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Spiral regularities in magnetic field variations and auroras

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Abstract. The conception of spiral shaped precipitation regions, where solar corpuscles penetrate the upper atmosphere, was introduced into geophysics by C. Størmer and K. Birkeland at the beginning of the last century. Later, in the course of the XX-th century, spiral distributions were disclosed and studied in various geophysical phenomena. Most attention was devoted to spiral shapes in the analysis of regularities pertaining to the geomagnetic activity and auroras.
We review the historical succession of perceptions about the number and positions of spiral shapes, that characterize the spatial-temporal distribution of magnetic disturbances. We describe the processes in the upper atmosphere, which are responsible for the appearance of spiral patterns. We considered the zones of maximal aurora frequency and of maximal particle precipitation intensity, as offered in the literature, in their connection with the spirals.
We discuss the current system model, that is closely related to the spirals and that appears to be the source for geomagnetic field variations during magnetospheric substorms and storms. The currents in ionosphere and magnetosphere constitute together with field-aligned (along the geomagnetic field lines) currents (FACs) a common 3-D current system. At ionospheric heights, the westward and eastward electrojets represent characteristic elements of the current system. The westward electrojet covers the longitudinal range from the morning to the evening hours, while the eastward electrojet ranges from afternoon to near-midnight hours. The polar electrojet is positioned in the dayside sector at cusp latitudes. All these electrojets map along the magnetic field lines to certain plasma structures in the near-Earth space. The first spiral distribution of auroras was found based on observations in Antarctica for the nighttime-evening sector (N-spiral), and later in the nighttime-evening (N-spiral) and morning (M-spiral) sectors both in the Northern and Southern Hemispheres. The N and M spirals drawn in polar coordinates form an oval, along which one observes most often auroras in the zenith together with a westward electrojet.
The nature of spiral distributions in geomagnetic field variations was unabmibuously interpreted after the discovery of the spiral's existence in the auroras had been established and this caused a change from the paradigm of the auroral zone to the paradigm of the auroral oval. Zenith forms of auroras are found within the boundaries of the auroral oval. The oval is therefore the region of most frequent precipitations of corpuscular fluxes with auroral energy, where anomalous geophysical phenomena occur most often and with maximum intensity.
S. Chapman and L. Harang identified the existence of a discontinuity at auroral zone latitudes ($\Phi \sim 67°$) around midnight between the westward and eastward electrojets, that is now known as the Harang discontinuity. After the discovery of the auroral oval and the position of the westward electrojet along the oval, it turned out, that there is no discontinuity at a fixed latitude between the opposite electrojets, but rather a gap, the latitude of which varies smoothly between $\Phi \sim 67°$ at midnight and $\Phi \sim 73°$ at 20 MLT. In this respect the term "Harang discontinuity" represents no intrinsic phenomenon, because the westward electrojet does not experience any disruption in the midnight sector but continues without breaks from dawn to dusk hours.

Keywords. spirals, auroral oval, auroral forms, high-latitude magnetic variations, field-aligned currents, equivalent ionospheric currents, dynamo theory

1 Introduction

1.1. This review is dedicated to one of the branches of planetary-scale research on geomagnetic field variations and the morphology of discrete auroral forms – the spiral distributions, which are used in geophysics for the description of various phenomena. A comprehensive view of the results obtained in the scientific literature is given, in particular the contributions in Russian language. Such information will be most notably interesting and useful for those scientists, who often have problems to get proper access to scientific publications in Russian tongue either due to the language barrier or because of undue hardship to obtain such informations, which are buried in Institute's collections or in particular topical proceedings. The scientific development in the USSR, including geophysics, was detached to a large extent from global science progress for a long time period. Only the participation of the Soviet Union in the International Geophysical Year (1957-1958) and in subsequent international geophysical projects changed the situation fundamentally. There arose the additional possibility for publications in international journals, but many results continued to be known primarily in Russia only and were not cited in the global literature. We hope that the present review attracts attention to researchers in the field of Earth's magnetism and auroras, as they are such phenomena that intrigues mankind's exploratory spirit for many centuries. The following elaborations about the development of scientific knowledge on a specific geophysical problem might also be interesting for historians of science.

1.2. The conception of spirals, along which the precipitation of corpuscular solar fluxes occur, is closely related to the model experiments of Kristian Birkeland (Birkeland, 1908, 1913) and the theoretical calculations of Carl Størmer (Størmer, 1917a,b, 1955). Birkeland illuminated a magnetised model sphere ("terrella") representing the Earth by bundles of low-energy electrons. The bundles of charged particles were bent towards the night side of the terrella and toward the magnetic poles. The regions of precipitation were made visible through a phosphorecent layer which covered the terrella. Glowing stripes, one in each hemisphere, surrounded in the experiments the magnetic poles of the terrella. The stripe winded up around the near-pole region of the Northern Hemisphere in counter-clockwise direction. The terrella experiments have been repeated and extended by Bruche (1931).

1.3 Størmer (1917a,b, 1955) developed the methodology and performed mathematical calculations of the trajectories of positively charged particles (protons and α-particles) and of electrons in a dipole magnetic field. Figure 1 shows results of Størmer's calculations for the distribution of precipitations of positively charged particles at high latitudes of the Northern Hemisphere. The entire precipitation region has been obtained by a series of calculated orbits. It explains the formation of a spiral shaped region of precipitation in Birkeland's terrella experiment. This "laboratory" spiral has been obtained from calculations, adopting particular values of the γ-parameter (constant of integration) and of Ψ (declination of the corpuscles' source region). In the theory of Størmer, γ can assume arbitrary values, while the sun's declination Ψ varies in the course of the year by $\pm 34°$ with respect to the equatorial plane of the dipole. The "laboratory" spiral in Fig. 1 results from a ~1-year long integration time of the calculations. Not the whole spiral in Fig. 1 corresponds to a given UT moment with its particular Ψ value, but only a few discrete points along the spiral.

1.4 The variation of Ψ along the spiral is non-uniform; there is rather a bunching of points within four sectors, centred around $\Psi = 0$, i.e., close to the equinoctial periods. The higher density of points occurs near 03, 09, 14, and 20 hours local time, when the direction of the corpuscular source region varies most quickly.

1.5 In order to move the theoretical auroral spiral to the $\sim 23°$ colatitude required for agreement with auroral observations during the night time, Størmer postulated the existence of a ring current at higher geocentric distances. The magnetic field of this current deflects the path of solar particles, so that they precipitate at lower latitudes, but at the Earth's surface its field strength is small.

1.6 Precipitations of charged particles into the upper atmosphere leads to a series of phenomena. Certainly it could be assumed that the most intense specific geophysical phenomena, caused by these precipitations, occur along the spirals, which are oriented in a determinate way according to the sun's direction. The preciptiation region in the upper atmosphere has the form of a spiral in the coordinates of magnetic latitude versus magnetic local time. At the Northern Hemisphere, the spiral wind up clockwise from the magnetic pole for positively charged particles and in anti-clockwise directions for electrons.

1.7 Based on observations of the geomagnetic field, Birkeland (1908, 1913) concluded that the magnetic disturbances and the closely related aurorae are caused by the precipitation of electrically charged particles from the sun into the upper atmospheric layers. He assumed that the currents, calculated from the geomagnetic perturbations are real free currents, probably consisting of free electrons coming in from space towards the auroral zone and bent back again. The problem of the Birkeland–Størmer theory consisted in the unsteadiness of solar charged particle fluxes of one polarity, which are dissipated before they can reach the Earth. The energy of protons with a flux velocity of $\sim 500\ km/s$ amount to a few keV. Such a particle velocity within the flux was deduced from the time lag of the beginning of magnetic disturbances on Earth with respect to the flare at the sun. This lag comes along with the ejection of a particle flux, the subsequent development of a magnetic storm and the appearance of auro-

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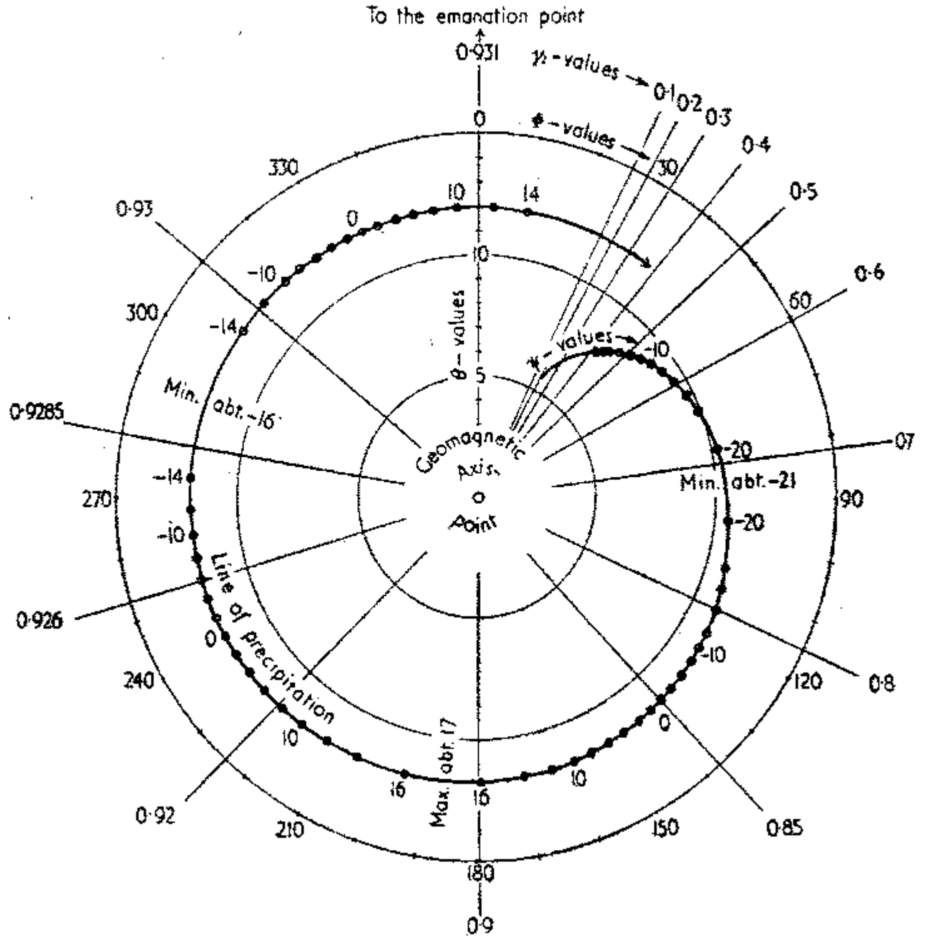

Figure 1. Spiral of positive corpuscles' precipitation around the magnetic axis. Here, γ stands for a constant of integration and Ψ is the declination of the sun (Størmer, 1955, Fig. 177).

ras. Protons of such energy precipitate, according to Størmer, into a much smaller region than the polar latitudinal distances of auroral features. Electrons with energy of a few eV, corresponding to velocities of $\sim 500\ km/s$, would precipitate close to the geomagnetic pole. However, their energy appears to be too small to penetrate down into the upper atmosphere to a level of $\sim 100\ km$ above the Earth's surface, where discrete auroral forms are usually seen (Harang, 1951). The results of Størmer's theoretical calculations appeared to be applicable to the particles of cosmic radiation, whose energy is several orders of magnitude larger than those of the plasma fluxes, which are responsible for the geomagnetic disturbances and auroras.

In the following sections, we sum up the basic findings concerning the spiral distributions in its historical progression, discuss the results of various authors, and in Section 6 we consider the relationship between the spirals and models of the magnetospheric-ionospheric current systems. In the Conclusions we list the basic steps in exploring the spiral distributions of geomagnetic variations and auroras and discuss their place within the magnetospheric plasma structure.

2 Spiral distributions in regular (S_D) geomagnetic field variations

2.1 The variations of the magnetic field D, which are observed at the Earth's surface during geomagnetically disturbed days are composed of various sources:

$$D = DCF + DR + DPC + DP + DT + Di \qquad (1)$$

where DCF describes the field of magnetopause currents, DR the field of the ring current in the inner magnetosphere, DPC the field of the current system with the electrojet in the dayside cusp, DT the field of the cross-tail current and its closure magnetopause current, DP the field of elementary polar magnetic disturbances (substorms) with characteristic lifetimes of some tens of minutes to several hours, and Di the field of irregular oscillations of the geomagnetic field. The DP variations are refered to the substorm type variations ($DP1$) only in the following. $DP2$ variations are of different

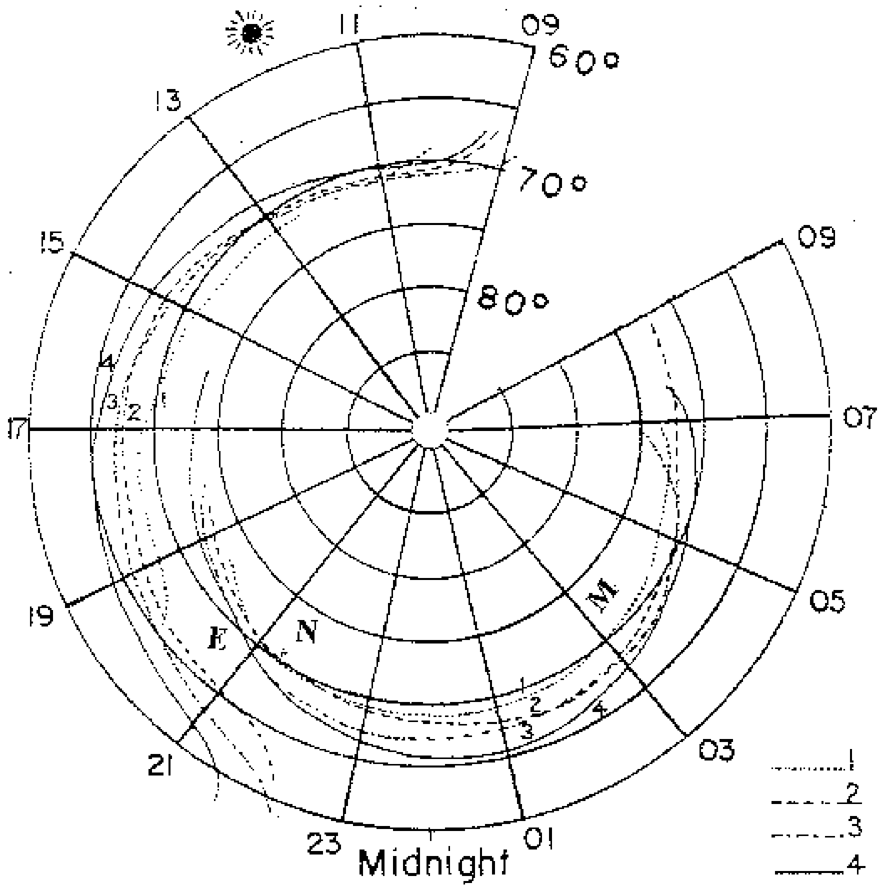

Figure 2. Loci of maximum intensity of auroral-zone electric currents (electrojets), as observed on geomagnetic meridian 120°, for different ranges of storminess (1,2,3,4). Mean picture for ΔH and ΔZ fields, letters M, N, and E correspond to morning, nighttime, and evening spirals (Harang, 1946).

nature and are not considered here. The *DCF*, *DR*, *DPC*, and *DT* variations are significantly smaller than *DP* and *Di* at high latitudes on ground level, except for magnetic storm intervals, so that one usually assumes:

$$D = DP + Di \tag{2}$$

Avereaged over the international magnetic disturbance days, one obtains the regular solar-daily variation field S_D, which represents the integral effect of the polar disturbances *DP*. The S_D variations are calculated as difference between the hourly averaged values of the magnetic field elements for the international disturbance days and the quiet days.

The current system obtained and named by Chapman as solar-daily disturbed variation S_D has influenced the study of geomagnetic disturbances to a high degree and became the standard model. This was a major paradigm for a few decades. The S_D current system consists of a pair of electrojets along the auroral zone as a circular belt with the centre at the geomagnetic pole. The westward electrojet (WE) in the morning sector and eastward electrojet (EE) in evening sector are usually considered. On average, the WE has its maximum intensity at 03.5 MLT, while the EE at 17.5 MLT (Allen and Kroehl, 1975).

The observations of the magnetic field variations were primarily of experimental character until the campaign of the Second International Polar Year (IInd IPY, 1932/1933). There were practically no permanent magnetic observatories at high latitudes by that time. The observations of high-latitude geomagnetic field variations by a network of magnetic stations during the IInd IPY period extended the possibilities of the researchers considerably. Based on observational material of the IInd IPY, Harang (1946) in Norway, Meek (1955) in Canada, and Burdo (1960) in the Soviet Union proposed models of polar magnetic disturbance current systems.

2.2 Harang (1946) used measurements of a chain of magnetic observatories along the 120° magnetic meridian from Spitzbergen (Svalbard) over Scandinavia till Potsdam to determine the S_D variations from three-component measurements of 11 observatories for four disturbance levels. He obtained so-called isopleths (lines of equal disturbance intensity) of these components.

2.2.1 Figure 2 shows the position of the maximum isopleths for all four magnetic disturbance levels. The diurnal variation of the isopleths' position is shown in the coordinates of geomagnetic latitude versus geomagnetic local time. The letters M, N, and E indicate segments of maximum isopleths, which researchers interpreted afterwards as morning (M), nighttime (N), and evening (E) spirals. The current flow is westward along the M and N spirals, but eastward along the E spiral. The isopleths run approximately parallel with the geomagnetic latitude for the H and Z components, and the maximal isopleths of the H component coincide with the auroral zone at 67° magnetic latitude. The H component within the auroral zone is positive during the evening hours (maximum at 17 MLT) and negative in the midnight to early morning hours (maximum intensity at 24–01 MLT) with a gap between the isopleths of opposite sign.

2.2.2 A characteristic Z component variation is observed at the auroral zone stations Tromsø ($\Phi = 67.1°$), Bossekop ($\Phi = 66.6°$), and Petsamo ($\Phi = 64.9°$): negative values are north of and positive to the south of the maximum H isopleths during the evening disturbance, and this reverses to the opposite during the nighttime disturbance. Throughout this paper, Φ stands for geomagnetic latitude and Φ' indicates corrected geomagnetic latitude. The significance of the distinction between Φ and Φ' consists in that to determine the deviation between the auroral zone and the geomagnetic parallel of 67° or, with other words, in the consideration of higher order harmonics of the internal potential sources, additional to the dipolar field (Hultqvist, 1958; Gustafsson, 1970). The curve for S_D in Z appears as a double wave. This double wave appears in all four disturbance levels. Assuming that the field of the magnetic disturbances is produced by a linear overhead current, it is evident that maximum values in ΔH and a zero crossing in ΔZ are located just below this current flow. This variation in ΔH and ΔZ in a certain distance from the line current is qualitatively in accordance with the isopleths. Between the evening and the nighttime isopleths at auroral latitudes ($\Phi \sim 67°$) exists therefore a longitudinal discontinuity, both in the variations of the magnetic field and in the current system of polar magnetic disturbances. Resulting from the existence of a discontinuity in the auroral zone, the zone itself consist of two separate branches. The discontinuity of the current system in the nighttime auroral zone causes the existence of the double wave structure in the Z component variations.

2.2.3 From the consideration of Figure 2 follows:

1. a shift of the maximum intensity current toward the equator with increasing disturbances;

2. the existence of a discontinuity in MLT for the isopleths at auroral latitudes in the midnight sector (discontinuity between E and N spirals);

3. the placement of the evening isopleths with an eastward current in the auroral zone latitudes over the whole interval of 11–21 MLT;

4. the shift of the isopleths with westward current (M and N spirals) to higher magnetic latitudes from the midnight auroral zone both toward the morning and the evening hours;

5. in the evening hours there exists a latitudinal gap between the positive and negative isopleths (E and N spirals). The N spiral with the westward current is at higher latitudes than the E spiral. Harang didn't give due attention to the existence of the latitudinal gap but to a discontinuity at a fixed latitudinal distance near midnight. At the time of the publication (1946), there was a generally accepted paradigm about a auroral zone at $\Phi \sim 67°$ and about the position of electrojets along this zone (but not along the auroral oval yet unidentified at that time), so that he couldn't make an adequate conclusion about the nature of the gap between the electrojets.

6. Based on the close connection between the magnetic disturbances and the auroras and the existence of a local time discontinuity in the current system between the electrojets, Harang (1946) concluded, that the auroral zone should also consist of two parts with a discontinuity between them. The most intense auroras occur during 17-18 LT and 21 LT with a quiet period during the intermediate interval.

7. the currents producing polar magnetic storms as well the diurnal variations are most simply explained according to the dynamo theory (Harang, 1951).

2.3 Meek (1955), in his analysis of the magnetic field variations, uses data from all high-latitude geomagnetic observatories north of 40°, which participated in the IInd IPY. Based on S_D variations, moments of the diurnal positive maximum of the disturbance vectors as well as their negative diurnal minimum were determined. Then a polar plot of magnetic latitude versus local geomagnetic time was made to display the diurnal maximum of the H component decrease for all stations. The points drawn lie along a spiral which expands clockwise (M spiral with westward current). The corresponding plot of the diurnal maximum of the H component increase shows a spiral expanding in the opposite direction (E spiral with eastward current). M and E spirals intersect on $\sim$ 10 a.m. (MLT) at $\Phi \sim 70°$ and on $\sim$ 10 p.m. at $\Phi \sim 60°$. It is assumed that the magnetic spirals obtained are Størmer's spirals of precipitating particles from a plasma cloud arriving from the sun.

The spiral M expanding clockwise will be due to the precipitation of negatively charged particles, while the spiral E expanding anticlockwise due to positively charged particles.

2.3.1 The patterns of spirals with currents in the papers of Meek (1955) and Harang (1946) differ in the number of spirals, their positions, and with respect to their sources:

1. two spirals M and E, which form the oval of Meek (1955) versus three spirals M, E, and N at auroral latitudes of Harang (1946);

2. the spirals M and E intersect on 22 MLT at $\sim 60°$ latitude without any disruption according to Meek (1955), while there exist a discontinuity in MLT according to Harang (1946);

3. Meek relates the maximum decrease in the H component of the magnetic field along the M spiral with precipitating electrons, and the maximum increase in the H component along the E spiral with proton precipitations (the sign of the charged corpuscles precipitating along the spirals oppose the sign of those in Størmer's calculations). The winding of the spirals is therefore opposite to the assumption in the model of Størmer. For the explanation of the configuration of maximum isopleths (spirals), Harang utilises the dynamo theory of magnetic variations, and Meek the precipitating corpuscles;

4. after the midnight intersection of the spirals with westward and eastward currents, the westward current in the evening sector is positioned equatorward of the eastward current according to Meek (1955), while it is poleward of the eastward current in the evening sector according to Harang (1946).

2.3.2 Meek (1955) modifies the opinions of Størmer by assuming the corpuscular solar flux as a plasma, but not as an ensemble of individual charged particles. It ensued just from such a modification, that electrons precipitate along the M spirals and protons along the E spirals. The westward electrojet ($\Delta H < 0$) yields from the precipitation of electrons, while the eastward electrojet ($\Delta H > 0$) is related to protons.

Assuming that the magnetic disturbance deviations are due to the motion of electric charges near the base of auroral forms, Meek (1955) expected some peculiarities in the distribution of auroras, caused by the spiral distribution of maximum intensities of magnetic variations and by particle precipitations of different charges along the M and E spirals. The auroral luminosity configuration along the spirals allows the interpretation of some peculiarities of their morphology in the auroral zone and equatorward of it according to the descriptions in the literature: the diurnal variation of their occurrence frequency; the motion during the evening and morning hours; the orientaion of the arcs; the appearance of auroras as due to separate precipitations of electrons and protons.

2.4. Based on data from 22 high-latitude observatories in the Northern Hemisphere with $\Phi > 60°$, Burdo (1960) has shown that the diurnal variations of the disturbance intensity of the horizontal magnetic field components (ΔT) have 2 or 3 maxima in dependence on the latitude. The positions of the maxima in (ΔT) within plots of MLT versus Φ' (corrected geomagnetic latitude) are arranged in 3 groups: morning (M), nighttime (N), and evening (E) points. The time of maximum ΔT changes with latitude for each group separately. These changes are for all three groups practically linear in the orthogonal projection used here. This relation can be written as $\Phi' = \Phi_0 + kt_m$. In polar coordinates for a particular UT moment, this relation transforms into a part of a spiral with $r = A + B\Lambda$, where r is the distance (colatitude) of Φ' from the pole, Λ is the geomagnetic longitude or the geomagnetic time, and A, B are constants. The ΔT vectors are drawn onto this polar projection as arrows. Such a use of perturbing vectors as "current arrows" at a network of stations gives a direct picture of the field distribution and was often applied by Birkeland.

2.4.1 The arrows cut the spirals under an angle near 90°. Numbers at the arrows' footpoint indicate the values of the vertical component of the disturbance vector ΔZ. Each spiral sub-divides areas with positive and negative ΔZ. The ΔT vector assumes therefore a maximum value along the three spirals at high latitudes with the direction perpendicular to the spirals and at the intersection points the vertical component ΔZ of the disturbance vector changes its sign. Under the assumption that the horizontal current system constitutes the source of the magnetic disturbances, the spirals are the places of maximum current density. The direction of ΔT and the sign of ΔZ to both sides of the spiral determines the direction of the current along the spiral: along the morning and nighttime spiral the current is westward, while along the dayside spiral the current points eastward.

2.4.2 Burdo (1960) proposed that the dynamo-effect plays a notable (or even main) role in the generation of magnetic variations during disturbed time intervals. The currents producing the Sq variations and the polar magnetic disturbances are most simply explained according to the dynamo-theory proposed by Steward (1882). According to this theory the air in the upper atmosphere is ionised and thus electrically conducting. The tidal and other motions of the atmosphere will set up horizontal motion in the layers across the lines of force of the Earth's permanent magnetic field. Due to this electromotive forces will be formed, and electric currents will be caused to flow in directions which agree with those required to produce Sq variations. The precipitation of electrically charged particles which produce the aurorae, strongly increases the ionisation and thus the conductivity of the ionized layers, which leads to cardinal changes of the high-latitude current system. This system of ionospheric currents is - according to the dynamo theory - responsible for the generation of magnetic disturbances, so-called S_D variations, as well as for polar magnetic storms. Processes, which are generated in the ionosphere due to the penetration of corpuscular fluxes, play the main role for the generation of magnetic disturbances. These fluxes enter the upper atmosphere at auroral latitudes and a 2-D current system, which generates the magnetic disturbances, spreads out in the ionosphere.

2.5 The most exhaustive development of the dynamo theory, which is applicable to the magnetic field variations at high latitudes, was accomplished in the works of Japanese scientists. Nagata and Fukushima (1952) and Fukushima (1953) used the dynamo theory for the interpretation of two specific types of the geomagnetic variations, which were observed during the IInd IPY: a single-vortex current system with the westward electrojet at auroral latitudes in the nighttime sector, or a double-vortex system with westward and eastward electrojets at auroral latitudes during the nighttime and evening hours, respectively. The conductivity is steeply enhanced in the auroral zone (colatitude range of $\Theta \sim 20° \div 25°$) during magnetic disturbances and stays at the higher level of about one order of magnitude compared with the polar region. The neutral wind in the conducting layer depends on colatitude, longitude and the phase angle α. The model current system can be brought in accordance with the corresponding calculated magnetic field variations by varying the input parameters of the model. In case of enhanced conductivity in the auroral zone along all longitudes, the model current system results in a double vortex with westward and eastward electrojets. If the conductivity is enhanced only within a limited longitudinal range, then the model current system remains a single-vortex system with an electrojet in those longitudes of enhanced conductivity. The angle α controls the direction of the current closure across the polar cap.

2.6 Fukushima and Oguti (1953) considered the dynamo theory with an anisotropic ionospheric conductivity. Under several simplifying assumptions they obtaind an expression for the current function J_D in northern and southern auroral zones, in the polar caps, and in the equatorial zone.

The current function has the form:

$$J_D = 2\,K_3^0\,G\,k_1^1 \quad \left\{ A_1 U_1(\Theta)\sin\lambda + B_1 U_1(\Theta)\cos\lambda \right\} \qquad (3)$$

... in the Northern polar cap

$$\begin{aligned} J_D = 2b\,K_3^0\,G\,k_1^1 \quad \Big\{ & \frac{(b-1)}{b}\, S_1^1(\Theta)\cos\lambda + \\ & [A_2 U_1(\Theta) + A_3 V_1(\Theta)]\sin\lambda + \\ & [B_2 U_1(\Theta) + B_3 V_1(\Theta)]\cos\lambda \Big\} \end{aligned} \qquad (4)$$

... in the Northern auroral zone

where K_3^0 represents the height-integrated ionospheric conductivity in the polar cap during quiet times, G is the Earth's magnetic field strength at the equator, k_1^1 is the coefficient of a spherical harmonic series for the potential field of the ionospheric wind velocity, $U_1(\Theta) = \tan\Theta/2$, $V_1(\Theta) = \cot\Theta/2$, $S_1^1(\Theta) = \sin(2\Theta/4)$, A_1–A_3 and B_1–B_3 are numerical constants, obtained from the boundary conditions, and b, finally, is the enhancement factor of the conductivity in the auroral zone during disturbed intervals in comparison with the quiet time level.

2.7 The model current system reminds of the S_D current system, though of a somehow smaller intensity, with two electrojets in the auroral zone ($65° < \Phi < 70°$) and its distributed currents in the polar cap ($\Phi > 73°$). The ionospheric neutral wind system for the model calculation of S_D was adopted analogous to the calculations of S_q variations. There is a very essential difference between the observed and the modelled S_D systems: the current direction in the polar cap differs by an angle between 110° and 150°. This problem is usually avoided in the dynamo theory by assuming different neutral wind systems for the S_q and S_D variations at ionospheric altitudes (Nagata et al., 1950).

2.8 A series of articles of M. I. Pudovkin is devoted to the use of the dynamo theory for interpreting the specifics of the evolvement of magnetic disturbances at high latitudes, generalized in his thesis on "The morphology and nature of polar magnetic storms" (Pudovkin, 1968). In these articles the authors estimated the changes of the ionospheric conductivity and deduced the neutral wind circulation at high latitudes based on observations of geomagnetic field variations, of plasma densitites, of drift velocities deduced from plasma irregularities in the ionospheric E-layer, and from movements of discrete auroral forms. It is assumed that currents, which cause the magnetic field variations, flow during magnetic disturbances along extended auroral forms (arcs).

These currents are carried by the neutral wind away from the arc and their position is determined from magnetic field observations, while the direction and velocity magnitude of the neutral wind in the ionosphere is calculated from the direction and extent of the transport (Pudovkin, 1960; Pudovkin and Evlashin, 1962). The current is usually shifted toward south relative to the arc during positive disturbances (in the evening) and toward north during negative disturbances (nighttime to early morning hours). The velocity of the current shift amounts to ~ 100 m/sec. It is assumed that this shift results from the action of neutral wind at ionospheric heights. The sign of the geomagnetic disturbances in the horizontal components is related to the direction of the causing currents: during positive disturbances the current shift toward the equator and during negative toward the pole (Pudovkin, 1965b). For the determination of the wind velocity it is assumed, that the source of ionization in the atmosphere (the auroral arc) is static or moves only marginally for the disturbance time (Pudovkin and Korotin, 1961; Pudovkin, 1964). The intensity of the magnetic disturbance is estimated from the increase of plasma density as due to the interaction of the corpuscular flux with the atmosphere and the velocity of the neutral wind in the ionosphere (Korotin and Pudovkin, 1961). A considerable contribution comes also from ionospheric irregularities in the E-layer. Owing to the generation of electric polarization fields, the velocity of the electrons in the electrojets increases by an order of magnitude compared to the neutral wind velocity. The Hall currents, which are hereby generated along the auroral zone, appear to be the cause for the observed magnetic field variations (Pudovkin, 1964).

2.9 Pudovkin (1965a) estimated the system of ionospheric neutral winds in the auroral zone from magnetograms and plotted it according to the longitude of the stations. At all stations in the evening hours the neutral wind is directed from north to south, while in the nighttime and early morning hours it is oppositely directed from south to north. The course of the S_D variations is controlled by the diurnal variation of the ionospheric neutral wind in such a manner that the currents, which are the cause for the S_D variations, are generated due to the dynamo action of the ionospheric neutral winds. The neutral wind system is comparatively stable according to the dynamo theory and experiences only a small variation, but the magnetic disturbances are caused by steep enhancements of the ionospheric conductivity due to the precipitating corpuscular fluxes (Pudovkin, 1965b). Based on the discussion of ionospheric processes, Pudovkin (1964, 1965b) concluded, that the dynamo theory is the best substantiated theory to explain the generation of ionospheric currents that are responsible for the high-latitude magnetic disturbances. These currents are excited due to the dynamo action of ionospheric neutral winds.

2.10 Viewed from the vintage point of the present, it is amazing how broadly and deeply the success of the dynamo theory was in interpreting the quiet-time features of the ionosphere. But the application of the dynamo theory as physical base to interpret the nature of the geomagnetic disturbances at high latitudes encountered distinct difficulties, both in observational as in theoretical respects. We already mentioned above the discrepancies in the results of the classical dynamo theory with regard to the phase and intensity of the observed current systems, both in magnitude and direction (phase) within the polar cap. The modifications of the theory by M. I. Pudovkin were also not without any problems as listed subsequently.

1. The assumption about the static behaviour of the corpuscular source (auroral arc), which is used for the determination of the neutral wind velocity at ionospheric heights, disagrees with present perceptions of the dynamics of discrete auroral forms. In the majority of cases the auroras appear and allocate not at a fixed latitude, but along the auroral oval, which is asymmetric with respect to the geomagnetic pole. In consequence of this there is a shift of the aurora with ~ 30 m/sec from north toward south in the evening and from south toward north in the morning. During substorm creation (growth) phases, the arcs in the evening–nighttime sector are shifted with a velocity up to ~ 250 m/sec southward. This is just the same range of velocities as that of the neutral wind velocities in the modified dynamo theory.

2. The magnetic variations at auroral zone latitudes ($\Phi \sim 67°$) in the evening sector are positive and, therefore, in the frame of the dynamo theory, the neutral wind in the ionosphere should be directed from north to south. In the same sector at latitudes of the auroral oval ($\Phi \sim 70°$), the magnetic variations are negative and consequently the neutral wind should be directed there from south to north. This divergence of the neutral wind orientation within close latitudinal distances at the evening sector suggests the presence of a neutral wind source within this small latitudinal range. But the existence of such a source is not envisioned in the frame of the dynamo theory.

3. The current system in the dynamo theory is a 2-D one, spanning at the ionospheric E-layer. According to present conceptions, based on experimental data, the current system of the magnetic disturbances is 3-D. The ionospheric electrojets are connected by field-aligned currents (FACs) with the magnetosphere. The character and the intensity of the magnetic disturbances at the Earth's surface is determined by a complicated system of ionospheric and magnetospheric currents.

4. Nowadays it it generally accepted, that the magnetic disturbances at high latitudes as well as the currents in the magnetosphere and ionosphere, which cause them, are controlled by the parameters of the interplanetary medium. The dominating parameter here appears to be the orientation and intensity of the interplanetary magnetic field (IMF), in combination with the solar wind velocity.

2.11 New approaches for the determination of the upper atmosphere neutral wind system at high latitudes were established during the "Sputnik era". It became possible to determine the velocity and direction of the neutral wind in-situ in the thermosphere. The satellite Dynamics Explorer–2 (DE–2) measured the velocity of the neutral wind at altitudes between 300 km and 550 km by use of an Fabry-Perot interferometer and a wind and temperature spectrometer (Killeen and Roble, 1988). The empirical neutral wind pattern obtained in geomagnetic coordinates is characterised by a strong antisolar flow over the geomagnetic pole bordered by sunward flow in the dawn and dusk sectors. Negative vorticity occurs in the dusk sector while positive vorticity in the dawn sector.

Measurements of lower thermospheric neutral winds at altitudes between 100 km and 300 km, where according to the dynamo theory ionospheric currents are generated, have been realized onboard the Upper Atmosphere Research Satellite (UARS). Richmond et al. (2003) used data of the Wind Imaging Interferometer (WINDII), which records the line-of-sight intensity of the green atomic oxygen line airglow emissions. They showed that the neutral wind motion is controlled by the IMF action down to 105 km altitude, while above ~125 km the wind patterns shows considerable similarity with the ionospheric convection patterns. The correlation between the IMF B_z component and the diurnal harmonic of the neutral wind is best, when the IMF is averaged over the preceding 1.0÷4.5 hours. Zonal wind below 120 km correlates with the IMF B_y component when the B_y component is averaged over the preceding 20 hours. Above 120 km, the dusk side clockwise circulation wind cell is prominent and it intensifies for IMF $B_z < 0$. Around 120 km one observes a dawn side anticlockwise wind cell that responds to IMF B_z variations. During intervals with IMF $B_z > 0$, the neutral wind modification is mainly confined to the polar cap, while for $B_z < 0$ it extends to subauroral latitudes. On timescales of ~20 hours an IMF B_y dependent zonal wind generally exists at 120 km altitude and 80° geomagnetic latitude with maximum wind speeds of $\sim 60\ m/s$. The paper of Richmond et al. (2003) includes a broad range of references on thermospheric neutral wind investigations and their modelling.

Cross-track accelerometer measurements at the CHAMP satellite were used to deduce statistical neutral wind pattern at the high-latitude upper atmosphere (Lühr et al., 2007; Förster et al., 2008). These measurements were obtained at altitudes of ~ 400 km and confirmed the existence of a strong antisolar flow with an average velocity of ~ 500 m/s and an azimuth of 168° over the central polar cap. At the evening side a large clockwise circulation cell is formed, resulting in the tendency for westward (sunward) neutral wind velocities in the auroral region of the duskside upper atmosphere. Förster et al. (2008, 2011) analysed the neutral wind observations of CHAMP in dependence on the IMF orientation. The data were sorted into 8 separate IMF sectors with 45° width each. Measurements over a 2-year interval resulted in a good data coverage for each IMF sector. The upper thermospheric neutral wind system is characterized in all sectors by a transpolar neutral wind orientation across the central polar cap and two vortex cells with opposite circulations on the dawn and dusk side, the strength and shape of which depend on the IMF B_y and B_z components. The amplitude of the cross-polar cap neutral wind flow is largest for negative IMF B_z values ($B_z < 0$) and amounts on average to ~ 570 m/s (cf. Förster et al., 2008, Table 1). A couple of characteristic phenomena of the IMF B_y and B_z dependence on the spatial distribution of the neutral wind in the upper atmosphere are gathered and described in detail.

The satellite observations of thermospheric neutral wind and ionospheric plasma convection revealed a fairly close similarity of their patterns. The correlation of the velocity and direction of the neutral wind and plasma convection with the IMF B_z and B_y components verifies the control of the thermospheric neutral wind regime by the IMF parameters. Both the plasma motion and the neutral wind appear as a result of the electric fields, generated in the outer magnetosphere. They are constituded due to the interaction of the solar wind with the geomagnetic field and then transmitted along the magnetic field lines down into the ionosphere. The plasma in the thermosphere drifts in the electric and magnetic fields. The neutral thermospheric component adopts the plasma motion due to the ion drag forces. The secondariness of the neutral wind results in a time lag of the neutral wind with respect to the convection. The magnitude and direction of the ion motion is determined by the intensity of the IMF components. Due to these relations, the neutral wind at high latitudes also depends on the IMF.

The global neutral wind system, that is due to this interaction, differs considerably from that system, which is essential for the generation of magnetic disturbances observed at the Earth's surface, as explained by the existing dynamo theory.

2.12 Patterns of magnetic disturbance spirals, that were obtained from the materials of the IInd IPY by L. Harang, J. H. Meek, and O. A. Burdo, differ both in the quantity of spirals and in their sources (2 spirals of corpuscular precipitation according to J. H. Meek, but 3 spirals in the dynamo theory according to L. Harang and O. A. Burdo). All three studies used yearly averaged data. There are, however, significant seasonal dependences in the variations on the geomagnetic field (Benkova, 1948; Feldstein, 1963a). Feldstein and Zaitzev (1965a) studied the S_D variations of three geomagnetic field components using data of 24 magnetic observatories during the IGY of the Northern Hemisphere separately for winter, equinox, and summer periods. The horizontal projection of the disturbance vector ΔT was determined according to the relation $\Delta T = \sqrt{(\Delta H^2 + \Delta D^2)}$ as deviations from the quiet time level with ΔD as the deviation from the East-West component.

2.12.1 During the winter season, the S_D variation at $\Phi' > 73°$ is characterized by one maximum near midday. In the latitude range $73° > \Phi' > 67°$ the maxima of ΔT occur in the evening and morning hours, and in the latitude range $67° > \Phi' > 60°$ they shift to nighttime and evening hours. Below $\Phi' < 60°$ the nighttime maximum in ΔT is the only one.

Figure 3a shows the patterns of ΔT and ΔZ for the winter season of the IGY (November 1957 – February 1958) in coordinates of Φ' versus MLT. The arrows indicate the disturbance vector directions in the horizontal plane; the arrow's length is in accord with the amplitude of ΔT. The scale is given in the upper left corner of the Figure. The numbers at the arrow's origin specify the amplitude of ΔZ. The dependence on the maximum moments in the course of the diurnal variation of ΔT over Φ' is indicated with thick lines: (1) – morning maximum (M), (2) – nighttime maximum (N), and (3) – evening maximum (E) in Fig. 3a. The sign of the Z-component of the geomagnetic variations changes along these lines. Such a distribution of the vector magnitude and direction implies, that intense equivalent currents are flowing along these lines. Along the lines 1 and 2, forming an oval belt, the current flows westward and decreases the horizontal magnetic component. Along line 3 the current flows eastward, increasing this component.

2.12.2 In the limited latitudinal range of $69° < \Phi' < 72°$, there exist only negative disturbances of the horizontal component during the whole day. This region at auroral latitudes, where we have $\Delta H < 0$ in the winter season during

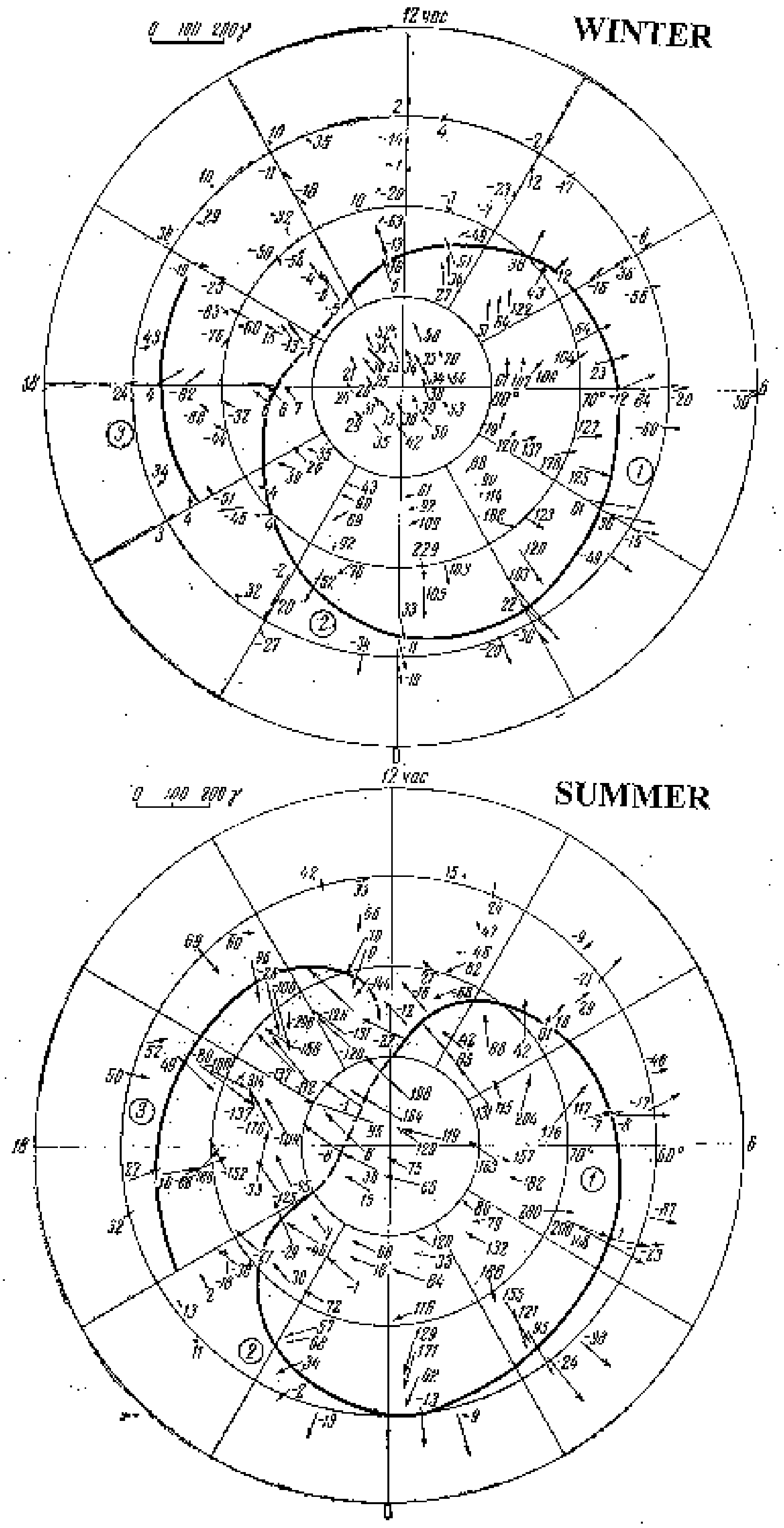

Figure 3. Loci of maximum intensity ΔT and minimum ΔZ fields in LMT versus corrected geomagnetic latitudes in Northern Hemisphere. The digits 1, 2, and 3 correspond to morning, nighttime, and evening spirals, respectively (Feldstein and Zaitzev, 1965a). a) winter season of IGY (upper panel) and b) summer season of IGY (lower panel).

the whole day, is fundamentally different from the character of the diurnal variation within the auroral zone. There occur beside the disturbances with $\Delta H < 0$ during the nighttime and morning MLT hours generally at the same UT also disturbances $\Delta H > 0$ in the evening MLT hours (Burdo, 1960). The existence of a latitude interval with $\Delta H < 0$ was confirmed by the observations of the drifting station North Pole 6 $68° < \Phi' < 70°$ during the period from September 1957 to April 1958 (Zhigalova and Ol, 1964). During all hours of the day, they practically observed only negative bays. The frequency of their appearance maximizes at 07 and 21 MLT, which corresponds to the times of the station's passage under the oval current belt (Fig. 3a, lines 1 and 2) in the course of the Earth's rotation. The current belt at Fig. 3a, which consists of the spirals 1 and 2, coincides with the position of the auroral oval (Feldstein, 1963b, 1966), Auroras were observed along the auroral oval during the winter season of the IGY practically continuously at zenith. The appearance of discrete auroral forms implies the precipitation of energetic electrons into the upper atmospheric layers. The electron precipitation with energies of $1 \div 5$ *keV* along the auroral oval leads to steep increase of the conductivity at dynamo region altitudes. The incoming and outgoing FACs result in the generation of a meridional electric field, directed equatorward. In this way the conditions for the appearance of the electrojet with a westward directed Hall current are established along the auroral oval.

2.12.3 Fig. 3b shows the patterns of ΔT and ΔZ for the summer season of the IGY in coordinates of Φ' versus MLT. The legend here is the same as for Fig. 3a. The dependencies of the maximum moments in the course of the diurnal variation of ΔT are depicted with the thick lines 1(M), 2(N), and 3(E), together with the corresponding sign changes of ΔZ. The M and N spiral with negative values of ΔH forms, as in the winter season, the auroral belt, along which the current flows in westward direction. In contrast to the winter season, ΔT increases sharply in daytime hours at $\Phi' > 75°$. The intensity of the disturbances in the dayside sector at the auroral oval is comparable with the nighttime–early morning disturbances at latitudes of the auroral zone. A noticable increase of the ΔT vector intensity, caused by the positive values of ΔH, occurs during evening MLT hours in the range $60° < \Phi' < 70°$. The patterns of ΔT and ΔZ for the summer and winter seasons during the IGY give no hint on the existence of two circular zones at fixed latitudes with maxima of the magnetic activity. The absence of such circular zones is confirmed by latitudinal cross-sections in ΔT during various MLT hours.

3 Spirals in the irregular geomagnetic field variations D_i (agitation)

3.1 The high-latitude diurnal geomagnetic variations contain a component, which displays an irregular character. It is usually investigated by studying the regularities of geomagnetic activities. Mayaud (1956) proposed the term agitation for the indication of geomagnetic disturbances, which are due to the precipitation of corpuscular radiation into the upper atmosphere, leading to irregular magnetic field variations. The intensity of agitation is estimated by means of various indices, which characterize the magnetic activity in different regions of the globe.

3.1.a The Polar Cap (PC) index is the most representative one for the polar cap, both for the Northern (PCN) and the Southern (PCS) Hemisphere (Troshichev et al., 1988, 2006). The PC indices are derived from ground geomagnetic measurements in the Northern (PCN) and Southern (PCS) Polar Caps. The PCN index is based on the data from Thule (Greenland) while the PCS index is based on data from Vostok in Antarctica. The PC index in its present form was first formulated by Troshichev et al. (1988) as a planetary index. PCN index values have been supplied from the Danish Meteorological Institute (DMI) while PCS index values have been supplied from Arctic and Antarctic Research Institute (AARI) (Troshichev et al., 2006). Basically, the PC index with a temporal resolution of 1 min represents the polar cap magnetic variations ΔF_{PC} in nT, associated with the transpolar part of the current system driven by the electric field of the solar wind–magnetosphere dynamo.

3.1.b The planetary indices AE, AU, and AL were introduced by Davis and Sugiura (1966) to characterize the UT variation (in nT) of the eastward (AU), the westward (AL) and the total electrojet intensity (AE). These indices were determined by the World Data Center A for Solar-Terrestrial Physics, NOAA, Boulder, USA (Allen et al., 1974, 1975) from 1966 to 1971. The indices were determined with a temporal resolution of 2.5 min as maximal deviation from the quiet time level for positive (AU) and negative (AL) values of the H-component of the geomagnetic field based on a network of 10–11 magnetometer stations. These observatories were distributed at auroral latitudes with a rather good coverage in longitude (Allen and Kroehl, 1975). During the subsequent years up to now, the AE, AU, and AL indices are determined with a 1-min cadence by the World Data Center for Geomagnetism, Kyoto, Japan, based on the data of 12 observatories.

3.1.c For the study of the regularities of agitation developments at high latitudes, one-hour amplitude averages of the horizontal components of H and/or D were largely employed (cf., e.g., Nikolsky, 1951; Burdo, 1960; Lassen, 1963, and references therein). Nikolsky (1947) used the curve-length of the D-variometer records as an every-hour characteristic of magnetic disturbances.

3.1.d Disturbances at mid-latitudes were estimated for particular geomagnetic observatories by means of the quasi-logarithmic index K (Bartels et al., 1939). This agreed measure, with values from 0 to 9, estimates the amplitudes of the H and D component variations as deviations from the quiet time level within 3-hourly intervals of UT. The estimation of

K indices in various observatories for one and the same time interval results generally in different values.

The averages of the K values from 11 different observatories within the latitudinal range of $44^\circ < |\Phi| < 57^\circ$, from which only one is localized at the Southern Hemisphere, represents the planetary index Kp. This index was introduced by Bartels in 1949. The Kp values counted according to a particular scale, translate to the equivalent 3-hourly amplitude index ap (in nT) and their daily averages Ap. The indices Kp, ap, and Ap were derived by the Geophysical Institute of the Göttingen University from January 1932 until the end of 1996. Since January 1997 the derivation and distribution of the Kp values have been moved to the Adolf Schmidt Geomagnetic Observatory Niemegk, part of the GeoForschungsZentrum (GFZ) Potsdam (now: GFZ German Research Centre for Geosciences, Helmholtz Centre Potsdam).

To characterize the value of the daily magnetic activity level, the indices C and Ci are used. The magnetograms of any observatory are quantified for each day (in UT) with a magnetic character figure of the value 0, 1, or 2. This character figure appears also as the C index of this day for the given observatory. Arithmetic mean values of the C index values from all reporting observatories result in the Ci index, which runs from 0.0 for very quiet conditions to 2.0 for very disturbed ones. The planetary index Cp for the daily disturbance characteristic, which varies from 0.0 to 2.5 in steps of 0.1, is calculated from the Ap index. The Cp index is used to discern the international magnetically disturbed and magnetically quiet days.

Mayaud (1967) assumed that the Kp index does not sufficiently reflect the planetary character of a magnetic disturbance and proposed its modification. The modified indices Km, am, and Am are based on the K index of 24 mid-latitude stations, including 9 at the Southern Hemisphere.

3.1.e Magnetic disturbances of more than 100 years are described with the aa index (Mayaud, 1972). This index was calculated from the K index of the observatories Melbourne and Greenwich (i.e., one station in each hemisphere), beginning from 1868. Later these stations were replaced by Abinger and Hartland for Greenwich and by Toolangui and Canberra for Melborne. From the aa values, daily means (Aa index) and monthly means are calculated.

3.1.f To describe the variations of the Earth's magnetic field during geomagnetic storms, the planetary Dst index is broadly used. A starting point for the studies concerning Dst derivation can be found at the end of the forties of the last century. More systematic determinations started after the IGY (Sugiura, 1964). For the derivation of the hourly Dst values, one usually uses hourly UT values of the low-latitude magnetic observatories Honolulu (USA), Kakioka (Japan), Hermanus (SAR), and San Juan (USA). These observatories were chosen for the reason that their locations are sufficiently distant from the auroral and equatorial electrojets and that they are distributed in longitudes as evenly as possible. The Dst index represents the axially symmetric part of the disturbance magnetic field at the dipole equator on the Earth surface (in nT). Nowadays the World Data Center for Geomagnetism, Kyoto, Japan, provides with 1-min resolution the so-called SymH index (replacing Dst) as well as an asymmetric index AsymH as difference between the maximum and minimum values of the H component from a network of low-latitude stations.

3.1.g Up to the nineties of the past century, i.e. practically over 50 years, it was generally assumed, that during geomagnetic storms the Dst index represents the magnetic variation fields of the magnetopause currents DCF and of the ring current DR (see, for instance, the reviews of Gonzalez et al., 1994; Kamide et al., 1998). The contribution of the magnetospheric tail current fields (DT) were assumed to be less than a few nT in the observations at the Earth's surface. Only resulting from the studies of Arykov and Maltsev (1993); Arykov et al. (1996); Alexeev et al. (1996); Maltsev (2004) it became clear, that the DT contribution in the Dst index during magnetic storm periods is comparable to the DCF and DR contributions.

3.1.h The Sa (used in the literature to identify the diurnal change of geomagnetic activity) has a complicated form at high latitudes, which changes with latitude. The consideration of irregular magnetic disturbances revealed, that they follow certain regularities at particular stations, i.e. the magnetic disturbance has a significant diurnal course. The onset time as well as the maximum intensity of the disturbance depends on the station's position with respect to the auroral oval. Below we present, according to our guess, basic results, summarizing the research on magnetic agitation regularities at high latitudes concerning the spiral distributions. We seek to follow in this review the historical progression according to the publication time of new ideas.

3.2. The first study on Sa at high latitudes was performed with observational material of the IInd IPY by Stagg (1935), carried out with data of six arctic , one mid-latitude, and three antarctic stations. It was shown, that the form of Sa is determined by the magnetic latitude and local time. In mid-latitudes the activity maximizes during evening hours of local time. Progressing to higher latitudes, the maximum moves to later hours and during midnight it is observed at $\Phi \sim 69^\circ$. The form of Sa changes at latitudes of highest activity between $70^\circ < \Phi < 78^\circ$. There two maxima are observed: one at the morning hours, the other during nighttime. At $\Phi > 78^\circ$, the maximum activity reaches morning or even midday hours. Nikolsky (1947) assembled observational results of 16 stations, partly positioned within the formerly inaccessible Eastern regions of the Arctic, and found some differences from Stagg's results: the morning maximum for stations along one and the same geomagnetic parallel occurs at different local times; the equatorial boundary of the active zone is recorded down to a latitude of $\Phi \sim 62^\circ$; the morning maximum appears in the western hemisphere almost concurrently at 15.5–16.5 MLT, while its appearance lags by

0.7 hours in the eastern hemisphere with Φ shifted by 1°; intensity variations with latitude are different during nighttime and morning maxima. Noting the differences of the evening and morning magnetic activities, Nikolsky (1947) assumed, that their behaviour follows different regularities. He didn't even exclude different natures of the corpuscular fluxes, responsible for the two types of magnetic disturbances.

3.3 Benkova (1948) considered 17 Arctic observatories and concluded, that the Sa value of high-latitude stations follow the scheme, that was proposed by Stagg (1935). The description of Sa as expansion of harmonic series according to

$$Sa = \sum_n C_n \cos(nt - \alpha_n) \qquad (5)$$

has shown, that over the range of $\Phi = 0^\circ$ to 90° the parameter α_1 varies between -2π and $+2\pi$ and the sign change of the first term of the expansion occurs at the latitude of the auroral zone. The dependence on α_1 from Φ in polar coordinates turns out to be a spiral, winding up in clockwise direction through the morning sector. This appears to be the first mention of a spiral distribution in the literature relating to the morning maximum of magnetic activity.

3.4 A.P. Nikolsky addressed the analysis of spiral distributions of the high-latitude magnetic activity in a large number of publications. The most important results are collected in the anthologies of the Arctic and Antarctic Research Institute (AARI) in St. Petersburg (Nikolsky, 1951, 1956, 1960a). It was shown, that the specific characteristic of the Sa consists in the appearance of maxima at morning, daytime, and nighttime hours, the relative amplitude of which varies in dependence on the stations's distribution. The intensity of the morning and dayside disturbances increases with increasing geomagnetic latitude, the nighttime disturbances are fixed to the local midnight and maximize at latitudes of the auroral zone. A.P. Nikolsky turned his particular attention to the study of morning and daytime disturbances. Considering observations at 30 places with $\Phi > 60^\circ$, the observational material is very broadly scattered about the indices of activity used. It turned out that the agitation during morning and daytime hours is not connected with the auroral zone. Considering contour maps of concurrent appearance (with respect to UT) of the morning agitation maxima, it became clear, that the isoline represent a system of spiral sections, which begin at the pole of homogeneous magnetization. At the Northern Hemisphere they wind up clockwise. Nikolsky assumed, that these sections of spirals should be seen as projections onto the Earth's surface of those real trajectories, along which the solar corpuscles penetrate into the upper atmosphere. The positions of the most frequent particle precipitations along the spirals are determined by the character and the parameters of the particles in the corpuscular fluxes.

3.5 Nikolsky (1960a) identifies the spirals of the morning agitation maximum with the Størmer's spirals of penetrating solar corpuscles. Because these spirals wind up clockwise in the Artic, these corpuscles should be protons according to Størmer's theory. The appropriateness of Nikolsky's assumption about the congruency of his spirals with the spirals of Størmer was challenged by Agy (1960). He paid attention to the fact, that the Nikolsky's spirals of the morning Sa maximum represent positions at the Earth's surface of the simultaneous (in UT) onset moment of maximum activity along the whole spiral. These spirals differ essentially from those of Størmer, along which the penetration of corpuscles occurs simultaneously only in a few points. The whole spiral of Størmer results from corpuscular precipitations over a longer time interval of the order of a year.

3.6 Based on the calculation results of Størmer (1955), Nikolsky (1960a) concludes, that there exist four regions within the morning spirals, where the solar proton trajectories are gathering closer (see Fig. 1). These regions ("A", "B", "C", and "D") occur at 02, 08-09, 14, and 20 hours LT, respectively. Nikolsky suggests that as the Earth rotates diurnally under the spiral, the high point density sections of the spiral on Fig. 1 will trace out four ring "auroral zones" or regions with auroras in the zenith and increased magnetic agitation. In Fig. 1 there are four such high point–density sections and therefore, according to Nikolsky, four auroral zones will occur. Fig. 4 from the paper of Nikolsky (1960a) shows the positions of all four regions "A", "B", "C", and "D" at the Earth's surface. The figure shows also the image replication of Størmer's spiral (named "S"), the position of which was arbitrarily changed by Nikolsky. The spiral in Fig. 4 is prolonged to low latitudes (observatory Bombay in India). The extension of each of the "auroral zones" to the equator is limited by the position of the high point density section of the spiral in Fig. 4.

3.7 Zone "B" is identified as second (inner) region, where the intensity of magnetic agitation and the occurence of auroras achieves maximum values at 08–09 LT. The summary effect of the precipitation zones "A" (02 LT) and D (20 LT) appears as the main auroral zone ("Fritz zone"), which is located at mid-latitudes over the American continent. Such a position of the "Fritz zone" is quite unusual and in case of its observational confirmation it would be a good argument in favour of the planetary distribution of corpuscular precipitation and the related auroras and magnetic agitation, as suggested by A. P. Nikolsky. Unfortunately, it is not possible to verify the appearance of zenith auroral forms in region "C" with observations - due to daylight conditions around 14 LT.

The appearance of auroral forms in the zenith discloses, in contrast to the magnetic disturbances, directly the location of precipitating corpuscular fluxes. Feldstein (1963a) verified hence the existence of four zones of maximum corpuscular precipitation useing auroral observations from the IGY period (Annals, 1962).

3.8 The appearance of auroras is usually very rare at mid-latitudes and if it appears, then preferably with northern azimuths. Near the zones "A" and "D", in case they are precipitation zones, the auroral forms should appear mainly at

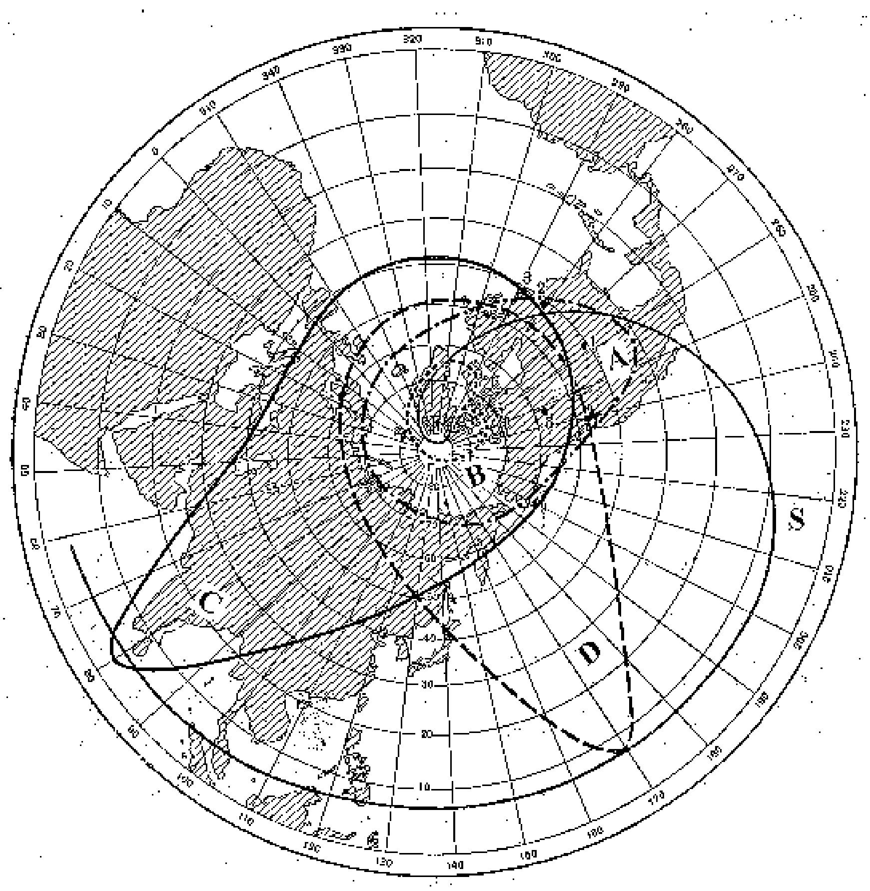

Figure 4. Location of solar corpuscular flux precipitation zones "A", "B", "C", and "D" above Earths surface and corresponding maximum values of agitation and appearance frequency of auroras according to Nikolsky (1960a). Letter "S" marks Størmers spiral, which is arbitrarily prolonged towards low latitudes.

zenith. The positions of some observatories in the environment of zones "A" and "D" are shown in Fig. 4 and their coordinates are given in Table 1 together with the respective probability for the appearance of auroras in the zenith in per cent of the total number of observations as well as the number of observation intervals with auroras northward and southward of the station.

#	Station	Coordinates			Zenith	Number	
		ϕ, N	λ, W	Φ', N	%	N	S
1	Fritz-Peak	39°52’	105°31’	48.7°	2.2	82	1
2	Delaware	40°30’	83°	51.6°	3.6	152	26
3	Ithaka	42°27’	76°31’	53.8°	5.2	275	90
4	Pulman	46°43’	117°10’	53.5°	11.0	236	94
5	Meanook	54°36’	113°20’	61.8°	90.0	888	506

Table 1. Auroral observatories during the IGY with their coordinates (geographic latitude ϕ and longitude λ as well as the corrected geomagnetic latitude Φ'; appearance of auroras in the zenith in per cent of the total and the number of observations northward (N) and southward (S) of the station.

From Table 1 follows, that the probability of zenith auroras at the stations Delaware and Ithaka are small, although these stations are close to the zones "A" and "D". The auroras are seen mainly northward from the observatories, as it is usually expected at mid-latitudes of the Northern Hemisphere, i.e., in the direction toward the auroral zone. The Fritz-Peak station is situated between zones "A" and "D", which suggests observations of auroras both northward and southward. But for the period from August 1st to December 1st, 1957, there was only one case of observations in southward direction. The station Pulman is close to zone "A" in the western part of the continent. The number of auroras in the zenith was small and they were recorded mainly in northward direction. At the station Meanook, which is north of the zones "A" and "D", one would expect by far more aurora toward south. But they appeared more often northward, toward the aurora zone.

3.9 The observations of auroras at the mid-latitude stations at the American continent, situated in the region of corpuscular precipitation that are formed by the mid-latitude parts of zones "A" and "D", show the incorrectness of the planetary precipitation scheme, which had been proposed by Nikolsky. Along these zones, which stretch into mid-latitudes, zenith auroras are practically missing. Consequently corpuscular precipitations, which would lead to discrete auroral forms, are non-existent there. The existence of corpuscular precipitation regions, which extent into mid-latitudes or even to the equator during evening and nighttime hours, that would lead to the appearance of auroras at these latitudes, belongs rather to the genre of scientific fiction than to scientific results.

Referring to some morphological characteristics of magnetic disturbances at mid- and subauroral latitudes, Hope (1961) suggests, that they may be explained as disturbances transported from high to low latitudes by the ionospheric current system, probably identical with the S_D circulation. In addition we note that one cannot preclude a certain contribution to the disturbances at these latitudes originating from the magnetic fields of the magnetospheric currents systems and from the FACs between ionosphere and magnetosphere.

3.10 Mayaud (1956) studied the magnetic agitation in the polar region by using three-hourly amplitudes, obtained from the K-indices of 49 magnetic observatories at the Northern and Southern Hemispheres with $|\Phi'| > 50°$. He separated nighttime and daytime types of agitation, which corresponds to the nighttime (N) and morning (M) maxima of activity according to the terminology of Nikolsky. Nighttime agitation is characteristic for magnetically disturbed days and maximizes at latitudes of the auroral zone (magnetic inclination of $I \sim 77°$). The time moment of reaching the maximum agitation in the diurnal variation at the auroral latitudes lagged behind those at neighbouring (northward and southward) latitudes. The daytime agitation is most characteristic for the near-polar region with $I \sim 85°$, whose maximum is observed at local magnetic midday and shifted to ∼06 MLT at $I \sim 81°$. The daytime agitation has maximum values in summer, minimum values in winter, and stays at a comparatively high level during magnetically quiet days. Daily averaged agitation values showed in the latitudinal dependence both for individual seasons and for the full year on average, that the 3-hourly amplitudes have one maximum at $\Phi' \sim 65°$, but there is no disturbance enhancement in the near-polar region, which should be expected in case of a second, high-latitude maximum of the agitation.

3.11 Mansurov and Mishin (1960) investigated the Sa by using data from high-latitude stations in the Northern (19) and Southern (11) Hemisphere. Again the 3-hourly K-index was employed as measure of agitation. It was assumed that the Sa is controlled by local time and UT. That part, which depends on local time, is described as: $S_0(t) = S_0 + K_1 \cos(t - \alpha_1) + ...$ They determined the amplitudes and phases of the first harmonics and modelled the dependence of the amplitude from geomagnetic latitudes for the winter and the summer season. During the winter, there exists only one maximum at $\Phi \sim 67°$, but during the summer season there are two maxima at $\Phi \sim 66°$ and $\Phi \sim 77.5°$ in the latitudinal variation with a deep minimum at $\Phi \sim 73°$ in between. These maxima are interpreted as zones of enhanced magnetic activity (agitation): the zone of maximal disturbances at $\Phi \sim 66°$ is thought to be coinciding with the main auroral zone and that at $\Phi \sim 77.5°$ coincinding with the second, high-latitude zone or region “B” according to Nikolsky (1960a). Such an interpretation of the latitudinal amplitude distribution of the first harmonic, that was made by Mansurov and Mishin (1960), differs from the general view on the zones of maximal magnetic agitation. The latter is usually characterized by the largest daily averaged agitation value, but not by the amplitude variation value in the course of the day. Further, the amplitude values of the first harmonic K_1 is determined not only from the activity level, but also from the characteristic Sa value. The minimum of K_1 at $\Phi \sim 73°$ might be caused by two Sa maxima at this latitude in different local times. The K_1 values appear to be minimal during sufficiently strong daily averaged disturbance levels.

3.12 Beside of those studies, which employ statistical methods to derive regularities of magnetic disturbances, a number of scientists investigated the morphology of magnetic storms by comparing the magnetograms of various high-latitude observatories. Such a method was used in the studies of Birkeland (1913). The possibilties for applying this kind of methods extended greatly after the IGY. The data of a planetary-scale network of stations, collected in the World Data Centers, give a comprehensive perception of the global magnetic disturbances at all latitudes and longitudes. Results obtained by this kind of methods were presented, e.g., by Bobrov (1960).

3.13 Whitham and Loomer (1956) addressed in their investigations the question of the existence and position of a second zone of enhanced magnetic activity in the Canadian sector of the Arctic. The magnetic observatory Resolute Bay ($\Phi' \sim 83°$) is situated, according to Alfvén (1955) and Nikolsky (1956), directly under the second zone, while the station Baker Lake $\Phi' \sim 73.7°$ sits between the first and the second zone of enhanced magnetic activity. The comparison of the magnetic data of these two stations for the years 1953-1954 showed an interconnection between their disturbance states, but no unambiguous evidence for the existence of the second zone of corpuscular precipitation that spans above Resolute Bay.

Whitham et al. (1960) analysed the latitudinal variation of the magnetic disturbances based on 16 magnetic stations in Canada with $54° < \Phi' < 86°$ for winter, equinox, and summer periods of the IGY. They used the hourly amplitudes of horizontal components (H, X, or Y) as the index of magnetic activity and the levels of activity were determined for all data as well as separately for the disturbed and the quiet days. It was concluded, that there exists a maximum in the latitudinal distribution at $\Phi' \sim 67°$ for all seasons and for all activity levels, in which during disturbed days the level reaches ~ 200 nT. Confirming the former results of Whitham and Loomer (1956), no anomaly effects were found at the station Resolute Bay, which could indicate a second zone of enhanced magnetic activity in the proximity of the station. Some activity enhancements at the station Alert ($\Phi' \sim 85.7°$) close to the geomagnetic pole were assumed to be due to a limited localized region of enhanced activity.

3.14 Some progress in the analysis of regularities in the spatial-temporal distribution of the magnetic activity at high latitudes came along with the research efforts of Burdo (1960). Observational material of 30 locations were used, unfortunately non-uniform in interval length, times of observation and the activity index used. He devoted particular attention in the study of the Sa forms, because the absolute amplitude of the magnetic disturbance depends essentially from the season and the index used. Seasonal variations could not be deduced, since the observations at 16 (out of 30) locations were shorter than one month. The latitudinal dependence on the maximum entry times in Sa appears to be more regularly when using the corrected geomagnetic latitude Φ', which takes into account the position of the station with respect to the auroral zone. This means according to Burdo (1960), that the magnetic activity at any time of the day is controlled by processes in the auroral zone. The activity is most intense at corrected geomagnetic latitudes of $64° < \Phi' < 66°$ between 01–03 MLT. This maximum splits up with increasing latitude and becomes effectively two maxima – one at morning and the other at nighttime. The distance between the two maxima increases with further shift toward the pole. A third (evening) maximum at $64° < \Phi' < 66°$ comes in at 17–19 MLT. With increasing Φ', the morning and evening maxima convene more and more and converge finally into one at $\Phi' \sim 78° - 80°$, which is found at 10–12 MLT. In observatories with the same distance to the auroral zone, but at different longitudes, the maximum occurs approximately at one and the same MLT. This fact serves as proof that the universal time has practically no influence on the form of Sa.

Synchronous hourly values of the disturbance vector ΔT_{hor} at the stations Fort Rae ($\Phi \sim 69.7°$) and Tromsø ($\Phi \sim 67°$) were compared for 15–16 UT, when these stations are under the intense current regions of the morning and evening vortices, respectively. It turned out that the disturbances at both stations appear at the same time, i.e., with the increase of the disturbance intensity at one station it also increased at the other. This disproves the conclusion of Nikolsky (1951) about the independence on disturbances during the morning and evening hours. The disturbances thus appear simultaneously at the morning and evening side of the Earth, comprising the whole high-latitude region with maximum intensities close to the magnetic spirals.

3.15 The regularities of magnetic disturbances at high latitudes were studied by Feldstein (1963a) using data of a global set of stations from the IGY period. Hourly Q-index values of magnetic activity were used, which allow the study of diurnal and latitudinal variations of the activity (Bartels and Fukushima, 1956). This index characterizes the amplitude variations of the horizontal geomagnetic field component for 15-min intervals and accounts further for the maximal deviation of these elements from the quiet time level. The disturbance of one hour is estimated at most by four 15-min intervals. Observations form 27 stations were used, which cover the high-latitudes of the Northern Hemisphere between $58.4° < \Phi' < 88.1°$. The IGY observations allowed at the highest level the use of homogeneous material both for the interval length and time of the observations as well as with respect to the activity index. Diurnal and latitudinal variations of the agitation were analysed separately for magnetically disturbed and magnetically quiet days. The form of the diurnal variation depends on season and to a great extent on the geomagnetic latitude of the observation.

3.16 The Sa has one maximum in the near-polar region during the winter season converging to the midday MLT hours (at stations Thule, $\Phi' = 86.2°$, Resolute Bay, $\Phi' = 83.0°$, and Godhavn, $\Phi' = 77.5°$). At lower geomagnetic latitudes, this maximum shift to the morning hours and in the Sa appears a second, evening maximum (stations Murchison Bay, $\Phi' = 75.1°$, Tikhaya Bay, $\Phi' = 74.7°$, Baker Lake, $\Phi' = 73.7°$, Cape Cheluskin, $\Phi' = 71.6°$, and Point Barrow, $\Phi' = 69.4°$. At even lower latitudes, these maxima are difficult to discriminate as they merge to one single maximum approaching midnight hours (stations Dixon Island, $\Phi' = 68.0°$, Leirvogur, $\Phi' = 66.8°$, Kiruna, $\Phi' = 65.4°$, College, $\Phi' = 64.7°$, Murmansk, $\Phi' = 64.1°$, Sodankylä, $\Phi' = 63.0°$, and Meanook $\Phi' = 61.9°$. The Sa forms are better controlled by the corrected geomagnetic latitude (Hultqvist, 1958; Gustafsson, 1970) than by geomagnetic latitude. The stations Julianehab ($\Phi = 70.8°$, $\Phi' = 68.7°$) and Leirvogur ($\Phi = 70.2°$, $\Phi' = 66.8°$), which are located at relatively high geomagnetic latitudes, have only one near-midnight Sa maximum, which is characteristic for the auroral zone, but the stations Point Barrow ($\Phi = 68.3°$, $\Phi' = 69.4°$) and Cape Chelyuskin ($\Phi = 66.2°$, $\Phi' = 71.6°$) at relatively low latitudes have clearly two maxima (nighttime and morning), which is characteristic for stations at latitudes adjoining the near-polar region. The latitudinal anomalies in the Sa forms disappear, when replacing the geomagnetic latitude Φ with the corrected geomagnetic latitude Φ'. When moving from the auroral zone toward higher latitudes, the morning disturbances shift to later hours, and the nighttime disturbances to earlier MLT hours. Drawn in polar coordinates Φ' versus MLT, the maxima in Sa are ordered along segments of spirals. The change in local time for varying latitudes s stronger for the morning maximum than for the nighttime maximum. There are no longitudinal differences in the time of maximum appearance for the Sa. This is an evidence for the unimportance of the UT moment for the positions of maxima in Sa.

3.17 In the summer season, the Sa behaviour is subject to substantial changes. From the geomagnetic pole down to $\Phi' \sim 70°$, Sa is characterised now by one maximum in the prenoon MLT hours. At lower latitudes, one observes two maxima of Sa: one in the post-midnight to early morning hours and one in the afternoon to evening MLT hours. The Sa maximum in the afternoon to evening hours turn up as the

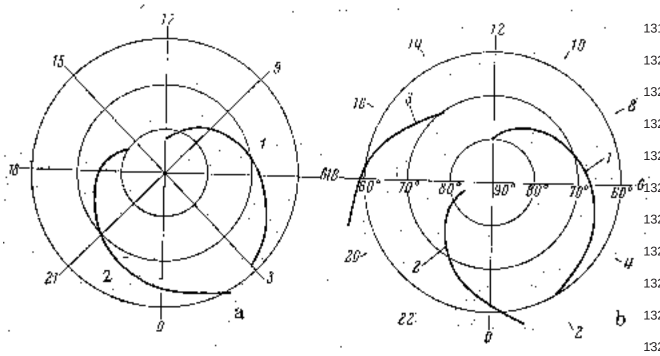

Figure 5. Dependencies of local geomagnetic time of Sa maximum occurrence on corrected geomagnetic latitude for magneto-disturbed days. a- winter, b summer 1 morning (M) maximum of agitation; 2 night (N) maximum of agitation; 3 evening (E) maximum of agitation (Feldstein, 1963a).

characteristic pecularity of the summer season as it is missing in winter. Its appearance changes the form of Sa fundamentally during the transition from winter to summer at $\Phi' \sim 60° \div 70°$.

The analysis of Sa based on the Q-index of magnetic activity over all days of the winter and the summer season during the IGY proves the existence of morning, nighttime and evening agitation maxima at $\Phi' > 60°$. Thereby each season has its own specified maxima: during summer in the morning and evening and during winter in the nighttime and morning hours. In the near-polar region one observes one single maximum during daytime hours.

3.18 Fig. 5 shows the moments of maxima in Sa in polar coordinates Φ' versus MLT as observed during magnetically disturbed days of the winter (a) and the summer (b) season. The basic characteristics of Sa are kept during all days in the winter season (Fig. 5a). The diurnal activity variation has two maxima – during morning and nighttime hours. The morning maximum appears at later morning hours with increasing Φ', while the nighttime maximum appears earlier in the evening hours. The nighttime maximum, however, shifts faster toward earlier evening hours with increasing Φ' than for observations, which comprise the full day, and at $\Phi' \sim 80°$ this difference in MLT attains four hours. The nighttime maximum appears at all stations up to the highest latitudes. The morning maximum clearly traces from the near-polar region to the latitudes of the auroral zone. The segments of the spiral, that correspond to the nighttime and morning Sa extremes, establish a shape, which reminds an oval, whose symmetry axis traverses the meridian 02–14 MLT.

During magnetically disturbed days of the summer season (Fig. 5b), there are three clearly established maxima of Sa activity at many stations. Three maxima appear crystal clear at the stations Arctica 2 ($\Phi' = 77.5°$), Tikhaya Bay ($\Phi' = 74.7°$), Cape Chelyuskin ($\Phi' = 71.6°$), Dixon Island ($\Phi' = 68.0°$), Murmansk ($\Phi' = 64.1°$), Sodankylä ($\Phi' = 63.0°$), Cape Wellen ($\Phi' = 62.5°$), Meanook ($\Phi' = 61.9°$), and Lerwick ($\Phi' = 59.4°$). The three distinct maxima in Sa are obviously the characteristic pecularity of the summer season during days of intense magnetic disturbances. Apart from the dependence on the magnetic activity level, during the winter season, as a rule, there exist not more than two maxima. The evening maximum does not appear related to the strong weakening of the disturbance intensity with $\Delta H > 0$ during these hours. Such disturbances exist, but they do not appear as maximum in Sa at the background of the subsequent more intense disturbances with $\Delta H < 0$.

The intensity of the disturbances along the winter and summer spirals is different. During winter, the nighttime and morning disturbances maximize at latitudes of the auroral zone and become smaller toward higher latitudes. This decrease is very small till $\Phi' \sim 75°$, but at higher latitudes the disturbance decreases sharply. During summer, the disturbances along the evening and morning spirals increases monotonically from mid-latitudes to the auroral zone and beyond that till $\Phi' \sim 72°$, but for the morning maximum it remains at a high level until the near-polar region at $\Phi' \sim 84°$.

3.19 What is the nature of the spiral distributions in the time moments of maximum values in Sa? There exist essentially two assumptions in the public literature: firstly, precipitation of corpuscular fluxes takes place along all spirals or at least along some of it (Nikolsky, 1956; Feldstein, 1963a) or, secondly, the spirals are the places of convergent current lines of the equivalent current system (Harang, 1946; Burdo, 1960). In the first case, the morning and nighttime spirals of the winter season should coincide with the position of auroras in the zenith, i.e., with the auroral oval, as the position of auroras points at the places of precipitating electrons with auroral energy into the upper atmospheric layers. The magnetic disturbance can be the result of processes, which take place far from the location of their records.

In Fig. 6 (from Akasofu, 1968) shows the M, N, and E spirals, obtained by Feldstein (1963a), together with the auroral oval according to Feldstein (1963b) in polar coordinates Φ' versus MLT. This compilation shows, that during magnetically disturbed days the nighttime spiral N and during morning hours the M spiral are situated within the auroral oval, i.e., within the region of precipitating electrons with auroral energy. The N and M spirals, obtained from observations of the magnetic disturbances, are therefore positioned within the auroral oval of precipitating electrons. The evening spiral E adjoins to the equatorial side of the auroral oval. This is the region of the eastward electrojet and of precipitating protons with auroral energies and soft electrons (Starkov and Feldstein, 1970).

4 Spirals in the distributions of auroras

4.1 The daily variation of the occurrence frequency of visible auroras is an important aspect of the auroral activity. The

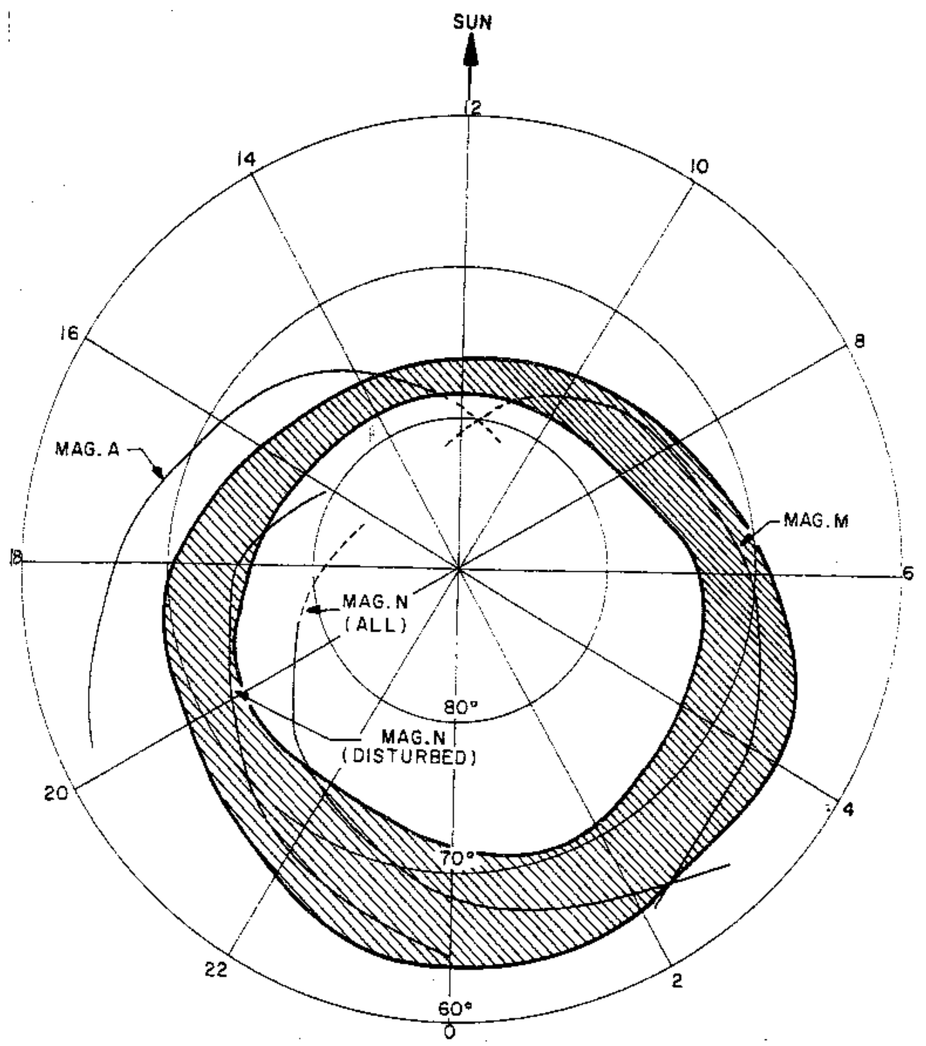

Figure 6. The M, N and E spirals determined by Feldstein (1963a) and the auroral oval by Feldstein (1963b) in dipole latitude and time coordinates (from Akasofu, 1968, Fig. 9).

simplicity of its determination and the informative value of this parameter for comparisons of the auroras with other geophysical phenomena of the electromagnetic complex stimulated the appearance of a multitude of publications in this field of research. Below we consider only a few of them, which generalize the observations and give general impressions about acting physical regularities.

4.2 There is a tendency, that intense active discrete auroral forms appear most often ~ 1 hour prior to magnetic midnight at latitudes of the auroral zone, as it was described by Vegard (1912) according to the materials of the First International Polar Year (1882–1883). Additional to the nighttime maximum, some high-latitude stations indicated a secondary morning maximum (Tromholt, 1882; Isaev, 1940; Pushkov et al., 1937). The accurate visual observations of auroras performed by Tromholt at the station Godthab ($\Phi' \sim 73.3°$) in Greenland attracted particular attention. The diurnal variation of the aurora occurrence frequency is characterized by two maxima, one during late evening, the other during morning hours, and a minimum shortly after midnight. The morning maximum at 05–07 MLT was afterwards interpreted as evidence for the existence of a second auroral zone in the polar cap, where the occurrence frequency of auroras and of intense magnetic disturbances maximizes (Nikolsky, 1960b). The maximum during morning hours appears clearly in the daily variations of visual data sets at the stations Kinga Fjord ($\Phi' \sim 77.8°$) in Canada (Neumayer and Börgen, 1886) and Tikhaya Bay ($\Phi' \sim 74.7°$) at Franz Joseph Land (Pushkov et al., 1937; Isaev and Pushkov, 1958). This maximum is absent in the records of some other stations. Analysing a large amount of observational data, Hulburt (1931) comes to the conclusion that the probability of the occurrence of a secondary morning maximum is as high as its absence.

Full-day visual aurora observations at Greenland are not possible even during winter season, because of the daylight period from ∼07–17 local time. This complicates the precise determination of the morning maximum and the frequency of its occurrence. Observations by Carlheim-Gyllenskiold (1887) at the station Cap Thordsen, Spitzbergen ($\Phi' \sim 74.3°$), where practically a full-day monitoring is possible, confirmed the existence of two maxima - one in the morning and the other during pre-midnight hours MLT.

4.3 Based on hourly observations of the years 1954–1955 from 50 polar stations at geomagnetic latitudes $57° < \Phi < 80°$, Feldstein (1958) concluded: 1) the nighttime maximum attains maximal values at auroral zone latitudes ($\Phi \sim 65°$); 2) the shape of diurnal variations changes gradually with increasing latitude, and there appears a second maximum in the morning hours at ($\Phi > 69°$) with a smaller intensity of the absolute value than the nighttime one. In the near-polar region, the diurnal variation is sparsely developed and discrete forms appear likewise rarely both during nighttime and morning hours.

Lassen (1959a,b, 1961) investigated the diurnal variation of auroral occurrences at 5 Greenland stations for the years 1948–1950. It was concluded that the different types of diurnal distribution can be arranged according to the following scheme: 1) at latitudes of the main auroral zone, there is one maximum of auroral occurrence around midnight; 2) at latitudes from the main to the inner zone of auroras ($8° - 10°$ poleward from the main zone), there appears a second, smaller morning maximum; 3) within the inner auroral zone, one observes clearly two maxima - one around midnight and the other at ∼06 MLT; 4) within the polar cap, the morning maximum dominates about the nighttime one. Subsequently Lassen (1963) analyzed the results of visual observations at many high-latitude stations for the interval of the I^{st} IPY (1882/83) and up to the begin of the IGY with respect to the daily variation of the frequency of auroral occurrences and obtained the following results: 1) stations in the latitudinal range $64° < \Phi < 69°$ show a maximum near midnight; 2) between $70° < \Phi < 76°$ an evening and a morning maximum of equal size are observed; 3) north of $\Phi \sim 77° \div 78°$, the morning maximum is dominating, it occurs late in the morning. Lassen (1963) could not find a regular displacement of the evening and morning maxima.

4.4 Visual observations in the above-mentioned investigations considered auroral forms that are visible over the entire sky. Assuming an elevation of 100 km for the lower borders of the auroras, such observations comprise $\sim 17°$ of latitude, from the northern to the southern horizon. Consequently, only a limited latitudinal discrimination was possible. By determining the geomagnetic times of the maximum occurrence probability for overhead auroras in $1°$ wide latitudinal ranges, Malville (1959) demonstrated at the stations Ellsworth ($\Phi \sim 67°$) and South Pole ($\Phi \sim 77°$), Antarctica, that the maximum time occurs systematically earlier in the evening as the pole is approached from the auroral zone. This dependence in polar coordinates Φ versus MLT arises as a part of the spiral in the range $64° < \Phi < 71°$ in the evening sector. The publication of Malville (1959) is the first one, where the existence of a spiral regularity in the spatial-temporal distributions of aurorae is mentioned. Later it was extended both in latitudinal range and by including the distribution of the morning spiral.

4.5 During the IGY, a network of all-sky cameras operated at high latitudes, which produced photos of the sky in 1-min cadence with exposure times of 20 sec or 5 sec. The results of the perusal of the all-sky films were recorded in special tables - the so-called ascaplots, which allowed to localize the aurora on the sky, to exclude intervals of illumination times and of bad meteorological conditions. The ascaplots were assembled according to the instructions of Stoffregen (1959). The full sky was divided along the geomagnetic meridian into three zones: zenith (from $30°$ elevation north to $30°$ elevation above the south horizon), North (from $10°$ to $30°$ elevation above the north horizon), south (from $10°$ to $30°$ elevation above the south horizon). The extent of each stripe amounts to $\sim 3°$ of geomagnetic latitude. The report about the ascaplots of a global network of stations is given in Annals (1962).

4.6 Feldstein (1960) determined the diurnal variation of auroral occurrence frequency in the zenith for 24 stations of the Northern Hemisphere in the latitude range $55° < \Phi' < 85°$. Fig. 7 shows the characteristic shapes of the diurnal variation for various latitudes. In the auroral zone and equatorward of it clearly appears a maximum. It occurs at ∼03 MLT in Verkhoyansk ($\Phi' = 56.6°$) and around midnight MLT for $\Phi' \sim 65° \div 66°$ (Murmansk, $\Phi' = 64.1°$ and Wrangel Island, $\Phi' = 64.7°$). At higher latitudes between $67° < \Phi' < 78°$, there exist two maxima - one in the evening hours, the other in the morning (Arctica I at $\Phi' \sim 72°$ and Piramida, Spitzbergen at $\Phi' \sim 77°$). With increasing latitude, the morning maximum occurs later in the morning and the evening maximum occurs earlier. Already at $\Phi' \sim 80°$, the auroras don't emerge at midnight as at auroral latitudes, but around midday. In the polar cap (Arctica II at $\Phi' \sim 82°$, the auroras are rare, but if so, they appear mainly during daytime hours. The maximum around midnight at $\Phi' \sim 73° \div 75°$ appears in visual observations of the full sky during the I^{st} IPY at Greenland and Spitzbergen as intense auroras with a southern azimuth at latitudes of the nighttime auroral zone.

The appearance times of the "nighttime" and "morning" maxima in Φ'–MLT coordinates are distributed along two segment of straight lines. Transferring this relationship into polar coordinates (Fig. 8), then it results in a pattern, which reminds of an oval with minimum distance to the geomagnetic pole on dayside hours and maximum distance at night. The oval consists of two spirals with opposite sense. Fig. 8 represents the first full display of spiral regularities in the auroras of the Northern Hemisphere. A similar double spiral distribution for the Southern Hemisphere was obtained by Feldstein and Solomatina (1961). They are considered as the starting point for introducing the term "auroral oval" in

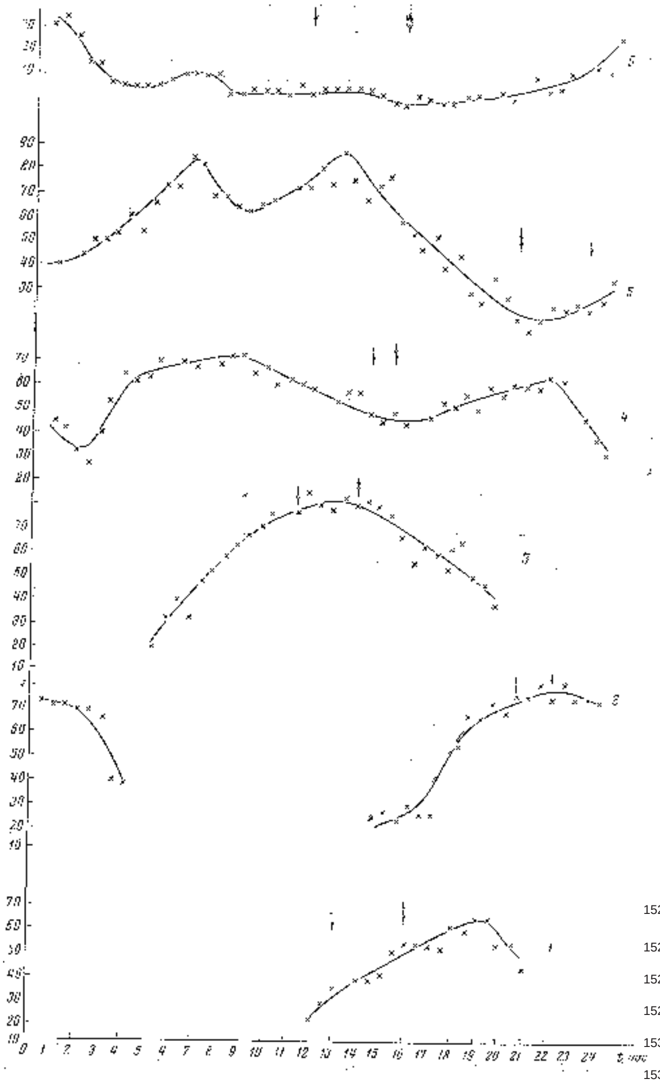

Figure 7. Diurnal variations of auroras appearance in zenith (Universal Time). 1 – Verkhoyansk; 2 – Murmansk; 3 – Wrangel Island; 4 – Arctic I (North Pole 6); 5 – Piramida (Spitzbergen); 6 – Arctic II (North Pole 7). Figures along the axis of ordinates signify the frequency of appearance of auroras at zenith (in percent). The arrow depicts local midnight, double arrow depicts local geomagnetic midnight (Feldstein, 1960).

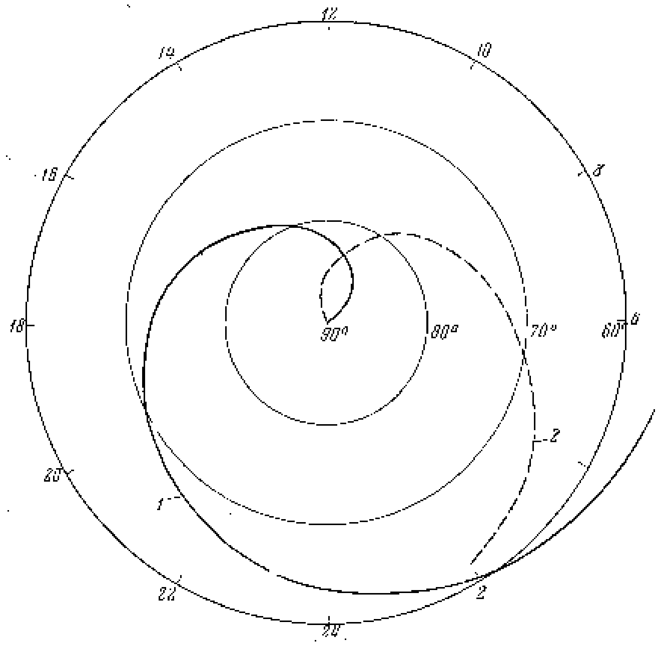

Figure 8. Dependence of occurrence times of MLT “night” and “morning” maxima in diurnal changes of probability of auroras appearance in zenith on geomagnetic latitude in polar coordinates (Feldstein, 1960). 1 – night maximum; 2 – morning maximum.

solar-terrestrial physics, signifying the region, where energetic charged particles penetrate into the upper atmosphere. On the one hand the auroral oval is the region of the most frequent appearance of auroral forms in the zenith at a given geomagnetic latitude, but it signifies also the actual zone of auroral lights for the given moment in time. The oval is asymmetric with respect to the geomagnetic pole due to the deformation of the geomagnetic field by the solar wind. The discussions about the conception of the auroral oval continued in the science community till the 70-ies of the past century as long as it didn’t find its affirmation in the “Sputnik era” of active space exploration.

4.7 Lassen (1963) used aurora observations at four Greenland stations during the IGY to determine the diurnal variation of frequencies of occurence in the zenith as well as northward and southward of the zenith. At the stations Godhavn ($\Phi' = 77.5°$), Kap Tobin ($\Phi' = 72.7°$) and Julianehab ($\Phi' = 68.7°$), auroral observations were not possible during 10 daytime hours because of the daylight. A continuous data set was achieved by the use of ascaplots from nine additional high-latitude stations in the Arctic and Antarkic. Four of them allowed auroral observations throughout the whole day. The moments of maxima in the diurnal variation are allocated close to two segments of straight lines. In polar coordinates the maxima rearrange along two spirals of opposite sense. These results coincide with the similar double spiral distribution shown by Feldstein (1960). Such a coincidence of the results of two independent investigations can be expected, considering the accordance in the selected data sets.

4.8 Magnetic disturbances and auroras constitute different aspects of the same electromagnetic complex of phenomena that take place at high altitudes. The magnetic variations, on the one hand, which are recorded at the Earth’s surface, represent the integral effect of the corpuscular fluxes and of the current systems in the ionosphere, covering a considerable part of Earth, but the positioning of the auroras points directly to the location of precipitating corpuscular fluxes, that cause the magnetic disturbance.

The discussion of the interrelationship between the auroras of different types and the plasma domains in the magnetosphere and their structure is beyond the scope of the present review. Detailed considerations about the present understanding of problems in auroral physics is contained in the collective monograph on "Auroral Plasma Physics" (Paschmann et al., 2002). Results about the projection of the boundaries of various aurora types from ionospheric level into the magnetosphere and the relation of their emissions with the magnetospheric plasma domains are sumed up by Feldstein et al. (1994) and Galperin and Feldstein (1996).

5 Interpretations of the spiral regularities in magnetic field variations and auroras

5.1 Magnetic spirals, their number and correlation with the ionospheric current system

The number of spirals appeared to be disputed, based on the analysis of S_D variations of the geomagnetic field as discussed in the previous sections; according to Meek there are two (M and E spirals), while according to Harang–Burdo–Feldstein ("H.–B.–F.") we have to deal with three of them (M, N, and E spirals). Referred to Meek (1955), there could be only two spirals, namely one that represents the maximimum decrease of the horizontal component ($\Delta H < 0$, M spiral) or the other that represents the maximum increase ($\Delta H > 0$, E spiral). A third spiral was not identified, as along it also applies $\Delta H < 0$, but with a smaller amplitude than in the deepest minimum. According to H.–B.–F., the spirals match both extremal values in $\Delta H < 0$ and a sign change in ΔZ. The number of extremal values in the diurnal variation of ΔH changes in dependence on magnetic latitude from one to three (the M, N, and E spirals). Three characteristic peaks were also found in the diurnal variation of the Sa activity (Chapman and Bartels, 1940; Nikolsky, 1951, 1956; Burdo, 1960; Feldstein, 1963a). Also Akasofu (2002) distinguishs three spirals M, N, and E.

The magnetic spirals specify regions, where concentrated isolines of the ionospheric equivalent current system S_D describe the magnetic field variations at high-latitudes. Two spirals form the current oval: for Meek (1955) it consists of the westward (M spiral) and eastward directed currents (E spiral), while for H.–B.–F. only of westward directed (M and N spirals). The current direction in the spirals is not unambiguously related to the direction of its winding: in the M and N spirals with westward currents, the winding is in different directions; in the N and E spirals, which turn in one and the same direction, the direction of the current is opposite to each other. The winding of the spiral is also not determined by the sign of the charged particles that precipitate into the upper atmosphere. Particles of the same sign are precipitating along the M and N spirals (electrons of auroral energy, that are forming the oval), but the winding direction of these spirals differs.

5.2 Discontinuity in the ionospheric current of the auroral belt

5.2.1 The equivalent current system, which characterizes the intensity and spatial distribution of geomagnetic disturbances at high latitudes, was introduced by Chapman (1935). It was a major paradigm for a few decades. Its characteristic pecularity consists in two concentrated current flows in the auroral zone, which were named by Chapman as electrojets: the eastward electrojet (EE) appears in the evening sector and the westward electrojet (WE) on the morning side. Between these electrojets exist discontinuities during a few hours around midnight and midday.

5.2.2 Harang (1946, 1951) confirmed with his investigations, that the electrojets are located within the auroral zone at $\Phi \sim 67°$ from evening to morning hours. This was to a great extent due to the paradigm (ruling at that time) about the positioning of a particle precipitation region at these latitudes. The Harang study presented no drastic revision of the conceptions regarding the structure of the high-latitude current system. As before, the electrojets were associated with the auroral zone. According to Harang a discontinuity between the WE and EE is located at latitudes of the aurora zone but not along the auroral oval (yet unidentified at that time). The morphology of the night time discontinuity between the electrojets was shown in detail in Harang (1946, Fig. 2). It does not come to an agreement with his statement about the discontinuity in the localisation at aurora zone latitudes. The electrojets overlap each other in the dusk sector (in the sense that the EE and WE coexist at the same local time but at different latitudes) and the westward current is located there poleward of the eastward. Between the electrojets there exists no discontinuity, according to his data, but rather a gap, whose latitude varies between evening and nighttime hours. The westward electrojet is not delimited by the midnight meridian, but extends toward the evening sector, positioned at higher latitudes with respect to the eastward electrojet. Due to this, the electrojets don't stay strictly within the auroral zone at $\Phi \sim 67°$ from the evening to the morning side, but comprise also slightly higher latitudes. For the western electrojet during nighttime any discontinuity is absent; the jet rather continues steadily in LT from morning hours over the nighttime to evening hours.

5.2.3 According to Burdo (1960) the latitude of the discontinuity between the electrojets increases from $\Phi' \sim 65°$ at midnight to $\Phi' \sim 75°$ at ~ 20 MLT. Those processes that lead to the generation of currents, which are responsible for the observed geomagnetic variations, are both for Harang and Burdo the precipitation of corpuscular fluxes at auroral zone latitudes (the existence of an auroral oval was not known at the time of their publications). Currents at higher latitudes start-up due to the dynamo effect. The existence of dynamo electric fields is also necessary, as they are generated at ionospheric altitudes owing to the neutral wind motion within these layers. The dynamo current system at ionospheric altitudes is two-dimensional and controlled by processes in the upper atmosphere close to Earth.

5.2.4 The discovery of the auroral oval brought about a new stage for the interpretation of the discontinuity between the electrojets. This discovery led to a fundamental change in the conception of the planetary morphology concerning the electro-magnetic complex in the near-Earth space (Akasofu and Chapman, 1972). The active auroral forms and hence the most frequent and most intense corpuscular precipitations into the upper atmosphere are distributed along the auroral oval and not along the auroral zone. It was shown, that the westward electrojet runs along the auroral oval from the evening to the morning MLT hours (Feldstein, 1963b; Feldstein and Zaitzev, 1965b; Akasofu et al., 1965; Akasofu and Meng, 1967a,b,c; Starkov and Feldstein, 1970).

The location and configuration of the auroral oval is intimately connected with the asymmetric shape of the Earth's magnetosphere in the Sun-Earth direction (O'Brien, 1963; Frank et al., 1964; Feldstein, 1966), with the plasma structure of the magnetosphere (Vasyliunas, 1970; Frank, 1971; Winningham et al., 1975; Feldstein and Galperin, 1985), and in particular with the plasma sheet in the magnetospheric tail. The eastward electrojet runs in the evening sector at latitudes of diffuse luminosity, adjoining the auroral oval at the equatorial side. This luminosity is caused by the precipitation of low energy electrons from the inner magnetosphere with energies up to ~ 10 eV, which are convected from the plasma sheet in the Earth's magnetotail (Nishida, 1966; Feldstein and Galperin, 1985), and by protons with energies of ~ 10 keV, which are formed in the magnetosphere in the partial ring current of westward direction (Grafe et al., 1997; Liemohn et al., 2001). Its short-circuit by FACs through the ionosphere causes the appearance of the eastward electrojet in the ionosphere. This way the emergence of the auroral oval conception combined the existence of the gap between the eastward and westward electrojet with the magnetospheric plasma structure.

5.2.5 In the course of 30 years (from 1935 till 1965), both the morphology and the physical conception of the nighttime discontinuity in the equivalent ionospheric current system changed successively, Heppner (1972) proposed to call it the Harang discontinuity. This term has been consolidated since that time in the scientific literature as designation of the discontinuity between the electrojets. Note that the existence of the discontinuity was found by Harang in 1946 (see, e.g., Zou et al., 2009). Apparently, when discussing the discontinuity between the electrojets as a natural phenomenon, debated intensively for a long time, one has to give credit to various cutting-edge research efforts:

– Chapman–Harang (CH) – discontinuity at auroral zone latitudes during near midnight hours;

– Harang–Burdo (HB) – for increasing latitude of the discontinuity in the evening sector, it shifts from midnight to evening hours. The generation of electrojets in the ionosphere and the discontinuity between them are caused by the precipitation of auroral particles and therefore the enhanced ionospheric conductivity at latitudes of the auroral oval as well as by the neutral wind system in the ionosphere. The dynamo action is responsible for the appearance of a 2-D current system at ionospheric heights;

– Feldstein–Akasofu (FA) – no discontinuity, but rather a gap between the eastward and westward electrojets. The morphology of the current gap is analogue to the current discontinuity of HB, but the physical reason for the gap appearance is different. In actuality, there occurs no discontinuity of the electrojet, because in the westward electrojet any discontinuity is missing. The electrojet does not break apart, but continues from nighttime to evening hours, shifting toward higher latitudes. Resulting from that, between the electrojets appears a gap. This gap reflects the boundary of large-scale plasma structures in the nightside magnetosphere. The westward electrojet along the auroral oval is connected with the central plasma sheet in the magnetospheric tail, while the eastward electrojet – with the Alfvén layer in the inner magnetosphere (Feldstein et al., 2006). The electrojets appear as elements of a 3-D current system, which extends throughout the Earth's ionosphere and magnetosphere (Lyatsky et al., 1974; Akasofu, 2004; Marghitu et al., 2009).

6 Current systems of polar magnetic disturbances

6.1 The description of geomagnetic field variations by means of equivalent currents at ionospheric level and later also in its 3-D extension within the Earth's magnetosphere, has a long history. The sequential progression of perceptions in this field of geophysics was accomplished by the contributions of such "titans" of science like Kristian Birkeland, Sydney Chapman, Hannes Alfvén, Takesi Nagata, and many other outstanding scientists. It is beyond the scope of this review to consider this history, we rather have to confine ourself to a short demonstration of the present-day views about the spatial-temporal characteristics of the current system in the near-Earth space (Akasofu, 2002; Feldstein et al., 2006).

6.2. Modelling of equivalent ionospheric currents, based on magnetometer data on the Earths surface, can be realized with different methods. The direction and intensity of the linear current can be found by rotating the horizontal magnetic disturbance vector clockwise by 90° (Kamide and Akasofu, 1974; Baumjohann et al., 1980). Based on data from 70 magnetic observatories, including six meridional chains of magnetometers, Kamide et al. (1982) obtained the spatial distribution of ionospheric current densities for four UT cross-sections during a substorm on 19 March 1978. An overview of various techniques used for simulations of the equivalent currents from ground-based magnetometer data was given by Untiedt and Baumjohann (1993).

6.3. Kotikov et al. (1991) developed a practical inversion scheme to infer the fine structure of the auroral electrojet by utilizing a series of linear ionospheric currents (50 altogether) of different intensities located at 100 km altitude. The current distribution was adjusted to fit measurements on the Earth's surface. This numerical method for estimation of equivalent ionospheric currents, using magnetic field observations along meridian chains of ground-based vector magnetometers, allows not only for the determination of the latitudinal distribution of the ionospheric current intensity, but also for the separation of the contributions to the observed geomagnetic variations of the fields from external (ionospheric and magnetospheric) and internal (induced by telluric currents) sources. Popov and Feldstein (1996) and Popov et al. (2001) suggested a refinement of the Kotikov method by approximating the auroral electrojets with a series of narrow current strips of finite width. The strips with currents of different intensities were distributed along a geomagnetic meridian at 115 km altitude over the range of latitudes covered by the ground magnetometer stations. Both the accuracy of the method and its spatial resolution were considered in detail by Popov et al. (2001).

6.4. Feldstein et al. (2006) applied the refined method of Popov and Feldstein (1996) to some substorms and a magnetic storm in order to obtain the location and distribution of eastward and westward electrojet intensities as a function of latitude. For that study were used data from three meridian magnetometer chains: the IMAGE chain along the 110° CG (corrected geomagnetic) longitude meridian; the GWC chain along the 40° CG longitude meridian; the CANOPUS chain along the 330° CG longitude meridian.

The observed magnetic field variations in the vertical Z (downward) and horizontal H (northward) components at any point "l" along the geomagnetic meridian at the Earth's surface due to a single current strip is given by

$$H_{ext}(l) = \frac{j_i}{2\pi}\left\{\arctan\frac{x_i+d}{h} - \arctan\frac{x_i-d}{h}\right\} \qquad (6)$$

$$Z_{ext}(l) = \frac{j_i}{4\pi}\ln\left\{\frac{h^2+(x_i+d)^2}{h^2+(x_i-d)^2}\right\} \qquad (7)$$

where j_i is the current density in the i^{th} strip, d, h, and x_i are the half-width, the altitude, and the distance from the observation point to the ground projection of the centre of the i^{th} strip, respectively. Using these expressions for each of the K magnetometers in the chain we obtain 2K equations to determine the current densities in N strips (N=100). If N>2K, the problem is underdetermined and the solution is not unique. In order to constrain the solution the regularization method developed by Tikhonov and Arsenin (1977) is used.

6.5. Latitudinal current density distributions for every chain with a 10-min cadence were the basis for the creation of equivalent ionospheric current patterns in the course of the DP intervals. Such patterns are usually used for generalized representations of perturbed geomagnetic field vector distributions on the Earths surface. Fig. 9a-e shows schematically various current system patterns, that were reported in the literature by different authors. They comprise the classical two-vortex current system (Chapman, 1935; Fukushima, 1953) (Fig. 9a), the single-vortex system with a WE along the auroral oval (AO) and closure currents through the polar cap and at mid-latitudes (Fig. 9b) reported by Feldstein (1963b) and Akasofu et al. (1965), and the two-vortex system with a WE within the boundaries of the AO and with an EE in the evening sector at $\Phi \sim 65°$ (Feldstein and Zaitzev, 1965b) (Fig. 9c). It was concluded that during substorms the WE extends to all longitudes along the AO and its intensity decreases from midnight to noon hours. The EE as a separate current system, rather than a return current from the WE, is located at $\Phi \sim 65°$ in the evening sector.

6.6. A modification of these patterns (Fig. 9d,e) for substorm and storm intervals was realised by Feldstein et al. (2006). The space-time distribution of currents and their structure at high latitudes during a polar magnetic substorm with an intensity of AL~ -800 nT is shown in Fig. 9d. The locations of the WE (red strip), EE (green strip) and PE (polar electrojet: dark blue strip) are shown.

6.7. The narrow strip (2°-3° width in latitude) of the PE is located at the latitudes $78° < \Phi' < 80°$ under quiet magnetic conditions. These are typical for the ionospheric projection of cusp latitudes around noon. At substorm maximum both PE and cusp shift towards $\Phi \sim 73° \div 75°$ (Fig. 9d). Both intensity and direction of the PE are controlled by the IMF B_y component (eastward for $B_y > 0$ or westward for $B_y < 0$) [Feldstein, 1976 and references therein]. A number of pioneering investigations, devoted to PE and its connection with IMF, are quoted below. Svalgaard (1968) was the first who indicated the existence of two characteristic types of magnetic field variations in the polar regions. The disturbances occur simultaneously in the north and south polar caps and are controlled by the IMF sector polarity. The dependence on the magnetic field variations in the polar regions on the IMF sector polarity was independently obtained by Mansurov (1969). Friis-Christensen et al. (1972) and Sumaruk and Feldstein (1973) discovered independently and simultaneously, that those magnetic field variations are not controlled by the IMF sector polarity, but by the direction of the IMF azimuthal B_y component. Friis-Christensen and Wilhjelm (1975) and Feldstein et al. (1975) used a regression method for extracting the B_y-controlled fraction of the high-latitude magnetic field variations and identified the corresponding equivalent DPC(B_y) current systems. The detailed description of this type of magnetic field variations and corresponding DPC(B_y) current systems can be found in the review (Feldstein, 1976, and references therein). The PE is a characteristic feature of DPC(B_y) current system. The PE intensity during the summer season for the IMF $B_y \sim 6$ nT is $\sim 1.8 \times 10^5$ A.

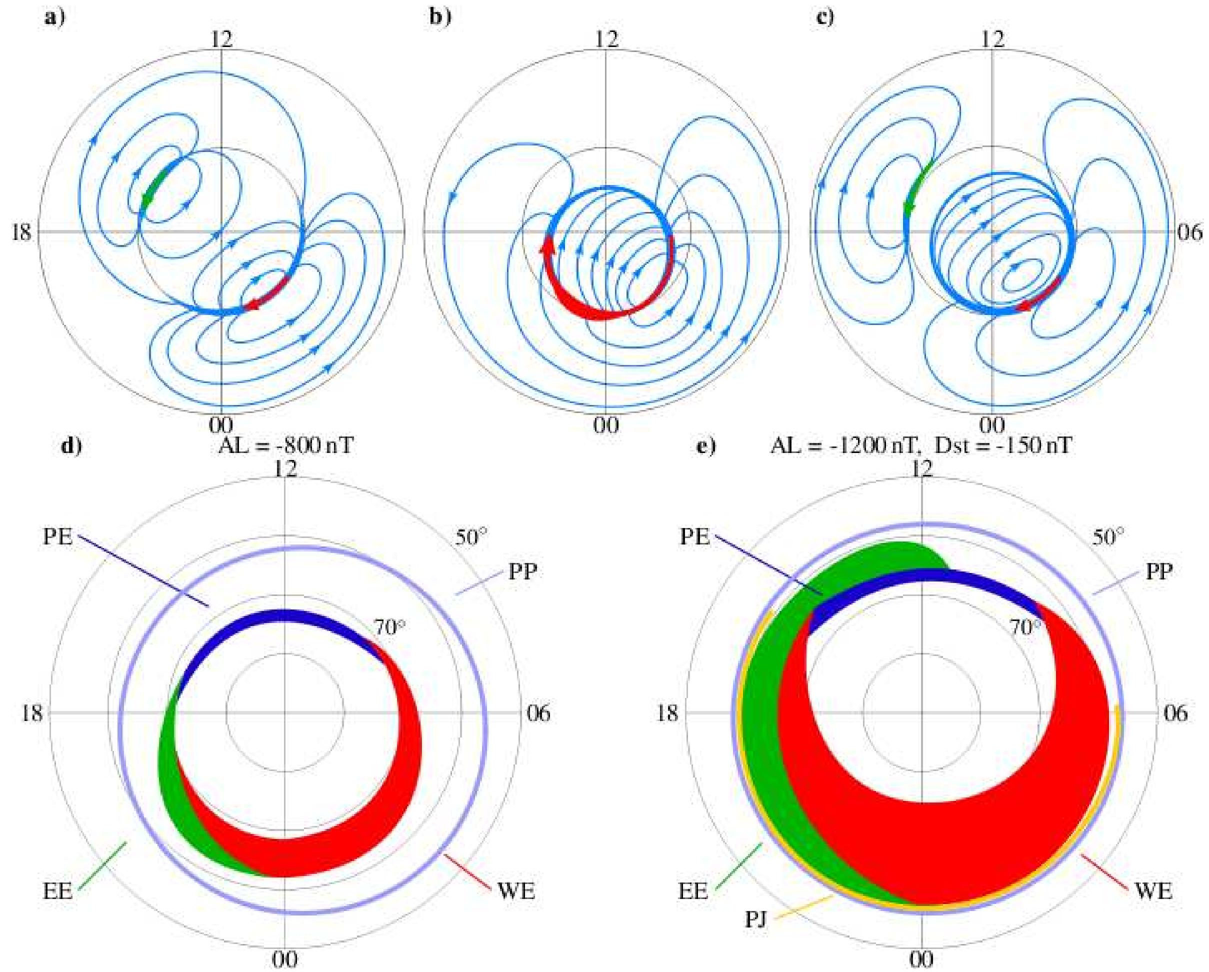

Figure 9. Schematic view of the electrojet's space-time distribution at ionospheric altitudes: a) classical current system according to (Fukushima,1953); b) single-vortex system with westward electrojet along the auroral oval according to (Akasofu et al., 1965); c) double-vortex system with westward electrojet along the auroral oval and eastward electrojet in the evening sector at latitudes of the auroral zone according to (Feldstein and Zaitsev, 1965b); d) the magnetospheric substorm with AL ~ -800 nT; e) the magnetic storm main phase with AL ~ -1200 nT, Dst ~ -150 nT (d and e by Feldstein et al., 2006).

6.8. During substorm intervals the characteristics of the eastward/westward currents as far as their intensities and locations are concerned, can be summarized as follows:

– westward currents are most intense after midnight hours at auroral latitudes of $65^\circ < \Phi < 70^\circ$, and are shifted to cusp latitudes ($\Phi \sim 73^\circ$) in the morning and evening sectors. Its latitudinal width is $\sim 6^\circ$ during midnight-dawn hours. As seen in Fig. 9d the WE does not cover all MLT hours (contrary to Figs. 9b,c) during the substorm, but is seen only within evening-night-morning hours. During pre-noon and late afternoon hours the WE adjoins the cusp, i.e., it is magnetically mapped to the magnetopause;

– eastward currents in the evening sector start from cusp latitudes ($\Phi \sim 73^\circ$) during the early afternoon MLT hours, become most intense in the evening MLT, and reach auroral latitudes at nighttime hours. The EE comprises the evening sector from early evening to midnight hours and is located at lower latitudes when approaching midnight. During midnight the EE latitude is the same as that of the WE equatorward edge. Both the EE width and its intensity reach maximum values during dusk hours;

– eastward currents are located just equatorward of the westward currents for evening hours where currents in opposite directions overlap in latitude. During evening hours, when overlapping occurs, the maximum eastward current intensity is higher than the westward current intensity at the same local time;

– the EE shown in Fig. 9d is not a closure current for the WE at higher latitudes, contrary to Fig. 9b, and is not located in the auroral zone ($\Phi \sim 65°$), contrary to Fig. 9c. During early evening hours the EE adjoins the ionospheric projection of the cusp (CU), i.e. the EE is magnetically mapped to the magnetopause during this MLT interval.

It is clear from Fig. 9d that the WE is located along M and N spiral segments, but it does not cover the MLT hours near midday. Such peculiarity in the WE structure is determined by the character of its connection with the central plasma sheet in the magnetospheric tail. The EE is located immediately equatorwards of the WE, along the E-spiral.

6.9. In Fig. 9d the location of the projection of the plasmapause (PP) to ionospheric altitudes is indicated by the quasi-circle (blue). There is a latitudinal gap (of a few degrees) between the PP and EE that decreases when reaching night hours. During substorms this latitude gap is comparable to the EE width.

6.10. Fig. 9e shows the distribution of equivalent currents and their structure during the storm main phase with activity indices of AL ~ -1200 nT and Dst $= -150$ nT. The following characteristics of the electrojet dynamics are apparent:

- during evening hours both the EE and WE shift equatorward and the intensity of the electrojets increases;
- the eastward and westward current intensities in the evening sector imply that the EE cannot be the consequence of the WE closing through lower latitudes; it is likely that these electrojets are signatures of different geophysical phenomena;
- at the peak of the storm main phase the equatorward boundary of the CU (and hence the PE) shifts to $65° < \Phi' < 67°$ and the width is $2° \div 3°$. During the late morning and early evening hours the westward currents adjoin the PE;
- at the main phase maximum the EE during near-noon hours adjoins the CU at $\Phi' \sim 65°$, the WE is absent in the day-time sector;
- the WE asymmetry with regard to the noon-midnight meridian is valid for storm intervals (similarly to the substorm intervals). However, the asymmetry pattern changes essentially; in the night sector the WE poleward boundary is located at higher latitudes than the PE in the noon sector;
- the WE in the midnight and early morning sectors has a current density of ~ 1.6 kA/km, and the integrated current is $\sim 2 \div 3$ MA.

6.11. During the main storm phase the bursts of the ion drift velocity attain as much as ~ 4 km/s at subauroral latitudes (outside of the plasmapause) in the region of the ionospheric trough. Galperin et al. (1974) was the first to report strong poleward-directed electric fields driving fast plasma convection bursts at subauroral latitudes in the evening local time sector and called them polarization jets (PJ). The new name SAPS (Sub-Auroral Polarization Stream) is generally accepted nowadays for this phenomenon (Foster and Burke, 2002). In Fig. 9e the location of the bursts are indicated by a yellow line, the longitudinal prolongation of which is adapted from Foster and Vo (2002). Galperin (2002) proposed a model that explains the formation of PJ or SAPS during magnetic substorms and storms in the evening-to-nighttime sector of the discontinuity region between the auroral electrojets. A detailed consideration of the interrelation between auroral luminosity, FAC and PE during magnetic disturbances in the dayside sector was given by Sandholt et al. (2004).

6.12. To show the structure of magnetospheric plasma domains and the 3D current systems, a cross-section of the Earth's magnetosphere is displayed in Fig. 10. It is shown there with cuts in the midday-midnight meridional plane and in the equatorial plane, using ground-based observations of different auroral luminescence types and auroral precipitation (Galperin and Feldstein, 1991). The majority of plasma domains seen in the figure are directly related to large-scale current systems in the magnetosphere. Such FAC systems exist permanently in the magnetosphere (Maltsev and Ostapenko, 2004).

6.13. The 3D structure of currents in the near-Earth space is enclosed by the magnetopause. The currents screening the magnetic field of the inner magnetosphere from penetrating into the solar wind are located on the magnetopause. These eastward Chapman-Ferraro (CF) currents screen the dipole field. The magnetopause screening currents for the ring current (RC) fields are in the same direction, but their intensity is an order of magnitude weaker. The tail current (TC) in the central plasma sheet (CPS) is in the dawn-dusk direction. The closure of the TC is attributed to currents on the magnetopause which exist not only on the night side, as well established, but on the day side as well. In Fig. 10 the TC in the equatorial plane of the magnetosphere is indicated by two vectors. At midnight one of them is located in the innermost part of the current sheet, the other along its boundary. Their continuation on the magnetopause can be seen. However, the first remains in the tail and the second reaches the day side of the magnetopause where the directions of the CF and TC are opposite as seen in Fig. 10. Since CF currents are always more intense than TC closure currents the resulting current on the day side is always eastward.

6.14. The field aligned current flowing into and out of the ionosphere in the vicinity of the PE are located on the cusp surface. In Fig. 10 PE-FACs are indicated by two green lines (not vectors) along the magnetic field. The PE-FAC direction is not shown since it is controlled by the IMF B_y component: under $B_y > 0$ ($B_y < 0$) the current flows into (out of) the ionosphere along the cusp inner surface and out of (into) it along its outer surface. The ionospheric closure of the inflowing

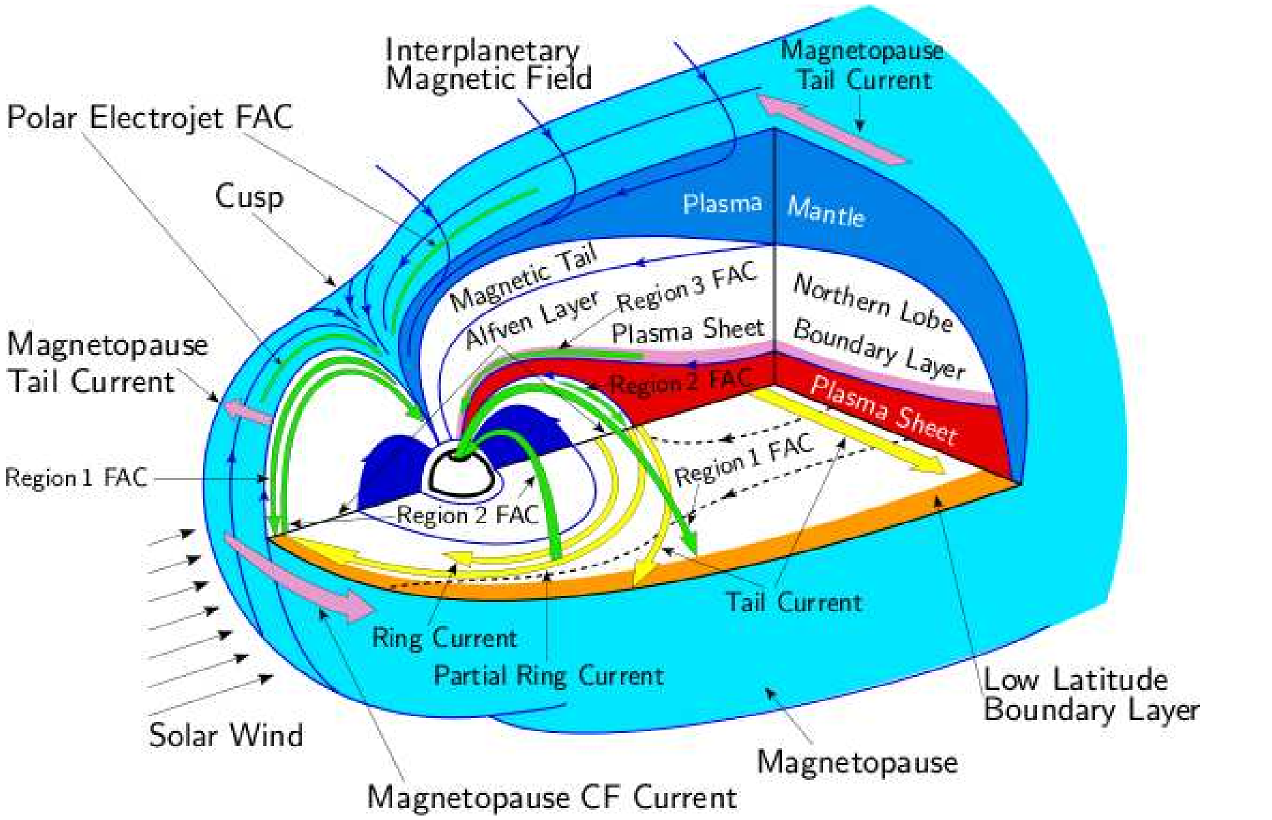

Figure 10. The 3-D system of electric currents in the magnetosphere during magnetic disturbances (Feldstein et al., 2006). Descriptions of the current system and the magnetospheric plasma structures are given in the text.

and outflowing PE-FAC is by Pedersen current. Its direction in the ionosphere is identical with the direction of the solar wind electric field component $V \times B_y$, i.e. under $B_y > 0$ ($B_y < 0$) the electric field in the cusp is poleward (equatorward) at ionospheric altitudes. In the cusp the Hall current in the form of the PE, spreading in the ionosphere (out of the cusp) is generated by this electric field. The PE is eastward (westward) under $B_y > 0$ ($B_y < 0$).

6.15. The Region 1 FAC in the dusk sector is usually believed to be mapped magnetically from the ionosphere to the low latitude boundary layer (LLBL), i.e., to the periphery of the magnetosphere, in the vicinity of its boundary with the solar wind. Such a pattern is valid for Region 1 FAC during day-time hours only and is shown by a current arrow, resting against the LLBL. During the dusk to pre-midnight hours, where Region 1 FAC is located at AO latitudes, FACs inflow to the CPS, i.e., into the deep magnetosphere. In Fig. 10 the second current arrow of the Region 1 FAC crosses the equatorial cross-section of the magnetosphere in the dusk sector of the CPS behind the TC vector that depicts the current along the TC boundary.

6.16. The Region 2 FAC flows into the ionosphere from the Alfvén layer periphery, where the partial ring current (PRC) is located. In Fig. 10, the Region 2 FACs are indicated by three vectors for day, dusk, and nighttime hours. It is generally believed, that the Region 2 FACs are located in the inner magnetosphere and part of a single current system with the EE and PRC. As seen in Fig. 10, the Region 2 FACs are flowing into the ionosphere during evening hours and are located in the magnetosphere at $L \sim 4$. In the early afternoon sector, where the EE adjoins the PE, the Region 2 FAC in the equatorial plane of the magnetosphere is near the LLBL.

6.17. The auroral electrojets present a continuation of the FACs at ionospheric altitudes. Eastward/westward electrojets are connected with magnetospheric plasma domains (the Alfvén layer / the CPS) via FACs. In known models of the EE, the Pedersen current in the ionosphere along with the Region 2 FACs constitute Bostrøm's Case I current system (Boström, 1964). At the same time, the Region 2 and Region 1 FACs in the evening sector constitute Bostrøms Case 2 current system. The northward electric field between these FACs leads to Hall currents along the EE. Hence, the EE has a joining effect of Pedersen and Hall currents in the ionosphere.

6.18. As mentioned above, a characteristic morphological feature of auroral electrojets exists in the evening sector, namely in their overlapping. This is due to an additional Region 3 FAC current flowing into the ionosphere from the

PSBL during intense magnetic disturbances. A triple FAC structure arises. In addition to the Region 1 FAC and Region 2 FAC, the Region 3 FAC (flowing into the ionosphere) located on the poleward boundary of the auroral precipitation region appears. As a result, the necessary prerequisites for overlapping auroral electrojets are created. A southward electric field, favourable for the appearance of westward ionospheric Hall currents near the PC boundary, appears between the Region 3 FAC and Region 1 FAC. As a result a spatial overlapping of electrojets takes place. Also worth noting is that the WE represents the resultant effect of Pedersen and Hall currents in the ionosphere.

7 Conclusions

Spiral distributions (spirals) were used in the first stage of investigations for explaning the positioning of charged particle fluxes, precipitating into the upper atmosphere. Later they found their place (and became an intrinsic part) in global spatial-temporal patterns of some high-latitude geophysical phenomena. Below we list the basic peculiarities, that characterize the spirals in magnetic disturbances and auroras.

With respect to geomagnetic disturbances:

1. There are three types of spirals at high latitudes independent of seasons, named as M (morning), N (nighttime), and E (evening) spirals. The first two (M and N) appear distinctly and visibly during all seasons; the third one (E) is characteristic for the summer season.

2. Maximum intensities of ionospheric currents are observed along these spirals - the westward electrojet along the M- and N-spirals, and the eastward electrojet along the E-spiral.

3. Spirals with westward ionospheric currents are situated along the auroral oval from the late morning, over the nighttime till the early evening hours.

4. The windings of the spirals in clockwise or anticlockwise direction are not determined by the current flow direction in the spiral nor by the sign of the charged particles, which precipitate into the upper atmosphere.

With respect to auroras:

5. The visual observation of auroras is confined at high latitudes primarily to the winter season for the most part of the day. Only M- and N-spirals are identified, which constitute the auroral oval. Most often there appear discrete auroral forms in the zenith along the auroral oval.

6. Discrete auroral forms along the M- and N-spirals are due to precipitating electrons with energies up to a few keV. In the vicinity of the E-spiral, one observes diffuse auroras, which are due both to low-energy electrons and protons with energies of 10 keV and higher.

7. The spiral distributions are not related to the dynamo action at ionospheric heights. The existence of the spirals and their distribution is determined by large-scale structures of plasma domains at the night side of Earth. The M- and N-spirals are connected with the inner (near-Earth) part of the central plasma sheet in the magnetospheric tail. The E-spiral relates, however, to the region between the central plasma sheet and the plasmapause, where the partial ring current is situated in the evening sector and where the low-energy plasma drifts in sunward direction out of the central plasma sheet.

8. There is no discontinuity between the westward and eastward auroral electrojet at a fixed latitude around midnight, but rather a gap, the latitude of which increases smoothly from nighttime to evening hours.

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