted lines mark instants of latitudinal cross-sections through the eastward (N°1 - N°5) and westward (N°6 - N°9) electrojets. Latitudinal cross-sections N°6 - N°9 were specially selected to characterize the westward electrojet dynamics during transition from relatively quiet interval prior to the substorm onset to the maximum of the substorm expansion phase. Fig. 1 data testify about clear shift of the eastward directed current ($\Delta X > 0$) to the lower latitudes as the magnetic storm main phase develops in the interval 12UT - 17UT on May 1, 1994.

At the bottom of the fig.1 Dst variation of the geomagnetic field for the same storm is shown. Arrows directed downward mark moments of latitudinal cross-sections through eastward electrojet, arrows directed upward mark cross-section through westward electrojet. Latitudinal cross-section of ΔX and ΔZ through the eastward electrojet at consecutive UT time moments are presented in Fig. 2. Arrows mark the eastward electrojet location ($\Delta X > 0$ has maximum and ΔZ ~0 nT). The equatorward shift of the eastward electrojet center from 71° at 12.04UT to 61° at 16.29UT is distinctly manifested during the storm main phase.

Character of latitudinal cross-sections through the westward electrojet, presented in Fig. 3, and the eastward electrojet are substantially different. During relatively quiet intervals between substorms, like time moments 22.00UT and 00.00UT, the electrojet center was located at Φ ~61° or 65° . At substorms maximum moments, which fall at 20.37UT and 23.20UT, the electojet center does not shift equatorward but the

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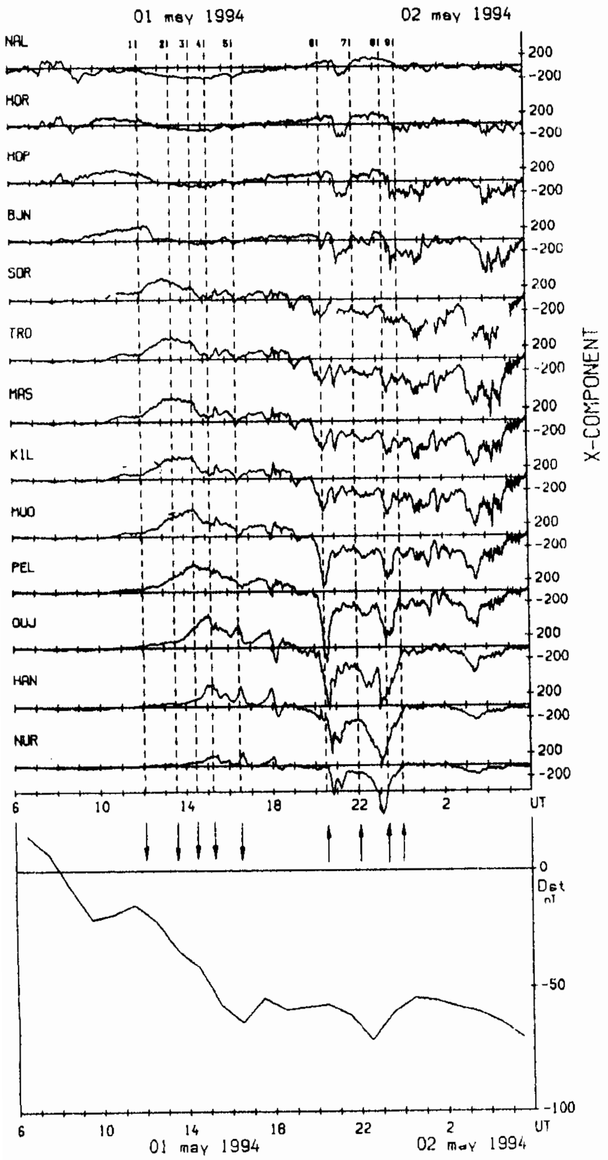

Figure 1. Variations of northern (X) geomagnetic field component along the digital magnetic stations chain IMAGE at geomagnetic meridian ~105° at invariant latitudes 75° < Φ < 57° in the course of the magnetic storm main phase on May 1 - 2, 1994 interval (at the top). The variations intensity was measured relative to the quiet level at 6UT - 7UT on May 1. Dotted lines (vertical) correspond to nine UT moments with latitudinal cross-sections of ΔX and ΔZ geomagnetic field components presented in the text.
Dst variation of the geomagnetic field for the same storm is shown at the bottom. Arrows directed downward mark moments of latitudinal cross-section through the eastward electrojet, arrows directed upward mark cross-section through the westward electrojet.

electrojet sharply widens poleward. The maximum ΔX field decrease occurs at Φ ~65° - 66°, i.e. at the auroral zone central part latitudes.

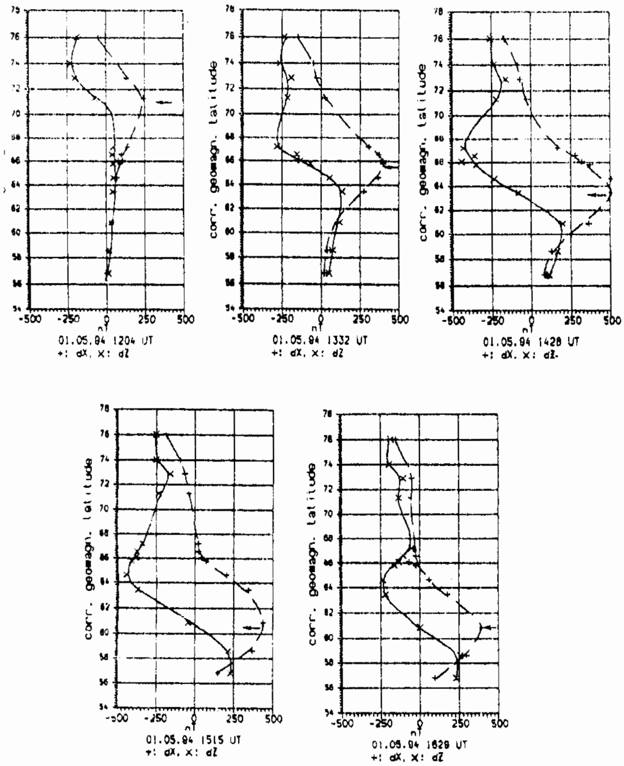

Figure 2. Latitudinal cross-section X (dotted line) and Z (solid line) through the eastward electrojet on May 1, 1994 at 12.04UT, 13.32UT, 14.28UT, 15.15UT, 16.29 UT. Arrows mark latitudes of the eastward electrojet center locations where ΔZ ~0 nT, ΔX > 0 nT and has maximum value.

3. AURORAL ELECTROJETS DYNAMICS IN THE INTERVAL OF MODERATE MAGNETIC STORM ON FEBRUARY 21 - 22, 1994

Fig. 4 shows variations of the northward (X) magnetic field component in the course of the moderate magnetic storm on February 21-22, 1994 main phase. For magnetic storms with maximum Dst ~ -150 nT it appeared necessary to attract observations of Russian magnetic stations located approximately along IMAGE meridian up to Φ ~51°, in order to determine precisely the eastward electrojet center location.

At the initial phase of the storm on February 21, 1994 at 09UT - 12UT magnetic disturbances intensity does not exceed 200nT for auroral latitudes (60° < Φ < 70°). Decrease of field till 1000 nT at 10UT - 12UT was recorded by observatories at Φ ~75°. Such variation character is conditioned by the existence in the course of the disturbance of the western current along the auroral oval (Ref. 7, Ref. 8). At day hours the auroral oval in dependence on disturbance level is located at geomagnetic latitudes from 75° to 80°. As its consequence, notable field variations occur at observatories with Φ > 71° and only weak disturbances in the auroral zone for Φ < 68°.

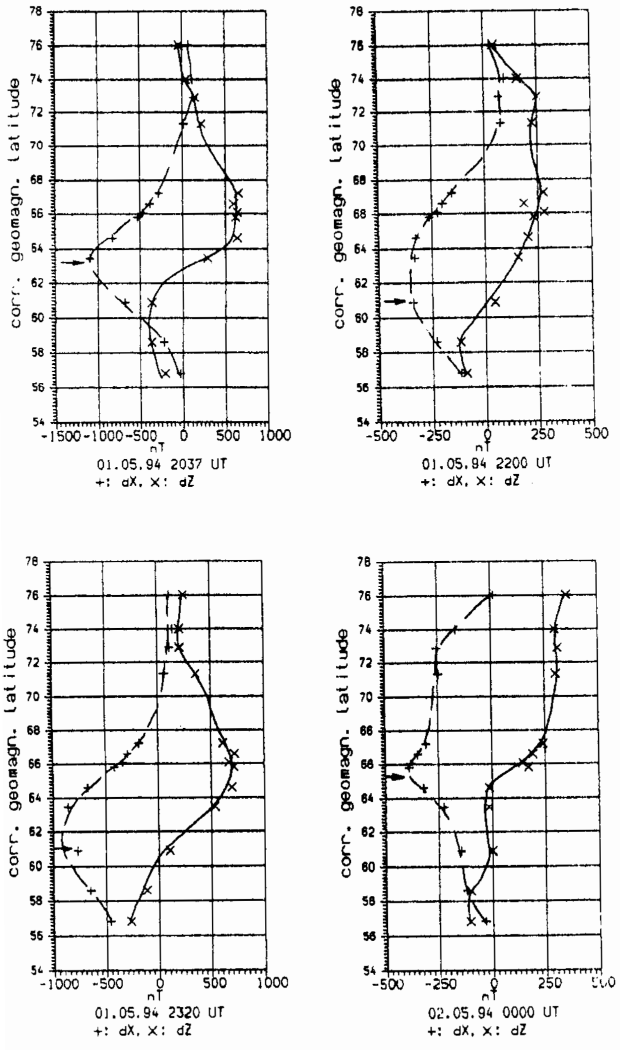

Figure 3. Similar latitudinal cross-sections through the westward electrojet. In the side of the figure cross-section are presented at the moments of quiet intervals between substorms (22.00UT and 24.00UT), in the side of the figure - at the moments of substorms maxima (20.37UT and 23.20UT). Arrows mark latitudes of the westward electrojet center locations where $\Delta Z \sim 0$ nT, $\Delta X < 0$ nT and $/\Delta X/$ has maximum value.

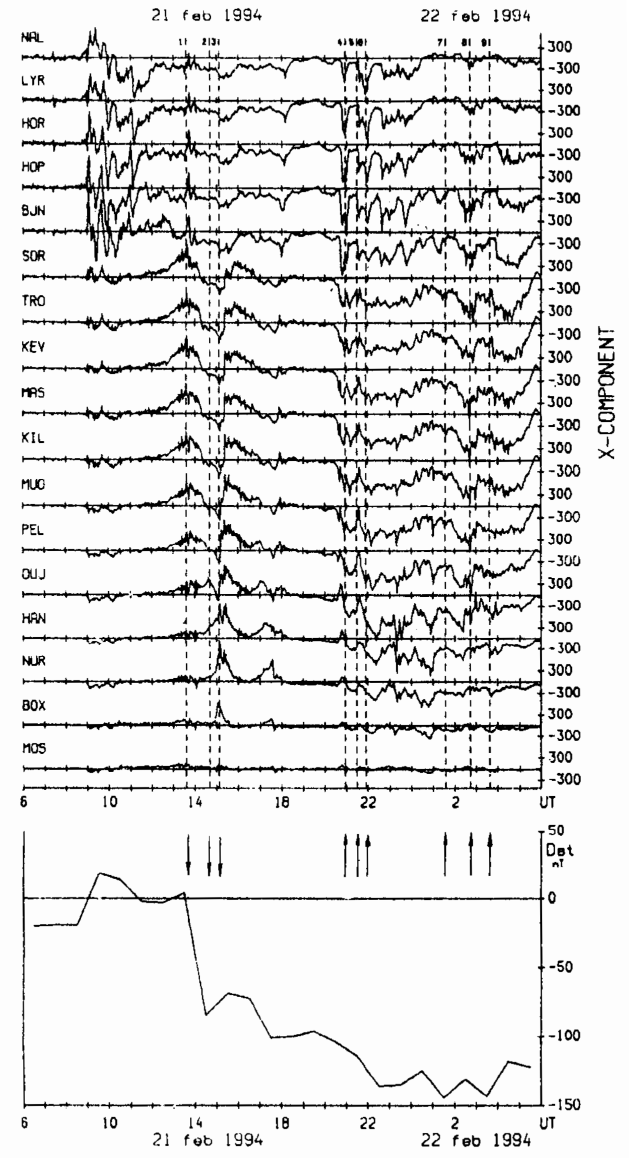

Figure 4. Variations of northern (X) component of the geomagnetic field along the IMAGE digital magnetic stations chain during the main phase of the magnetic storm on February 21 - 22, 1994 (at the top). The variations intensity was measured relative to the quiet level at 6UT - 7UT on February 21. Variations of X component are added for middle latitude stations Borok and Moscow near the IMAGE meridian.
Dst variation of the geomagnetic field for the same storm is presented (at the bottom). Notations are similar to Fig. 1.

In the auroral zone eastern currents are recorded since ~13UT, in the beginning at more high-latitude stations. The equatorward shift of maximum values $\Delta X > 0$ in the interval between 13UT and 15UT is clearly seen. Till ~14.30UT eastern current comprises the whole belt of auroral latitudes $60° < \Phi < 70°$, then in high - latitude region of the auroral zone the magnetic field component decreases to values substantially less than corresponding to quiet level. It testifies on appearance of western current at these latitudes, during which the more is observatory latitude, the earlier time western current is recorded. Only at the most equatorial stations $\Delta X > 0$ in the whole interval 13UT - 15UT. Co-existence of western and eastern currents at one meridian, with western current located poleward of eastern one, testifies on the intersection by the meridional stations chain of Harang discontinuity. At near midnight hours western currents are observed by all stations of the chain.

Latitudinal cross-sections ΔX and ΔZ, when magnetometer chain recorded the eastward electrojet, are presented in Fig.5. The eastward electrojet center shifts from $\Phi = 67°$ at 13.37UT to $\Phi = 57°$ at 15.08 UT. Current direction in the electrojet changes at $61° < \Phi < 70°$ (Harang discontinuity).

Fig.6 shows latitudinal cross-sections ΔX and ΔZ for time moments with the westward current above almost all the chain stations during quiet intervals between substorms (top) and at substorm maximum (bottom). The electrojet centers marked by arrows. In the course of quiet intervals they are located equatorward of their positions during substorms development maxima. Model calculations allow to follow the continuous changes of the electrojet parameters. Grafe et al. (Ref. 9) offered the method of the eastward electrojet parameters determination, namely: width of the ionospheric current layer, the current density, the total current intensity and the position of the electrojet center. The model has the following intrinsic assumptions: i) the electrojet center coincides with the location of the vertical component of ΔZ meridional profile turns to zero ($\Delta Z = 0$): ii) the electrojet flow inside the thin ionosphere layer above the ground at the altitude of 120 km; iii) current has constant density in its meridional profile.

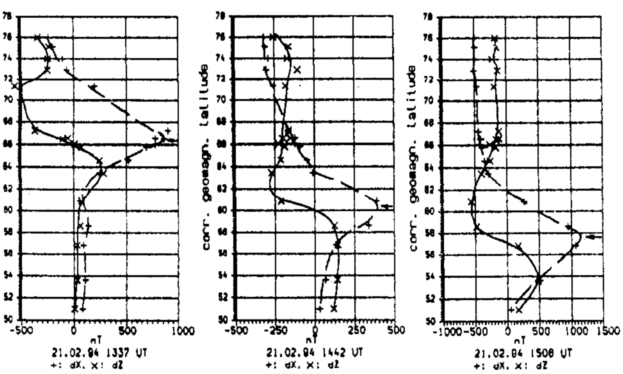

Figure 5. Latitudinal cross-sections ΔX (dotted line) and ΔZ (solid line) through the eastward electrojet on February 21, 1994 at 13.37UT, 14.42UT, and 15.08UT. Notations are similar to Fig. 2.

For infinite current layer with constant current density j the Biot - Savart law gives

$$\Delta X = 2*\mathrm{arctg}(2ch/h^2+l^2-c^2)$$
$$\Delta Z=j*\ln\{[(l+c)^2+h^2]/[(l-c)^2+h^2]\}$$

where c is electrojet halfwidth, h is height of the electrojet, l is horizontal distance of the observation point to the center of the current layer. Given l value from observed meridional profile ΔZ, c can be calculated if j is excluded based on $\Delta X/\Delta Z$ relation.

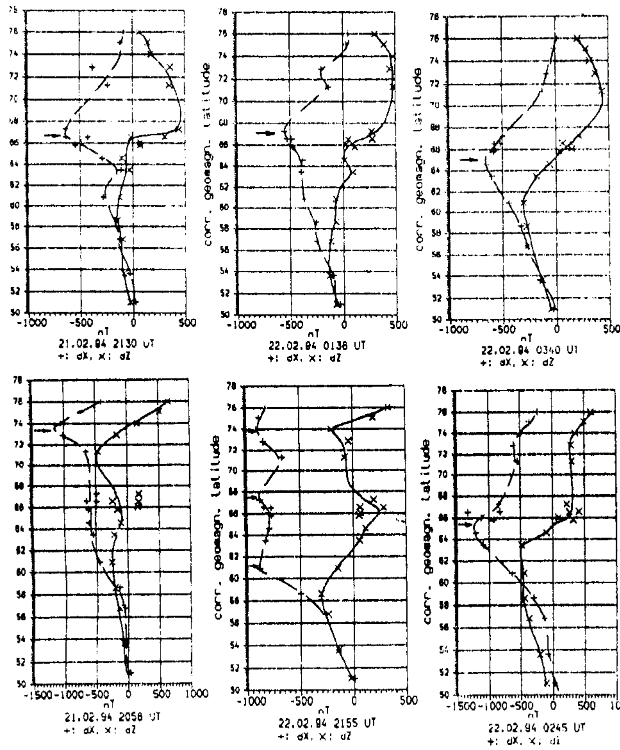

Figure 6. Latitudinal cross-sections ΔX and ΔZ through the westward electrojet during quiet intervals between substorms on February 21, 1994 at 21.30UT and on February 22 at 01.36UT; 03.40UT (top) and at substorms maximum on February 21 at 20.58UT; 21.55 UT and on February 22 at 02.45UT (bottom). Notations are similar to Fig.3.

Then

$$\Delta X/\Delta Z = 2\mathrm{arctg}[2ch/(l^2+c^2+h^2)]/\ln[((l+c)^2+h^2)/((l-c)^2+h^2)]$$

Graphical method was used for c calculations. Fig. 7 contains results of the eastward electrojet parameters calculations for 10 min intervals between 12.00UT and 16.00UT. Practically monotonic equatorward shift of the electrojet center between 12.00UT and 15.00UT is clearly seen. It is very slow in the beginning and sharply accelerates after 14.00UT. Such character of the equatorward shift corresponds to the Dst leap at 14UT -15UT. Subsequent return of the electrojet center to higher latitudes should be connected with Dst - variation intensity decrease and auroral activity level attenuation. The width of the electrojet is ~400 km, current density is ~0.5 A/m, total electrojet intensity may reach maximum of $\sim 10^6$A.

4. DISCUSSION

Consideration of the auroral electrojets dynamics testifies, that their centers shift equatorward during magnetic storms main phases. Fig. 8a,b shows dependencies of such shift on Dst index for the eastern electojet and for quiet intervals between substorms for

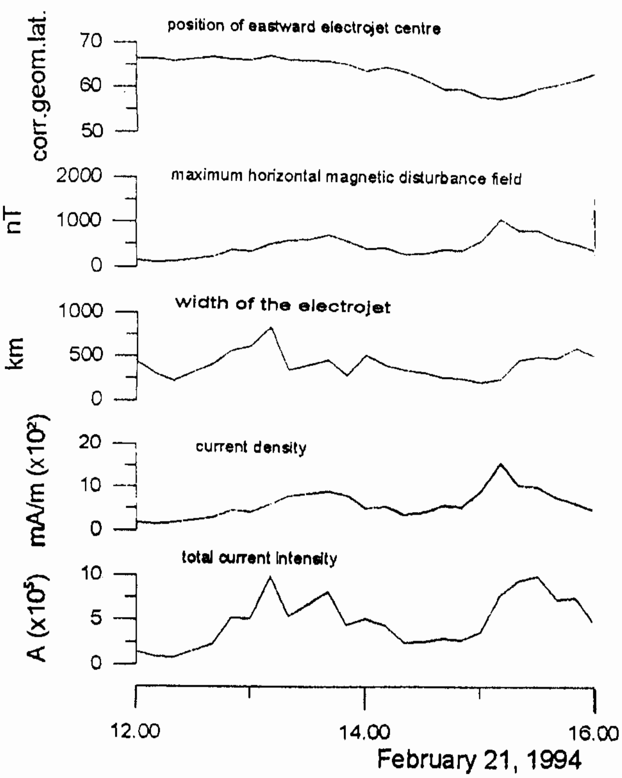

Figure 7. Parameters of the eastward electrojet on February 21, 1994, determined by Grafe et al. (1987) method.

the westward electrojet on the basis of Ref. 5 data supplemented by results of current research.

With Dst variation increase the electrojet centers shift equatorward. Straight line obtained by the least-squares method characterized the linear dependence between the westward electrojet center geomagnetic latitude and Dst intensity. For the eastward electrojet center equatorward shift occurs quickly when Dst is small and decelerates when Dst is large. For both electrojets equatorward shift begins from auroral zone latitudes (Φ ~65° - 67°) and with Dst ~-250nT ends at Φ ~55°. Thus during a magnetic storm main phase it is necessary to take into account subauroral and even middle latitude observatories data for the AE indices calculation.

During substorms on the main phase of magnetic storm the westward electrojet widens poleward covering auroral latitudes. The eastward and westward electrojets location and their dynamics in connection with substorms during a magnetic storm main phase allow to offer a natural interpretation of described in the literature some geophysical effects: AE indices saturation (Ref. 3), the relationship between AU and AL indices during initial and main phases of magnetic storms (Ref. 10). According to Ref. 3 the auroral electrojet index AE tends to saturate for minimum 1 min values of AE, which occurred during each hour

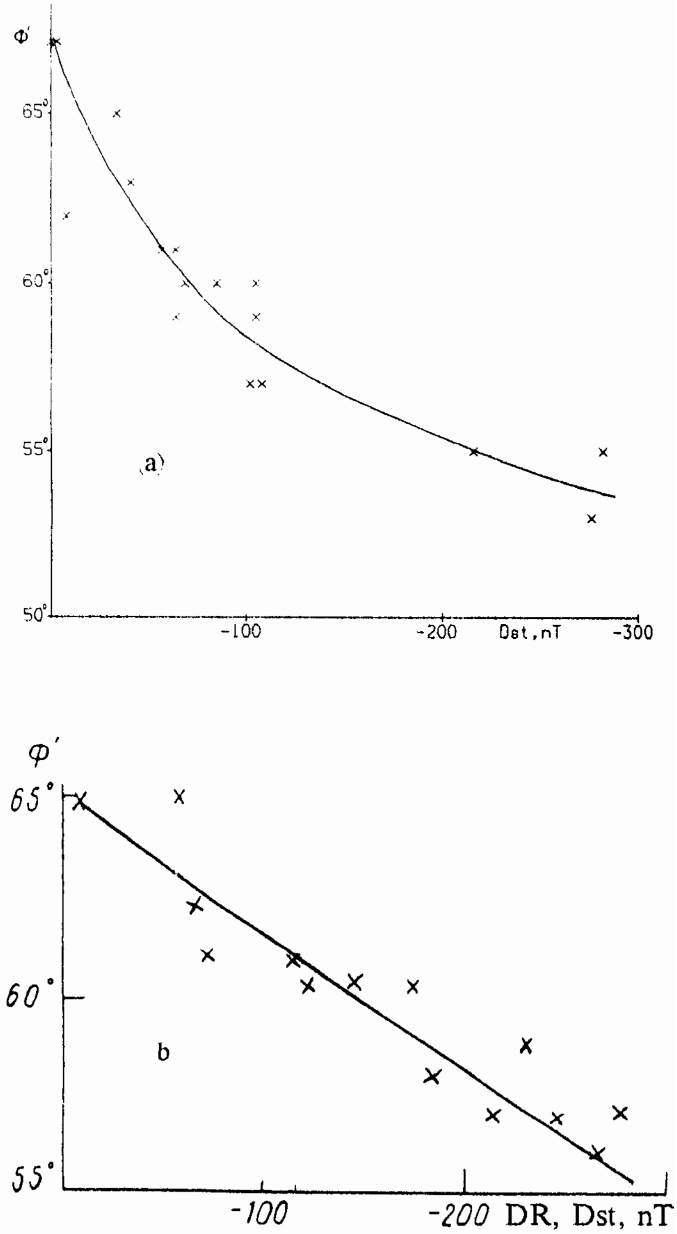

Figure 8. The positions of the eastward (a) and westward (b) electrojets centers as a function of Dst intensity. The straight line for the westward electrojet was obtained by the least-squares method.

and that saturation is absent for the largest 1-min values of AE which occurred during each hour when Bz is southward and has big magnitude, i.e. in the course of magnetic storms main phase. Based on the revealed above electrojet dynamics at a magnetic storm main phase the following interpretation can be offered for Weimer et al. effects. For small AE values, i.e. during intervals between substorms, both the eastward and westward electrojets are located equatorward of the longitudinal chain of auroral observatories for intervals of big southward IMF Bz component and, hence, intensive Dst. In this situation a change of the Bz IMF magnitude does not influence AE intensity, i.e. we have the saturation effect in the AE indices. The maximum of the hour AE indices is related to the sharp poleward widening of the westward electrojet. The chain of AE observatories begins to record the electrojet magnetic field with maximum intensity in close connection with the magnitude of the IMF southward component, i.e. the saturation effect in the AE indices is absent.

Kamide (Ref. 10) discovered interesting peculiarity in behavior of AU and AL indices during magnetic storms, namely, AU ~ /AL/ during initial phase and AU ~0.2/AL/ during main phase. This peculiarity of AU (AL) indices is a consequence of electrojets center dynamics in the course of a magnetic storm. At a storm initial phase, when the ring current is weak so far, electrojets centers are located at AE observatories latitudes and, therefore, AU ~ AE. During the main phase electrojets centers shift equatorward of the AE observatories latitudes, though the westward electrojet simultaneously widens poleward to the AE observatories latitudes. Such dynamics of electrojets is the cause of described in Ref. 10 peculiarly of AU (AL) indices behavior.

It follow from the presented above interpretation, that AU indices during a storm main phase at subauroral latitudes should be several times bigger, than for AE observatories latitudes. Such peculiarity is really observed during magnetic storms. So, for moderate magnetic storm on February 21 -22, 1994 at 15UT - 16UT $\Delta X > 0$ and is about 1,000 nT in Nurmijarvi (Φ = 56.79°), it is only ~300 nT in Tromso (Φ = 66.58°) and Kevo (Φ = 66.15°) observatories. Variations of X-components in Fig. 1 at 10UT - 17UT may be a good illustration of relationship between the eastward and westward electrojets in the evening sector. The westward electrojet in the course of magnetic disturbances is located along the auroral oval, the nature of the eastward electrojet was a theme of discussion (see Ref. 7 and Ref. 8). In Ref. 8 it was assumed, that eastern current in the auroral zone evening sector is a consequence of return via more low latitudes of the westward electrojet currents, which are located in higher latitudes at these MLT hours. Ref. 11 states that the increase of magnetic field horizontal component in the evening sector and stipulated by it eastern current are caused by the eastward electrojet independent on the westward electrojet. Analysis of magnetic field variations interrelationship in the evening sector has shown that the eastward electrojet cannot be the return current of the westward electrojet (Ref. 12, Ref. 13).

At 10UT - 17UT, i.e. from afternoon to evening hours, IMAGE intersected the region of eastern currents. In the auroral zone (60° < Φ < 70°) $\Delta X > 0$ and with intensity of several hundred nT, which is peculiar for the eastward electrojet magnetic fields, was observed at 13UT - 16UT. In the course of this UT interval western currents of any notable magnitude were not recovered poleward of the eastward electrojet up to Φ ~75°. It is a convincing argument in favour of conclusion, that the eastward electrojet cannot be the return current of nonexistent at this time interval of evening MLT hours western current located poleward of the eastward electojet.

5. ACKNOWLEDGMENTS

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