SUBSTORM CURRENT SYSTEMS AND AURORAL DYNAMICS

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Abstract. The implementation of the auroral oval concept lead to a change in the global interpretation of the space-time distribution of geomagnetic disturbances (1963-1965). It was found that along the auroral oval a westward electrojet stretches from midnight to evening sector poleward of eastward electrojet. A slot is produced between the electrojets in dusk sector. The auroral electrojets overlap in the dusk sector, which was supported by other geophysical phenomena accompanying of electrojets. The slot later was named the Harang discontinuity.

During substorms both driven and unloading processes take place. The equivalent current system during substorm growth phase is similar to DP2 current system, which is directly related to the enhancement of the convective electric field and which is controlled by the solar wind parameters. The driven process in the course of substorm is described by a DP2 current system.

The development of the ring current is accompanied by the equatorward shift of the auroral electrojets. During the magnetic storm main phase the auroral electrojet intensity is closely related to the energy flux supplied to ring current.

An interpretation of the patterns for auroral electron precipitations in the high-latitude upper atmosphere in near-midnight sector during quiet and substorm intervals is presented. The diffuse aurora is mapped to the outer radiation belt, the auroral oval of the discrete forms maps to the central plasma sheet, and a soft precipitation band lying just poleward of the oval maps to the boundary plasma sheet in the tail. A summarizing schematic of the polar precipitation regions and their mapping to the magnetospheric plasma domains is presented.

1. Introduction

Almost 30 years ago, during International Conference on Cosmic Rays and Earth Storms in Kyoto [September 1962], S. Chapman in his lecture "Earth storms: Retrospect and Prospect" traced the history of the evolution of ideas about the magnetic storms and substorm current systems (see Chapman [1962]). He focussed on the statistical laws governing the development of the magnetic storm and the equivalent current system, Dst and DS, of the magnetic storm field. He also discussed the possible relationship of magnetic storms to polar magnetic substorms.

This paper is devoted to the description of the further evolution of both statistical and temporal-spatial regularities of the equivalent current systems of geomagnetic disturbances at high latitudes. The interpretation is presented in the context of our understanding of the most intensive particle precipitations along auroral oval. Equivalent and three-dimensional current systems are discussed at different phases of magnetospheric substorms.

The location of the auroral electrojets is controlled by the ring current in inner magnetosphere. For a strong magnetic storm, as an example, there were obtained quantitative relations between westward electrojet shift as subauroral latitudes and the ring current intensity increase, and between auroral electrojets intensity and interplanetary medium parameters. For the main phases of 10 magnetic storms, the relation between the energy injected into the ring current and the energy entered inside the magnetosphere is presented.

The relationship of various auroral luminosity types to the parameters of precipitating auroral electron fluxes are discussed in numerous papers. Consideration was given to the two concepts concerning the conjugacy of the diffuse and discrete auroral features produced by the auroral electron precipitation with different characteristic structures to the magnetospheric plasma domains in the nightside magnetosphere. Possible changes in the large-scale structure of plasma domains from magneto-quiet intervals, through the beginning of substorm, and to the maximum of the expansive phase are described.

2. Electrojets and Auroral Oval

According to Chapman's [1935] idealized equivalent current system for the total disturbance vector, the concentration of currents occur at auroral zone latitudes (the westward and eastward electrojets in the dawn and dusk LT sector). Harang [1946] obtained essential results for the current system morphology using data from a meridional chain of observatories. He found a discontinuity between the westward and eastward electrojets at pre-midnight hours at auroral zone latitudes. The auroral zone is separated into two segments characterizing the eastward and westward electrojets, respectively. In the dusk sectors intensive currents overlap each other, and the westward current is located polewards from the eastward current. However, the same concentration of

Magnetospheric Substorms
Geophysical Monograph 64

equivalent current exists also in the late dusk sector and in the Chapman current system. So Harang's study failed initially to produce any drastic revision of the concepts concerning the high-latitude structure of equivalent currents. The electrojets, as the regions of the highest-intensity currents, continued to be associated with the Fritz-Vestine auroral zone. The earlier concepts were maintained to a great extent, because Harang himself assumed the 67° geomagnetic parallel to be the region of the highest magnetic disturbance along which the auroral electrojets are located.

Burdo [1960] obtained the space-time distribution of high-latitude geomagnetic disturbance field vectors in geomagnetic latitude-local geomagnetic time coordinates. The peaks in the diurnal pattern are located along the spirals extending from the auroral latitudes to the deep inside of the polar cap. However, the Burdo equivalent current system does not, in principle, differ from somewhat modified Chapman system. Namely, the electrojets are located at auroral latitudes, and spread through higher latitudes. The electrojets arise from the dynamo-effect at the ionospheric altitudes. The generation of the electrojets and of the polar magnetic substorm current system was most comprehensively explained in terms of the dynamo-theory for geomagnetic disturbances by Nagata and Fukushima [1952], Fukushima[1953], Cole [1960], and many other researches. Based on the dynamo-theory concepts, Burdo also obtained the three spirals of the highest magnetic disturbances.

So the studies by Harang[1964] and Burdo [1960] have substantiated the fundamental fact that the westward electrojet is not only located within the night-dawn sector of auroral zone; it also extends to the dusk sector at higher latitudes. At the same time, the general opinion of the scientific community that the most active geophysical processes occur on the auroral zone latitudes ($\Phi \sim 67°$) demanded that both eastward and westward electrojets be located within the given zone. A certain concentration of the current lines at higher latitudes was successfully interpreted in terms of the ionospheric dynamo model. The current systems calculated by Fukushima and Oguti [1953] on assumption of an increased ionospheric conductivity along the auroral zone proved to resemble the observed systems both in form and in phase.

The analysis of the observations obtained during the IGY resulted in drastic changes of the concepts concerning the high-latitude auroral distribution. The region of the highest occurrence frequency and of the highest intensity of auroras proved to be oval-shaped. Auroras proved to be closely associated with geomagnetic disturbances. Therefore, the new concept of planetary distribution of auroras resulted in a revision in the early sixties of the earlier concepts concerning the space-time distribution of magnetic disturbances.

From the analysis of the IGY observations of geomagnetic disturbances it followed that the westward electrojet was not located within the night-dawn sector at auroral zone latitudes. It extended to the dusk sector at higher latitudes. In this pattern [Feldstein, 1963] the position of the westward electrojet proves to be closely associated with the position of the auroral oval.

Figure 1a shows the respective equivalent current system of magnetic disturbances observed during winter seasons of the IGY interval. The westward current covers all longitudes. The highest values of the current shift to higher latitudes and decrease in intensity from dawn hours at auroral zone latitudes ($\Phi \sim 67°$) to day hours at $\Phi \sim 78°$, with the currents being closed across polar cap or lower latitudes. In the dusk sector, the westward electrojet is located at higher latitudes compared with the eastern electrojet. The disturbance vector in the horizontal component vanishes on a certain latitude between the two electrojets. A gap between the electrojets is formed in the dusk sector: the latitude of the gap shifts polewards at earlier hours. The given characteristic features of the current system of geomagnetic disturbances was called later the Harang discontinuity. The concept that the westward electrojet is located along the auroral oval and extends to the dusk sector, polewards from the eastward electrojets, during the epoch of substorm maximum was further substantiated and developed by Akasofu et al. [1965] and by other researchers. Figure 1b presents the respective model current system after Akasofu et al. [1965]. The westward electrojet is located along the oval in the dusk sector, at higher latitudes compared with the eastward electrojet. The location of the westward electrojet along the auroral oval is also characteristic of particular disturbances.

After the concept of the auroral oval had been established, the fact that the auroral electrojets overlap in the dusk sector found an obvious interpretation in terms of the general pattern for the occurrence of geophysical events in high latitudes. At the Conference dedicated to Harang's seventieth birthday in 1971, Heppner proposed that the splitting of the ionospheric current system should be called the Harang discontinuity, whereupon the term got commonly adopted .

3. Current Systems During Different Phases of Substorms

The transition from the auroral zone concept to the concept of auroral oval entailed some changes in the spatial regular features of the current system distribution. Other substantial changes have arisen from the development of the magnetospheric substorm concept relevant to quite a complex of events observed on the Earth's surface and in the magnetosphere [Akasofu, 1964, 1968].

Figure 2 presents, after Baker et al. [1984], a schematic pattern of three-dimensional current systems connecting the magnetosphere to the ionosphere during a magnetic substorm. The solar wind-magnetosphere interaction results in separation of charges. The field-aligned currents at the polar cap boundary from the S1 system (a 20-min time constant) are closed by the Pedersen ionospheric currents, by the field-aligned currents at the equatorward boundary of the auroral zone, and by the the partial ring current (the S2 current system: a 1-2-hour time constant). The electric field is directed equatorwards at the dawn side, and polewards at the dusk side. As a result the westward and eastward electrojets of the Hall current are generated in the ionosphere. The current wedge with westward ionospheric current, which is extended far to the dusk sector during active phases of intensive substorms, thereby making the westward and eastward electrojets overlap each other at dusk hours, is located at the poleward side from the convective electrojets in the near-midnight sector.

Substorm evolution is usually divided into three phases, namely, (i) the growth or creation phase when the convection and the associated energy dissipation, as well as the energy accumulation in the magnetospheric tail, get enhanced; (ii) the expansion or active phase when the energy stored in the tail is

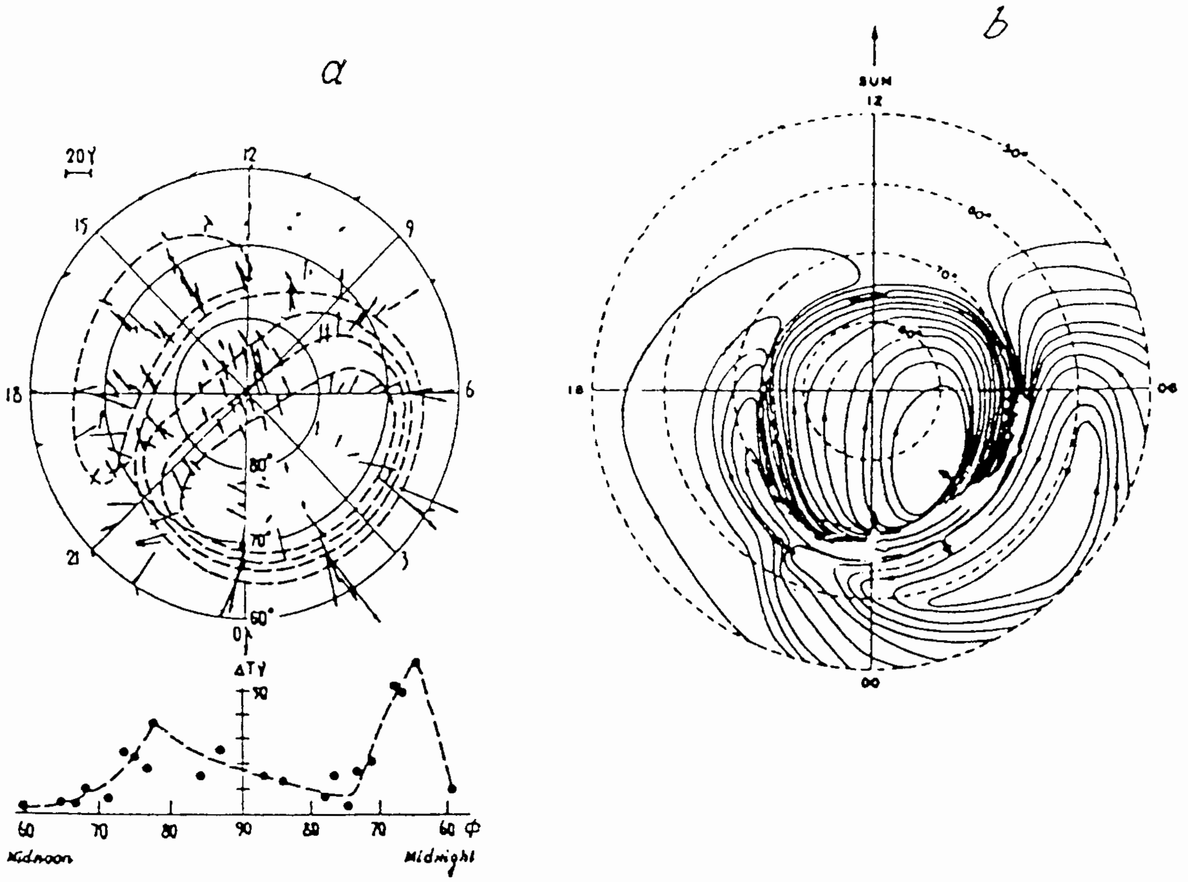

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Fig. 1. (a): First depiction of an equivalent current system with a westward electrojet located along auroral oval [Feldstein, 1963]. Arrows indicate direction and magnetude of ΔT intensity of disturbed geomagnetic field vector in horizontal plane is in nT, between the dashed current lines is 20,000 A. (b): Equivalent current system of DP type geomagnetic disturbances for IGY winter season [Akasofu et al., 1965].

suddenly released and dumped to the ionosphere, thereby intensifying auroras and magnetic disturbances; (iii) the recovery phase when the disturbance decays gradually and the magnetic field on the Earth's surface returns to its initial undisturbed level .

The onset of the substorm creation phase is frequently associated with a southward turn of the IMF. Most of the features of the creation phase result from the enhancement of the electric field of convection related directly to the solar wind and IMF parameters. Therefore, the driven process dominates during the creation phase.

Figure 3, I, II shows, after Lyatsky [1978], the current systems during the initial (Fig. 3, I) and final (Fig. 3, II) stages of substorm creation phase. The S1 current system, shown in the upper part of the figure and associated with enhancement of the solar wind electric field, is formed during the early stage. The magnetic disturbance observed at the beginning of the creation phase on the Earth's surface is described by DP-2 system of the equivalent ionospheric current shown at the bottom in the Fig. 3, I and discovered by Nishida [1966,

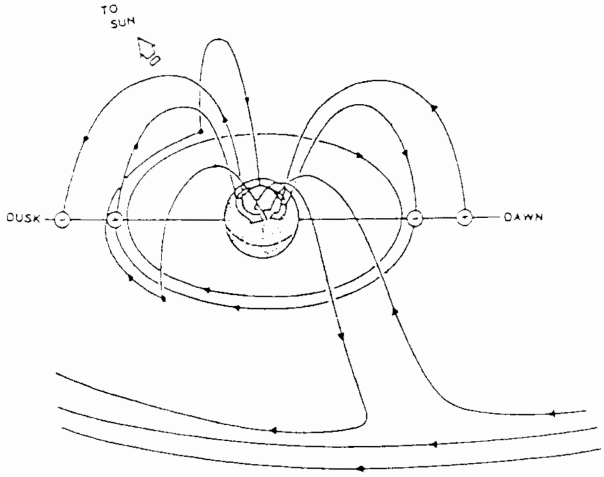

Fig. 2. Three-dimensional current system of magnetospheric substorm active phase [Baker et al., 1984].

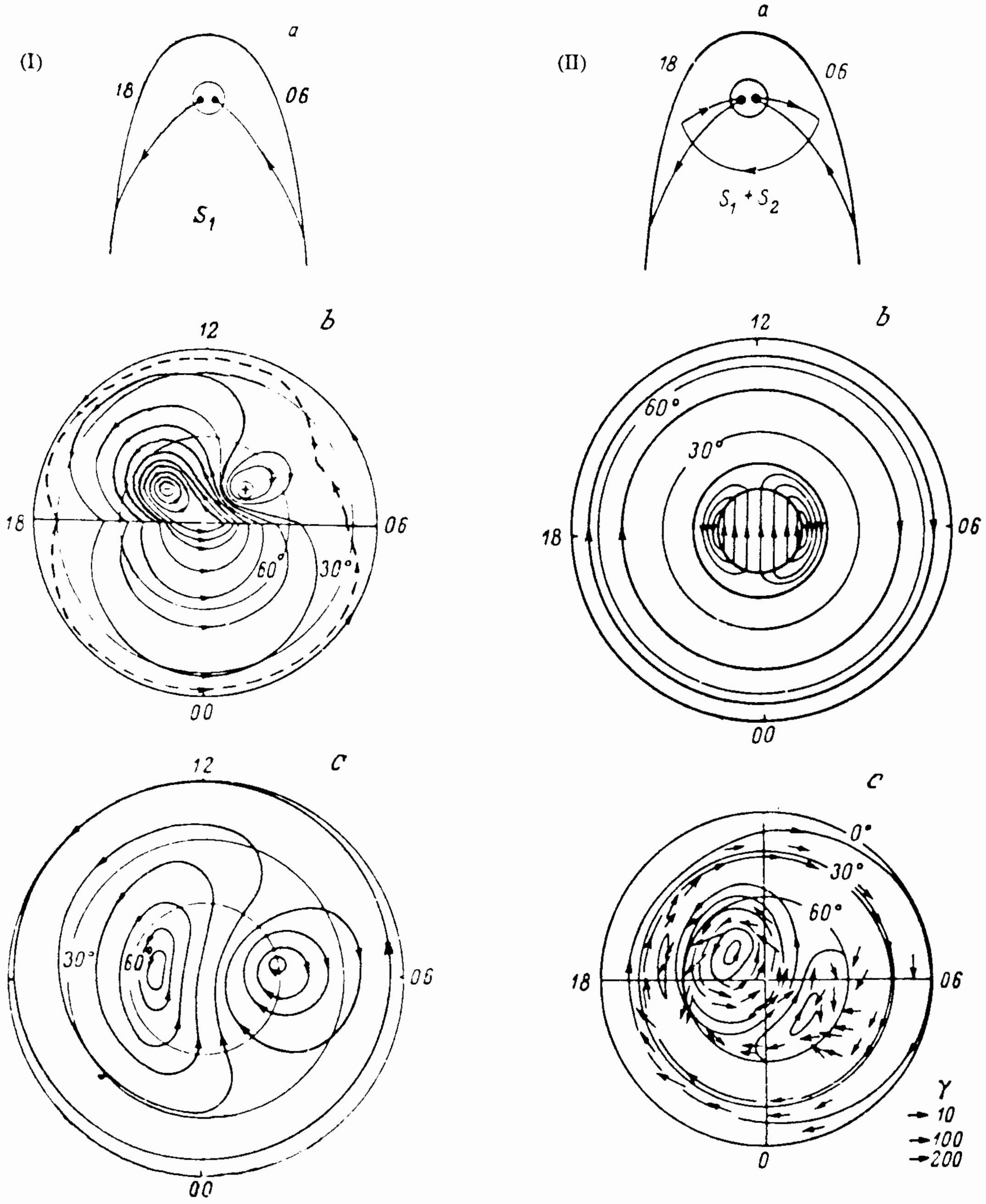

Fig. 3. Equivalent current systems for initial (I) and final (II) stages of substorm creation phase: (a) three-dimensional current system; (b) model equivalent ionosphere current [from Lyatsky, 1978]; (c) equivalent ionosphere current inferred from observations by Nishida et al. [1966] (I) and by Iijima and Nagata [1972] (II).

1968]. The current flows across the polar cap from night to day and is closed through lower latitudes down to the equator without exhibiting any features in the auroral zone.

The current system DP-2 discussed by Nishida is closely connected with southward orientation of IMF(Bz<0). It was first mentioned in the literature in terms of a direct influence of interplanetary medium on fluctuation of geomagnetic field at the Earth's surface. Magnetospheric convection enhancement, which is controlled by IMF Bz<0, is directly connected with driven part of magnetospheric substorm magnetic field.

During the late stage of the creation phase a partial ring current is formed, with field-aligned currents at the equatorward boundary of the auroral zone (the S2 current system in the Fig 3, II). The development of that current system results in middle and low latitudes being shielded from the convection electric field. The magnetic disturbance on the Earth's surface is described by the system of equivalent currents obtained by Iijima and Nagata [1972] and shown at the bottom in the figure. The DP-2 are pushed from middle latitudes to the auroral zone. Equatorward of the latter there are westward azimuthal currents which reflect the magnetic effect of the partial ring current. Analytic model calculations [Lyatsky, 1978] presented in the middle of the Fig. 3, I, II demonstrate that the theoretical and experimental patterns of currents are much alike. The calculations were made assuming that the ionospheric conductivity is uniform at both day and night hours, but suffers a discontinuity at the terminator (in the initial stage of the creation phase) or is uniform (in the final stage of the creation phase).

The substorm expansion phase is associated with a variety of phenomena. These include a rapid decay of the plasma sheet, the restoration of the magnetic field lines extended to the tail to their undisturbed state, rapid plasma motion towards the Earth, intensification of auroras, and the development of a magnetic disturbance on the Earth's surface that is described by a system of equivalent ionospheric currents with a strong concentration of current lines in the auroral zone (the unloading process).

During the expansion phase, the Pedersen and, particularly, the Hall conductivities of the auroral ionosphere increase sharply, thereby giving rise to westward and eastward electrojets. The equivalent ionospheric current system inferred from observations by Iijima and Nagata [1972] is shown at the bottom of Fig. 4c together with the calculation results obtained by Lyatsky [1978] for increased, but uniform (at the top) and nonuniform (at the middle) conductivity in the auroral zone. The main feature of the model current systems consists in the occurrence of two electrojets flowing in the auroral zone towards each other.

During the substorm expansion phase, the poleward region of the westward current, which penetrates deep into the dusk sector , seems to be associated with discontinuity in the currents flowing in the current sheet of the magnetospheric tail and branching to the ionosphere along field lines [Kaufmann, 1987]. A current wedge is formed, with the field-aligned current inflowing to the ionosphere at the eastward end and outflowing from the ionosphere at the westward end of the westward travelling surge. Such an outflowing current is detected during the expansion phase in the vicinity of bright aurora. Using the data from a dense network of magnetometers, of radar measurements of electric fields, and optical observations in the northern Scandinavia, Baumjohann et al. [1981] and Inhester et al. [1981] modelled a three-dimensional current system and obtained a localized,intense field-aligned current flowing out from the ionosphere at the westward edge of active aurora.

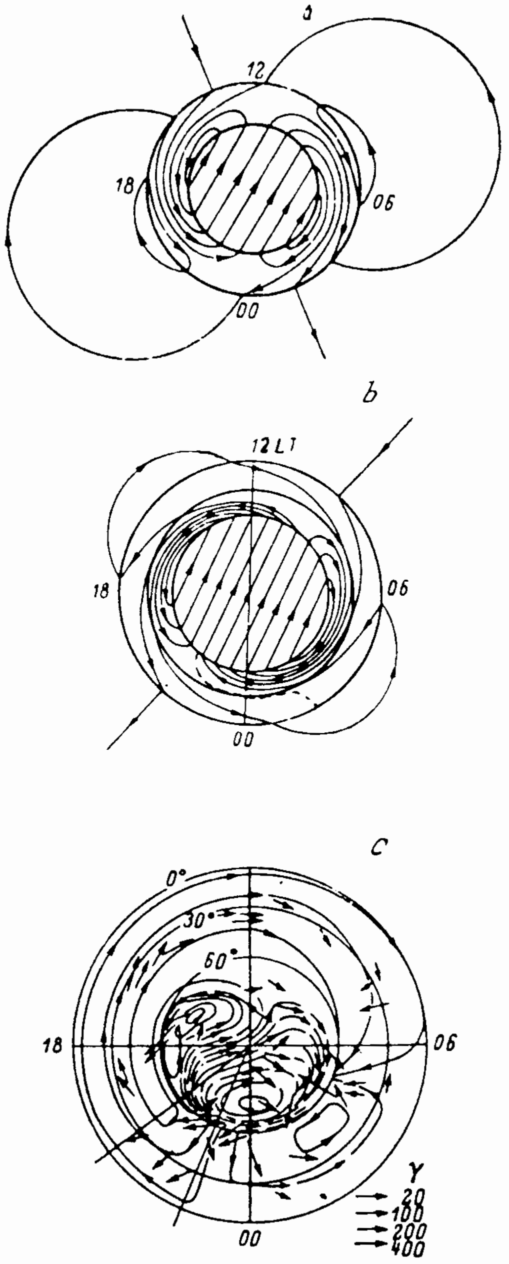

Fig. 4. Equivalent current system of substorm active phase: (a) model equivalent ionosphere current system for enhanced, but homogeneous, conductivity inside the auroral zone; (b) when inhomogeneouty of conductivity inside the auroral zone is taken into account [from Lyatsky, 1978]; (c) equivalent ionosphere currents inferred from observations by Iijima and Nagata [1972].

4. Auroral Electrojets and the Ring Currents-Dependence on the Interplanetary Plasma Parameters

The magnetic storms is the most global geomagnetic phenomenon. It includes the ring current and a number of other geophysical phenomena such as magnetospheric substorms. That is why magnetic storms were an early object of investigations in solar-terrestrial physics. But recently the main attention has turned to magnetic substorms which are assumed to be the elementary events of magnetospheric disturbances. However, a magnetic storm is accompanied by effects indicating that its evolution is different from a simple sum of single substorms. The development of DR in the inner

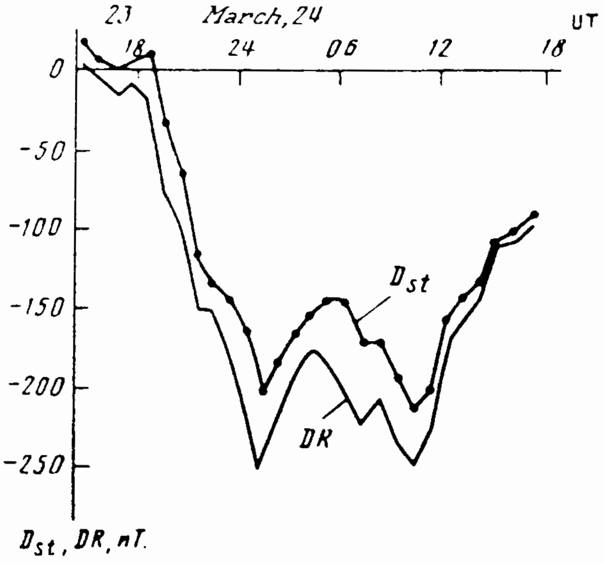

Fig. 5. The variations of Dst and DR magnetic field at geomagnetic equator during the March 23–24, 1969 strong magnetic storm [Sumaruk et al., 1989].

magnetosphere leads to the deformation of geomagnetic field lines, which also affects the location of plasma domains in the magnetosphere [Akasofu and Chapman, 1972]. As a result, auroral phenomena are observed down to middle latitudes. Some aspects of the magnetospheric activity are considered below as exemplified by the magnetic storm of March 23-24, 1969, which attracted the attention of several investigators [Akasofu, 1981a; Tinsley and Akasofu, 1982; Khorosheva, 1986; Sumaruk et al., 1989]. The Dst variation reflects a changing of the intensity of the ring current's symmetric part during the storm. This variation is distinctly traced in the X or H component.

Figure 5 gives the variations of Dst and DR according to hourly values from 11 low-latitude magnetic observatories, spaced rather uniformly with respect to longitude. The DR values were calculated using relation DR = Dst–DCFd+DCFq, where DCF is the magnetic field of the magnetopause current during the disturbed and quiet conditions. The development of DR is accompanied by the intensification of magnetospheric substorm activity, as manifested in auroral electrojet intensifications (the indices AU, AL, AE). The generation of DR and the deformation of geomagnetic field lines shifts the auroral electrojets equatorward. As a result, the AE index, which is based on the geomagnetic field measured at auroral latitude magnetic observatories (the longitudinal chain is at $62 \leq \Phi \leq 70$), ceases to reflect the electrojet intensity. The use of the ΔX and ΔZ latitude profiles in the near-midnight-early dawn MLT sectors at different UT moments has made it possible to find the position of the westward convective electrojet center as a function of DR intensity. Figure 6 according to Sumaruk et al. [1989] presents the position of the convective electrojet center (the time moments before pronounced substorm activizations were selected before the electrojet becomes stratified and the separated fraction begins moving rapidly polewards) as a function of the DR intensity at the UT indicated by numerals at the points. The crosses are the locations of visual aurorae at that time. The electrojet moves to lower latitudes as DR increases and its position is described by the relation

$$\Phi = 65.2^\circ + 0.035\ \mathrm{DR}$$

in the $0 > \mathrm{DR} > -250$ nT interval, where Φ is the corrected geomagnetic latitude in degrees and DR is in nT. Consequently, at DR<–100 nT the western electrojet moves out of the belt of auroral magnetic observatories by which AE indices are defined. Thus to estimate the auroral electrojet intensity during magnetic storms, it is necessary to use either data from subauroral observatories or Z-component variations. This conclusion is in agreement with the analysis by Khorosheva [1986] according to which the electrojets shift out of the belt of auroral observatories at Dst<–40 nT. At values of Dst<–40 nT, AE indices during the magnetic storm interval are defined by using a network of subauroral observatories, and are denoted by AE'.

Let us consider the relationship of magnetospheric activity (estimated in terms of AE' indices) with the energy input function from the solar wind into the ring current. Energy flux into the magnetosphere is controlled by the interplanetary plasma parameters and the IMF. The azimuthal electric field component of solar wind Ey [Burton et al., 1975], the energy flux into the magnetosphere ε [Akasofu, 1981a,b], and the energy flux into the ring current F [Pisarsky et al., 1989] are accepted below as geoeffective characteristics. Pisarsky et al. [1989] assumed the energy flux function $F=F(B_z,\sigma,v)$ and determined its functional form by comparison between the observed and modelled DR variations for some dozen of magnetic storms. The functional form F is given as $F=8.2(B_z-0.67\sigma)\cdot v\cdot 10^{-3}-14.1(v-300)\cdot 10^{-3}+9.4$, where F in nT·h, Bz and σ (standard deviation of B) in nT, v in km·s^{-1}.

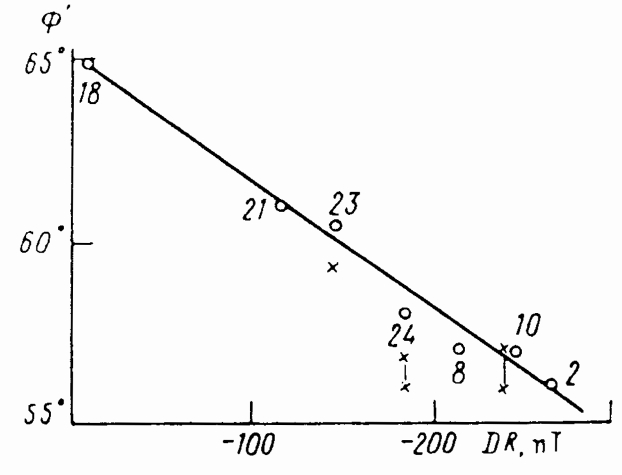

Fig. 6. The position of the westward convective electrojet center in the near-midnight-early dawn MLT sector as a function of DR intensity. The numerals at the dots are hours of UT. The straight line has been obtained by the least squares method [Sumaruk et al., 1989].

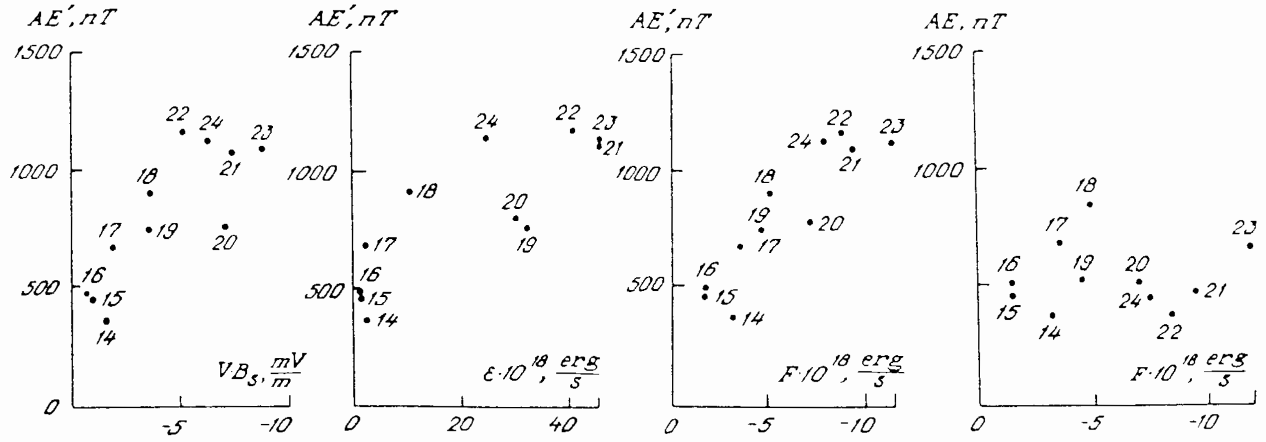

Fig. 7. Intensity of the hourly AE' indices of auroral electrojets versus different combinations of geoeffective parameters in the solar wind which characterize the energy fluxes during the March 23–24, 1969 storm main phase. The solar wind parameters lead the AE' index by 1 hour. The numerals are hours of UT. The right-hand side shows the same for the standard AE index.

Figure 7 gives the dependences of hourly values of AE' on Ey, ε and F also of AE on F. The geoeffective characteristics lead the AE' or AE indices by 1 hour.

All three characteristics are positively correlated with AE' namely with intensifying Ey, ε, or F the AE' index increases. During the storm recovery phase (when all the three characteristics are close to zero) AE' is also small. The linear regression equations and correlation coefficients are as follows:

$AE'=86.6\cdot(Bs\cdot v)+443$; $r=0.82\pm0.1$ at $/Bs\cdot v/\geq 1\,mV/m$

$AE'=13.0\varepsilon+527$; $r=0.82\pm0.1$ at $\varepsilon\geq 2\cdot10^{11}W$

$AE'=81.9F+326$; $r=0.9\pm0.08$ at $|F|>10^{11}W$

Here AE' is in nT, Bs·v is in mV/m, ε and F are in 10^{11}W.

While the correlation between AE' and all three geoeffective characteristics is high, it is highest between AE' and F. This means that during the storm main phase the auroral electrojet intensity is closely related to the energy flux supplied to ring current. It is no surprise that at low latitudes the field decrease (being a generally accepted indicator of a magnetic storm) occurs during the same time interval when intensive electrojets appear. Due to this fact, the close correlation between substorms and ring current generation takes place at the level of hourly values. The same fact can explain a wide-spread opinion that magnetic storms are nothing else quickly recurring intense substorms.

The relationship of AE' to F makes it possible to estimate the real hourly values of AE' indices during magnetic storm intervals if the interplanetary medium parameters are measured during the intervals. In such cases, the data from the network of subauroral observatories, which contribute much to the AE' values because of the equatorward shift in the electrojet as the ring current develops, must no longer be processed separately.

It should be pointed out that there is approximately a factor of four difference between the absolute values of ε and F characterizing energy fluxes in Fig. 7. Taking into account the fact that the input function F used in the present investigation generates the outer and inner parts of DR field, and that the ratio of the parts is 2, the difference between ε and F increases up to a factor of 6. The relationship between ε and F is defined more accurately according to the hourly values for the main phase intervals of 10 magnetic storms (Fig. 8). The linear relationship between them is obtained by the leaset square method $\varepsilon=(6.6\pm-0.3)F+(0.3\pm0.3)$, where ε and F are in 10^{11} W, r=0.9±0.05. Almost the same relationship is valid for each individual storm. Thus, only 15% of the value ε comes to the ring current. The difference between ε and F is surely caused by the fact that ε characterizes the total energy flux from the solar wind into the magnetosphere, whereas the value F characterizes the energy flux into the ring current. It is also probable that a difference between ε and F is connected with the fact that ε is only one estimate of the energy into the magnetosphere. F has also been calibrated against the particle energy in the ring current on the basis of Desseler-Parker-Sckopke theorem [Olbert et al., 1968]. Figure 7 also shown the dependence on F of the standard index AE according to Allen et al. [1974] for the previous hour during the storm main phase. The limitation of the observatory network in the auroral zone not only significantly underrates the AE index intensity, but leads to a noticeable spread in the points in the plot. The absence of a correlation between AE and F (r=0.08) can result in a wrong conclusion that the auroral electrojet intensity is not connected with injection into the ring current. When looking for a possible relation between the AE index and the interplanetary medium parameters for a given storm, one can perform an analysis to determine the confidence of the AE index series available. In a number of investigations, no relationship or a weak relationship could reflect nothing more than the need to improve the technique for determining the indices characterizing the auroral electrojet intensity. As an example of an improved technique, the AE' results in a sharply increased of correlation with the interplanetary medium parameters (see Fig. 7). The low AE correlation with the interplanetary medium parameters obtained by Gonzalez et al.

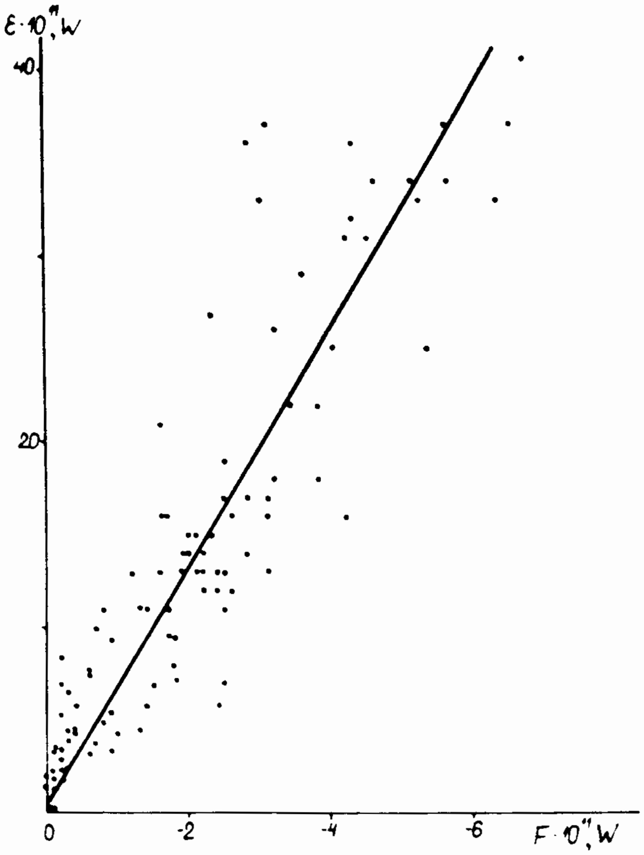

Fig. 8. Dependence of ε on F values during the main phase of 10 magnetic storms. The solid line represents the linear regression equation.

[1989] for the main phase of several magnetic storms can just be explained by the fact that Gonzalez et al. used the auroral observatory data only to calculate the AE index.

5. The Auroral Precipitation and Auroral Luminosity in Connection with the Large Scale Dynamics of Plasma Regions in the Magnetospheric Tail During Substorms

Substorm generation in the magnetosphere is closely associated with the variations of the space-time distribution of charged particle precipitations to the upper atmosphere [Akasofu and Chapman, 1972; Akasofu, 1977; Nishida, 1978; Kamide, 1988].

The relationships of various auroral forms to the parameters of precipitating auroral electron fluxes were discussed by Feldstein and Galperin [1985] and by Galperin and Feldstein [1990]. They examined two patterns discussed elsewhere for the relationships between the diffuse and discrete auroral forms produced by precipitation from plasma regions in the night-time magnetosphere during different phases of a substorm. The pattern proposed by Winningham et al. [1975], by Lui et al. [1977], and by Eastman et al. [1985] was used extensively to interpret the observations, including the latest DE, DMSP, and Viking experiments. The alternative pattern based on the results obtained by Vasyliunas [1970], Feldstein and Starkov [1970], and Lassen [1974] has proved to give the most comprehensive description of the atmospheric luminosity and auroral electron precipitation.

Figure 9 a, b presents the inferred latitudinal morphological patterns of auroral electron precipitations during various substorm phases [Winningham et al., 1975; Feldstein and

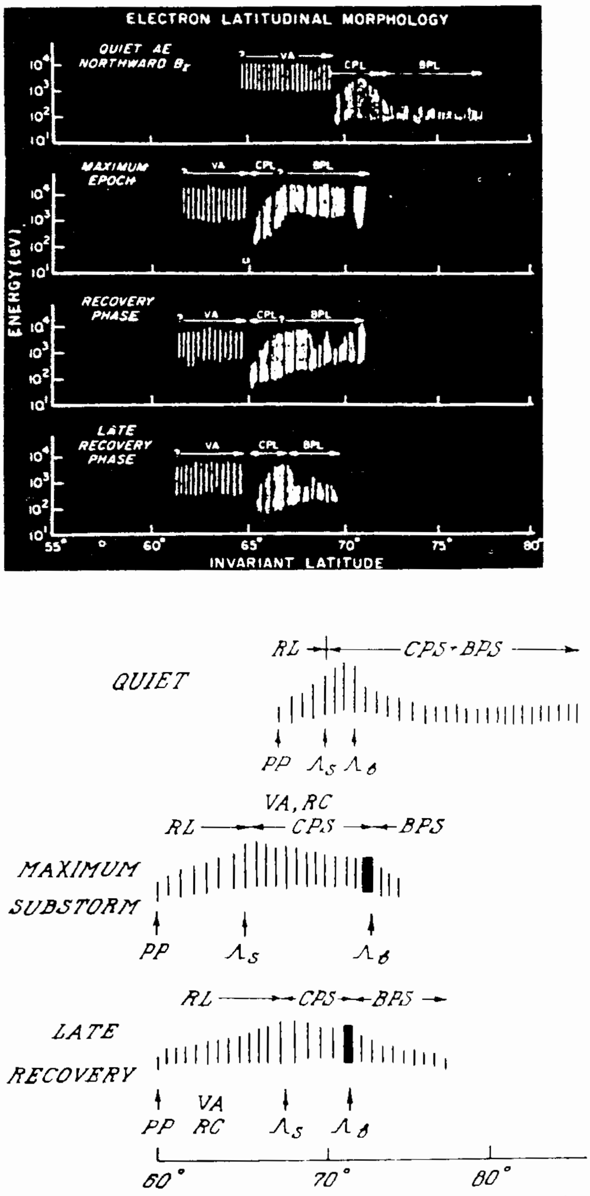

Fig. 9. Schematic representation of the latitude morphology of various types of auroral electron precipitations during different substorm phases and their assignment to generic magnetospheric plasma domains according to Winningham et al. [1975] (a. above) and their reassignment according to Feldstein and Galperin [1985] (b, below).

Galperin, 1985] in the quiet conditions-disturbance peak-recovery phase format. According to Winningham et al. [1975], the precipitations from the central plasma sheet (CPS) give rise to diffuse auroral luminosity, while the precipitations from the boundary plasma sheet (BPS) are associated with discrete auroras (arcs and bands) and cover the poleward region of the auroral electron precipitation zone.

As shown in Fig. 9 a, b, the equatorward region of the precipitation zone contains the electrons whose spectrum gets soft with decreasing latitude (CPS in Fig. 9a and remnant layer RL in Fig. 9b). The diagrams in Fig. 9a and in Fig. 9b differ substantially in that the given precipitations occur polewards from the outer radiation zone (VA in Fig. 9a), but within the radiation zone, equatorwards from the boundary of stable trapping of high-energy electrons, Λs (RL in Fig. 9b). In the pre-midnight sector, this region coincides with zone 2 of field-aligned current (inflowing to the ionosphere in the dusk sector) which is mapped spatially [Roelof, 1989; Iijima et al., 1990] to the zone of ring current (RC) in the inner magnetosphere. This particular type of auroral electron precipitations with a softening spectrum is observed up to the plasmapause (PP) and gives rise to diffuse aurora, while the similarity between the electron spectra in conjugate regions above the ionosphere and in the equatorial plane of the magnetosphere indicate that any potential difference is absent along magnetic field lines. In Fig. 9a, the diffuse aurora is located poleward of Λs, i.e. from the boundary of stable trapping of ≥35 keV electrons, whereas in Fig. 9b the boundary Λs separates the diffuse aurora region located equatorward of Λs and the discrete aurora region located poleward of Λs.

The second substantial difference in the patterns shown in Fig. 9a and in Fig. 9b is that the discrete aurora region is mapped spatially to the CPS (Fig. 9b), rather than to the BPS (Fig. 9a). In the case (i) we avoid the difficulties arising from the necessity to interpret the closing of the major magnetic field flux during active substorm phase from the night-time sector of auroral oval through a sufficiently thin (~0.5–2.0 Re) BPS: (ii) an intensive and long-lived active discrete aurora which form the polar edge of the auroral bulge is mapped on the above mentioned thin layer in the magnetospheric tail [Frank and Craven, 1988] where high-velocity plasma streams are observed [Huang and Frank, 1986]. The given auroral arc is shown in Fig. 9b with black rectangle; (iii) during a quiet interval, the near-midnight sector contains but a single auroral arc on $\Phi \sim 70°$ which is difficult to identify with the BPS extending from $\Phi \sim 71°$ to $\Phi \sim 77.5°$(Fig. 9a).

The third substantial difference in the examined patterns is that a soft precipitation band with an almost isotropic pitch-angle distribution and a falling spectrum without field-aligned acceleration exists continually in Fig. 9b poleward of the discrete aurora region. The band is broad during the magnetically-quiet interval and narrow during the active substorm phase. In Fig. 9a, such a soft precipitation is absent during the substorm and is associated with discrete auroral forms during quiet interval. According to the pattens shown in Fig. 9a, b, they differ by the character of the relationships of BPS to various luminosity types (precipitations), namely, the BPS is associated with discrete forms (with accelerated electrons) in Fig. 9a and with diffuse aurora (with soft precipitations) is Fig.9b. The occurrence of the BPS-forming auroral electron precipitations poleward from the most equatorward auroral arc in Fig. 9b indicates that the substorms are initiated deep in the plasma sheet, rather than near the plasma sheet boundary.

The auroral electron precipitation patterns shown in Fig. 9a, b at different activity levels reflect the existence of different ideas concerning the localization of the substorm generation onset region, namely, in the remote magnetotail region (a substorm begins in the BPS) or in the inner magnetosphere (a substorm begins at the boundary between the regions of discrete and diffuse auroral forms where an auroral arc is located at the inner boundary of the CPS).

Figure 10a, b presents the scheme of the meridional cross sections of the plasma domain locations in the night-time magnetosphere during the pre-storm quiet period and during the substorm development maximum which correspond to the above mentioned localization ideas.

According to the scheme shown in Fig. 10a [Lyons and Nishida, 1988; Nishida, 1988], the substorm begins along the magnetic field lines threading the BPS and located near the plasma sheet boundary. The substorm onset is due to formation of a new neutral line (NNL) within the magnetotail current sheet which is the source of isotropic precipitation of accelerated ions to the night-latitude atmosphere. Actually, the auroral arcs occur always on the field lines which include the isotropic ion precipitations from the current sheet [Lyons and Evans, 1984; Lyons et al., 1988].

An alternative dynamical process in the magnetospheric tail during a substorm is shown schematically in Fig. 10b. During quiet intervals, the auroral arc occurs at the boundary of stable trapping of high-energy electrons, Λs, which is due to a pronounced curving of magnetic field lines because the current sheet is located near the magnetotail neutral sheet (NS). The CPS located on either sides from the NS is filled with low-energy auroral plasma up to the magnetic field line mapped on the distant neutral line (DNL). The auroral electrons responsible for soft precipitations up to very high latitudes precipitate from throughout the given region to the ionospheric altitudes.

The onset of the auroral substorm expansive phase is marked with brightening or splitting of an existing arc, i.e. deep inside the magnetosphere, near the inner boundary of the plasma sheet, rather than in the periphery of the latter. The substorm expansive phase onset results from violation of the magnetospheric electrodynamic configuration stability inside the closed magnetosphere, thereby giving rise to a discontinuity in the large-scale current flowing across the magnetospheric tail [Kaufmann, 1987]. Such a discontinuity, as well as a branching of a current fraction from the tail to the altitudes of the auroral ionosphere, occur on the earthward side of the plasma sheet. Feasible mechanisms of substorm generation near the inner boundary of the plasma sheet were proposed by Lyatsky [1987], Trakhtengerts and Feldstein [1988], Kan et al. [1987], and Rothwell et al. [1988]. The substorm onset at the inner boundary of the plasma sheet coinciding with the McIlwain injection boundary [Mauk and McIlwain, 1974; Feldstein and Galperin, 1985] removes the contradiction [Siscoe, 1988] between the widely-adopted idea that the discrete auroral forms are mapped on BPS and the fact of substorm onset at the inner boundary of injection.

We assume the following sequence of events in the evolution of a substorm active phase. The expansive phase

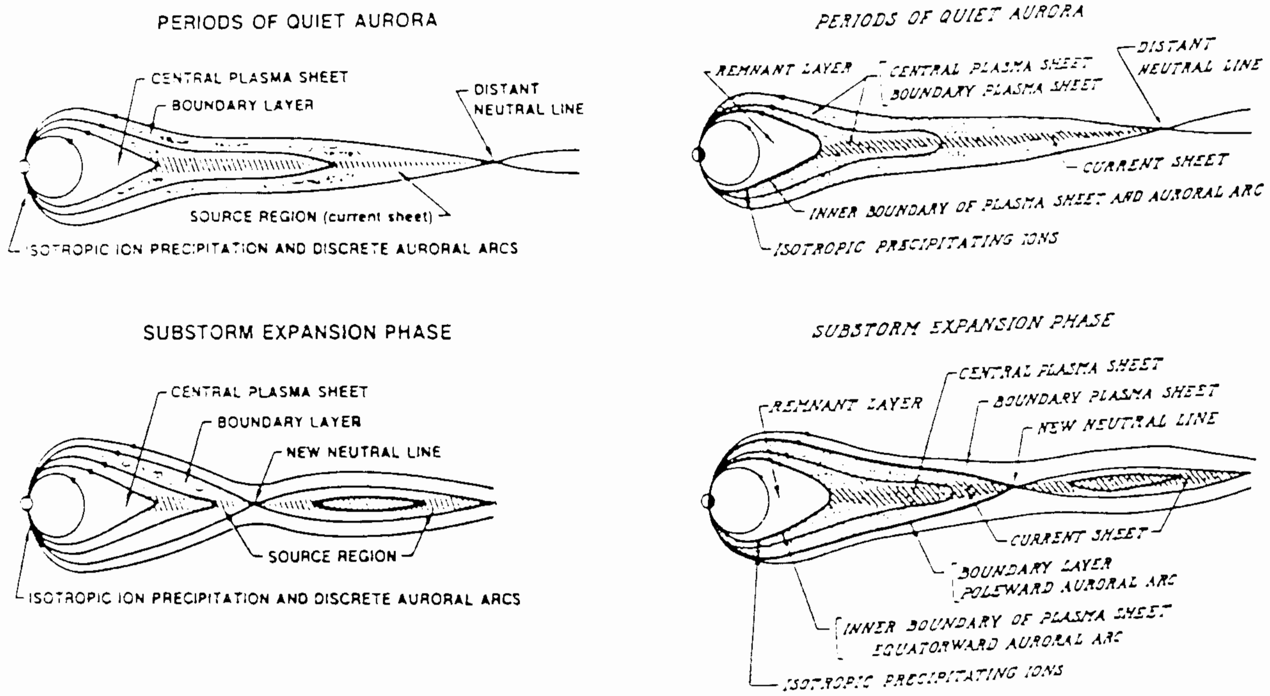

Fig. 10. Schematic representation (not to scale) of the magnetospheric tail plasma domains and some structural features of the magnetotail in the interval of quiet auroras before a substorm onset (at the top) and during substorm expansion phase (at the bottom) according to Lyons and Nishida [1988] on the left (a) and Feldstein and Galperin [1991] at the right (b).

originates deep in the magnetosphere, near the inner boundary of the plasma sheet. The onset is characterized by a brightening of the equatorial arc, or by the occurrence of new nearby arc, which forms the poleward edge of auroral bulge moving to higher latitudes. The movement corresponds to an increase of the geocentric distance of the magnetotail region magnetically connected to the arc. At some time a NNL can be formed across the tail. The NNL is formed at L~18 because of the persisting thinning of the plasma sheet at that distances during the expansive phase [Hones et al., 1984], although the plasma sheet on lower L-shells begins thickening in connection with formation of the auroral bulge. The occurrence of the NNL gives rise to a plasmoid moving rapidly away from the Earth. As a result the plasma sheet gets thicker, thereby giving rise to a pronounced increase of the velocity of the motion of the poleward auroral arc to higher latitudes [Hones, 1985]. Weak substorms may not be accompanied by NNL formation, so they evolve without any rapid jumps polewards [Craven and Frank, 1985; Anger et al., 1987]. Formation of a NNL some time after the onset of substorm expansive phase at a geocentric distance L >18 removes the difficulties [Siscoe, 1988] arising from the NNL formation deep in the plasma sheet at L~8.

During the active period, discrete auroral forms occur in the latitude interval that maps to the magnetospheric tail limited by the equatorial arc projection and by a magnetic field line running through the NNL. In this case the active aurora at the poleward edge of the auroral bulge is mapped on the ionospheric altitudes of the NNL. The mechanism of poleward arc excitation in some substorms differs from electron acceleration in the inverted - V structures for the arcs in the auroral oval. This characteristic feature is responsible for the often persistent conservation of intense auroras at the poleward edge of the auroral bulge.

High-velocity plasma stream during disturbed period were detected not only in the plasma sheet boundary layer, but also near the neutral layer [Baumjohann et al., 1990]. Having been generated near current sheet, the high-velocity plasma streams begin penetrating the entire plasma sheet during substorms, when the active discrete auroral forms are observed throughout the auroral oval. The existence of fast-ion fluxes throughout the plasma sheet at great geocentric distances has been inferred from the analysis [Nishida et al., 1988].

The auroral precipitations from the BPS with its poleward boundary along the line mapped on the DNL will form the soft precipitation region polewards from the auroral oval which will exist during both quiet and disturbed intervals. It cannot be excluded that the BPS will actually disappear during the maximum of strong substorms when the NNL moves away from the Earth to great distance.

The proposed model is one of the versions of the substorm evolution pattern involving formation of a neutral line within the magnetotail current sheet which, in turn, is a modification of the pattern [Lyons and Nishida, 1988] to be brought in agreement with the pattern presented in Fig. 1b. Though Lyons and Nishida [1988] consider the neutral-line formation within the CPS to conflict with the well-known experimental facts, we assume that:

(1) an NNL occurs deep in the central zone of the plasma sheet, rather than in the periphery of latter, within a certain period after the onset of substorm active phase. The CPS covers the magnetotail current sheet on two sides, wherein the substorm neutral line is just formed. The CPS is separated from the tail lobes by the BPS;

(2) the substorms development is not always associated with the NL occurrence. This relates in particular, to weak substorms;

(3) during quiet intervals the discrete auroral arc is mapped by magnetic field lines to the earthward region of the current sheet, rather than to the outer periphery of the latter. The occurrence of such an arc seems to be associated with the extreme values of field-aligned currents near the inner boundary of CPS. The soft diffuse precipitation zone mapped on the tail up to the DNL is located poleward from the arc which may be solitary during quiet interval. During the substorm expansive phase, the discrete arcs are located in the region that maps to the magnetospheric tail between the earthward part of the current sheet and the NNL, i.e. the entire CPS;

(4) the active aurora, which forms the poleward edge of auroral bulge, seems to be mapped to ionospheric altitudes by the magnetic field lines of the NNL in the magnetospheric tail, i.e. is the internal magnetospheric singularity irrelevant to solar wind;

(5) the soft auroral electron fluxes and the faint luminosity polewards from the poleward arc are due to precipitations from the BPS whose external surface is mapped on the DNL. Thus, the magnetotail region where the most active processes occur is located deep in the plasma sheet, rather than in the periphery of the latter. This fact may be treated to indicate indirectly that the energy released during substorm expansion phase is supplied mainly by unloading process of releasing the energy accumulated earlier in the magnetospheric tail, rather than from solar wind (the driven mechanism). Therefore, the BPS is not the channel of direct energy transfer from solar wind to the magnetosphere. The fast ion fluxes in the CPS, the external region included, occur during the substorm active phase because of dissipation of the solar wind energy accumulated earlier in the tail in the form of magnetic field and released during the expansive phase;

(6) the substorm generation processes occur within the region of closed magnetic field lines, for the lines get closed in the night-time magnetosphere throughout the whole plasma sheet, the boundary plasma layer included.

Conclusion

1. The transition from a concept of an auroral zone to a new concept of an auroral oval demanded changes in the planetary scheme of space-time distribution of geomagnetic disturbances. Such a planetary scheme was proposed in early sixties and its peculiar feature was existence of westward electrojet along auroral oval. In dusk sector the westward electrojet is located poleward of eastward one, and the latitude of the westward electrojet increases as it shifts towards earlier hours of local time. A slot is produced between the electrojets in dusk sector. The slot later was named the Harang discontinuity. After the auroral oval concept had been established, the fact that auroral electrojets overlap in the dusk sector found its quite obvious interpretation in terms of the general pattern for the occurrence of geophysical events in high latitudes.

2. Substorm current systems are different during growth and expansion phases. During the growth phase the driven process dominates, which is directly related with the enhancement of the convective electric field, controlled by the solar wind parameters. The equivalent current system during the start of the growth phase is similar to DP-2 current system. It embraces the whole glove from the pole to the equator without current increase in auroral zone. During the active phase unloading processes prevail, manifested by the release of stored in the magnetotail energy, sharp increase of conductivity at high-latitudes and the generation of westward and eastward electrojets.

3. The development of DR is accompanied by the intensification of magnetospheric substorm activity, as manifested in auroral electrojet intensifications. The auroral electrojets shifts equatorward. As a result, the AE index ceases to reflect the electrojet intensity. To estimate the auroral electrojet intensity during magnetic storm it is necessary to use data from subauroral observatories (AE' index).

This new index is closely connected with interplanetary medium parameters. The highest correlation is between AE' and the energy flux F into the ring current. This means that during the magnetic storm main phase, the auroral electrojet intensity is closely related to the energy flux supplied to ring current. The close relationship between AE' and F makes it possible to estimate the real hourly values of AE' indices during magnetic storm interval if the interplanetary medium parameters are measured during those intervals. If energy flux into the mag-netosphere is determined by Akasofu parameter ε, then only approximately 15% of the ε value is injected into the ring current.

4. An interpretation is presented of the patterns for auroral electron precipitations to the high-latitude upper atmosphere in near-midnight sector as an alternative to the one commonly accepted. The model differs from that of Winningham et al. [1975] that in the near-midnight sector, the diffuse aurora is mapped to the outer radiation belt rather than the CPS, and the oval of the discrete forms maps to the CPS proper, but not to BPS. A diffuse precipitation band lying just poleward of the oval maps to the BPS in the tail.

An active aurora during an expansion phase which forms the expanding poleward border of the auroral bulge maps to the border between CPS and BPS. In this region of the tail Eastmann et al. [1985] and other have observed ion beams and plasma flow irrespective of activity. But during a substorm active phase such high speed flows, sometimes very localized, were observed throughout the CPS by Baumjohann et al. [1990].

A summarizing schematic of the polar precipitation regions and their mapping to the magnetospheric plasma domains is presented. It can be considered as a modification of the Lyons-Nishida [1988] scheme for magnetospheric plasma domains, and it characterizes the relationship of the gross magnetospheric structure to region of the auroral electron precipitations in the upper atmosphere.

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