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The Discovery and the First Studies of the Auroral Oval: A Review

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Abstract—The auroral oval concept radically changed the view that existed for a century in geophysics on the patterns in aurora planetary spatial–temporal distributions. The auroral zone, which is located around the geomagnetic pole as a continuous ring at a constant angular distance of ~23°, was replaced by the auroral oval in 1960. The auroral oval spatial position reflects the shape of the Earth's magnetosphere, which is compressed by the solar wind on the dayside and stretches into the magnetotail on the nightside. The oval is fixed relative to the direction toward the Sun and is located around the geomagnetic pole at altitudes of the upper atmosphere at an angular distance of ~12° at noon and ~23° at midnight. After an animated discussion over several subsequent years, the existence of the auroral oval was accepted by the scientific community as a paradigm of a new science, i.e., solar–terrestrial physics. The oval location indicates the zone where electron fluxes with energies varying from ~100 eV to ~20 keV precipitate into the upper atmosphere and is related to the structure of plasma domains in the Earth's magnetosphere. The paper describes the scientific studies that resulted in the concept of the auroral oval existence. It has been shown how this concept was subsequently justified in the publications by Y.I. Feldstein and O.B. Khorosheva. The issue of the priority of the auroral oval concept introduction into geophysics has been considered. The statement that the concept of the oval is an archaic paradigm of solar–terrestrial physics has been called into question. Some scientific fields in which the term auroral oval or simply oval was and is the paradigm have been listed.

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1. INTRODUCTION

When the auroral oval concept replaced the idea of the auroral zone as a region where auroras occur most frequently, this meant that the morphology of this natural phenomenon, which existed in geophysics for almost a century before the International Geophysical Year (IGY), radically changed (Feldstein et al., 1969; Feldstein, 1990). Past observations naturally agree with the regularities resulting from the oval concept. Therefore, statements that the existence of the auroral oval was established as a result of visual aurora observations far before IGY rather than after this year appeared in some studies. The studies performed in Greenland from 1865 to 1880 (Tromholt, 1882) during the Spitsbergen expedition in 1882–1883 (Carlheim-Gyllenskiold, 1887) and the Russian–Swedish expedition on the same archipelago from September 1899 to March 1900 (Chernouss et al., 2005; Chernouss and Sandahl, 2008) are among such studies.

Changes in the aurora occurrence frequency were registered in different sky areas according to local time during observations at all sites. These changes were interpreted as northward nighttime shifts of the auroral zone (Alfvén, 1939, 1940, 1950; Lassen, 1963). However, the observations did not make it possible to estimate the amplitude of the zone daily displacements and the latitudinal interval occupied by luminosity or to determine that the zenith auroral forms almost constantly exist at the zone latitudes. Alfvén (1950) indicated that it is desirable to observe also the location of auroras. Thus, visual aurora observations could not be used to justify the statement that the auroral oval exists (Stauning, 2011; Moss and Stauning, 2012). This problem was also discussed in (Jorgensen, 2011; Akasofu, 2011).

Past visual observations of luminosity do not contradict the auroral oval concept; however, they also do not result in an unambiguous conclusion that this oval exists. The researchers could only conclude that the oval concept resulted from these observations based on reliable data obtained during IGY that the auroral oval actually exists, having processed these data in a new fashion and having analyzed the results of the visual observations of auroras in the contemporary manner. The observations correspond to the oval concept but cannot be used to conclude that the oval exists. Moreover, researchers could hardly use this concept in order to obtain the auroral oval spatial position.

Auroras can be visually observed in the daytime on Frantz Josef Land and on islands in the Kara Sea. In the winter of 1954–1955, hourly visual observations of auroras were performed at 50 meteorological stations at 67.3°–87.5° N geographic latitudes and 50°–110° E longitudes (Feldstein, 1958). The vector diagrams of the aurora distribution over geographic azimuths indicate that the diagram shape at the stations located on

Frantz Josef Land (Rudolf Island, Nagurskaya, Tikhaya Bay; Φ' ~ 78°) are the same as in the auroral zone at Φ' ~ 65°. It was assumed that such a situation resulted from the existence of a second (circumpolar) auroral zone at Φ' ~ 78° (Alfvén, 1955; Nikol'skii, 1956). This was actually one of the auroral oval manifestations, and researchers did not yet know reliably at that time that this oval exists.

The goal of this work was to consider the historical sequence of the auroral studies that resulted in the auroral oval concept and that such a concept is preferred in geophysics. This paper was, to a certain extent, motivated by the fact that it has become necessary to dispute the statement that the oval concept is an obsolete paradigm of solar–terrestrial physics put forward in (Lazutin, 2015).

2. AURORAL ASCAPLOTS AND SPIRALS

In 1959, after eight years of operation at Dixon Island Arctic observatory, the author of the present paper entered the IZMIRAN auroral group headed by N.V. Pushkov, who supervised auroral studies in the Soviet Union and organized aurora visual observations in the USSR and adjacent countries during IGY. One of the first scientific publications by N.V. Pushkov (Pushkov et al., 1937) was devoted to visual observations of auroras and their relation to magnetic disturbances on Frantz Josef Land. Upon entering IZMIRAN, the author of the present paper was on deployment to the Research Institute of Nuclear Physics (NIIYaF), Moscow State University (MGU), to the group headed by Professor A.I. Lebedinsky, who was among the leading astrophysicists and geophysicists during the Soviet period. Before primary data processing, up to 70 km of ascafilms of auroras accumulated at this institute during two seasons of observations (1957–1959). These data had to be transmitted to the World Data Center (WDC) after preliminary processing and the compilation of tables in a specially developed format (ascaplots). The tables included 30-min data on the aurora location in the sky along the geomagnetic meridian and the aurora intensity in the zenith; daytime intervals and meteorological conditions unfavorable for observations are indicated. This work had to be performed at NIIYaF, which was a leading institution on photographic observations of auroras and gathered all observational data from stations.

In addition to routine work, we also analyzed ascaplot data, which resulted in a key publication (Feldstein, 1960) on the regularities in the spatial–time distribution of the aurora occurrence frequency and discrete aurora orientation. We studied diurnal variations in the aurora occurrence frequency. This problem has a long history. The results of the studies were contradictory with respect to the number of extremums and the extremum formation time at different latitudes (Isaev, 1940; Feldstein, 1958; Lassen, 1963). We for the first time distinctly determined the regularity in the diurnal variations in the zenith aurora occurrence frequency at different latitudes and the existence of one or two maximums and presented the magnetic local time (MLT) of the morning and nighttime extremum appearance, which linearly depends on geomagnetic latitude (Feldstein, 1960).

Figure 1 presents the diurnal variations in the zenith aurora occurrence frequency at several stations in the interval of geomagnetic latitudes, which were obtained in (Feldstein, 1960). We for the first time propose to use the oval term and concept in order to describe the spatial–time location of the region in which the zenith aurora occurrence frequency is maximal (Feldstein, 1960; p. 69). In this work we for the first time propose the concept of the auroral oval as a region that is located acentrically with respect to the geomagnetic pole at minimal and maximal distances in the daytime and nighttime hours, respectively. We indicated that auroras most frequently occur near local geomagnetic midnight at Φ' ≤ ~65° latitude. The occurrence maximums are registered in the morning and evening hours at 67° < Φ' < 78° latitudes and near noon at the polar cap boundary (Φ' ~80°). The data from all stations indicated that MLT of the formation of the morning and evening occurrence maximums in the Cartesian coordinate system (Φ'–MLT) is almost linearly related to the station geomagnetic latitudes.

Note that the Φ'–MLT linear variations are transformed into two spirals in the polar coordinate system. The problems of the spiral distribution of magnetic field variations and auroras are discussed in detail in (Feldstein et al., 2012). However, we should note that two spirals for zenith auroral forms twisting in different directions were for the first time obtained in (Feldstein, 1960) and (Feldstein and Solomatina, 1961b) for the Northern and Southern hemispheres, respectively. We can consider that this statement is indirectly confirmed by the spirals used in Fig. 4.9 in the review (Lazutin, 2012) for the Southern Hemisphere, which were taken from (Feldstein and Solomatina, 1961b) but were erroneously assigned to A.P. Nikol'skii.

The transition from the diurnal variations in the aurora occurrence frequency in the zenith to the auroral oval is also described in (Lazutin, 2015) but with a specific citation of individual words from page 69 in (Feldstein, 1960), as a result of which such a transition is considered incorrectly.

We now discuss and comment some result of the usage of the auroral oval (or simply oval) term and concept in the scientific terminology.

1. Why was the generally accepted term "maximal isochasm" or the auroral zone, which surrounds the geomagnetic pole as a ring at a polar distance of ~23°, was replaced by a new term and the concept "oval" or "auroral oval" in order to describe the location of the region where zenith auroral forms occur most frequently? When the oval term is used to describe auroras, this characterizes a certain spatial–temporal dis-

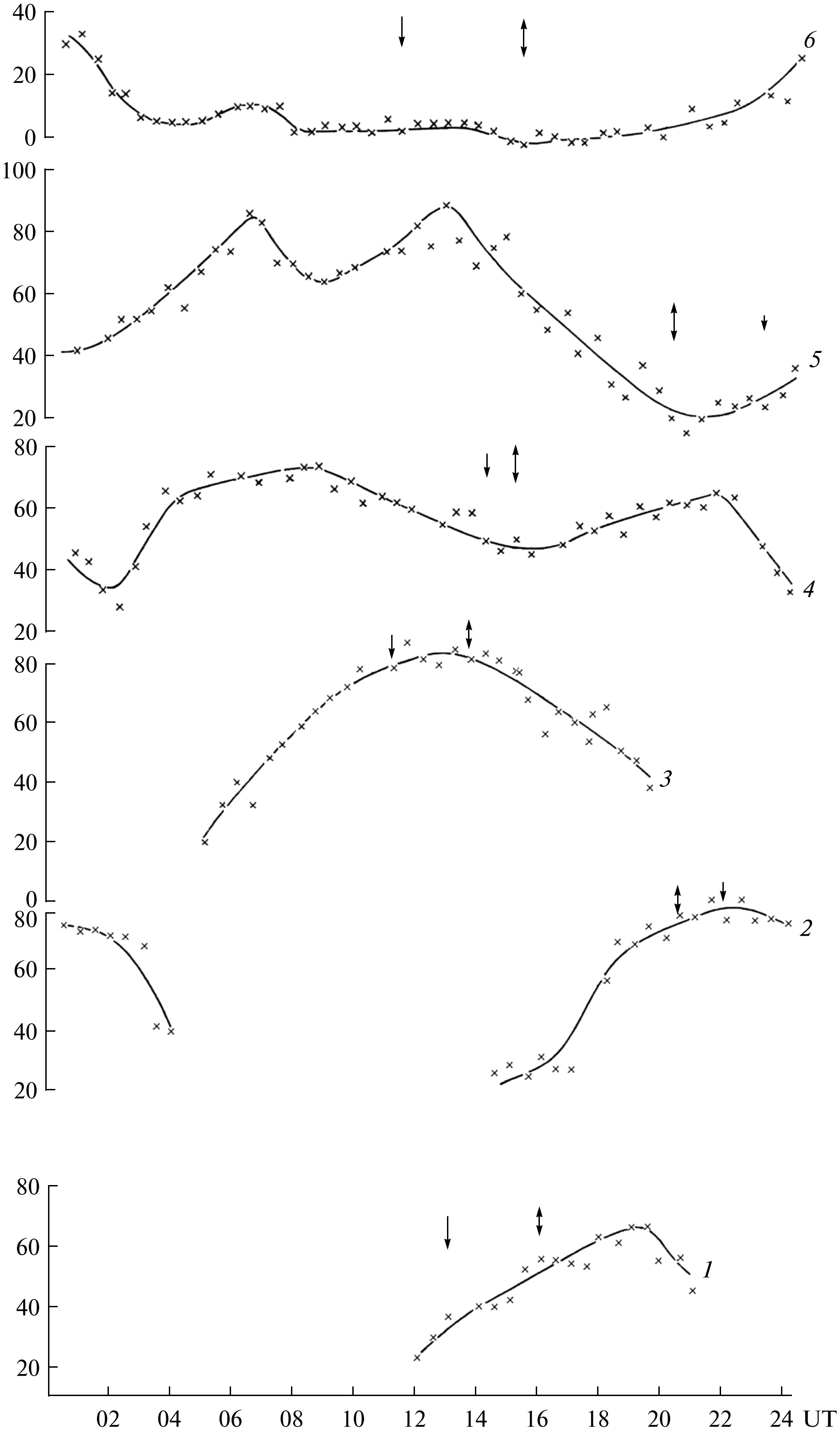

Fig. 1. Diurnal variations in the zenith aurora occurrence frequency (UT): (*1*) Verkhoyansk (Φ' ~ 57°), (*2*) Murmansk (Φ' ~ 64°), (*3*) Wrangel Island (Φ' ~ 65°), (*4*) Arctic 1 (SP6, Φ' ~ 69°), (*5*) Piramida (Φ' ~ 74.5°), and (*6*) Arctic 2 (SP7, Φ' ~ 81°). Numerals on the ordinate: the zenith aurora occurrence frequency in percent. An arrow and a double arrow mark local midnight and local geomagnetic midnight, respectively (Feldstein, 1960).

tributions of auroras. This distribution fundamentally differs from the previously accepted description of the auroral zone as a maximal isochasm in the form of a ring at the ~23° polar distance. A new term was introduced in order to describe unambiguously the large-scale distribution of auroras.

2. We will indicate below that the auroral oval shape can change from a narrow band with boundaries approaching circles during magnetically quiet periods (the auroral ring) to the band with a variable width and boundaries in the form of deformed circles during magnetic disturbances. The band and ring are varieties of the auroral oval under different geophysical conditions.

3. The cause of differences in the location of the Fritz (1881)–Vestine (1944) maximal isochasm with the auroral oval in the form of two spirals consists in that the maximal isochasm is located at geomagnetic latitudes where nighttime auroras predominate. Therefore, the auroral zone averaged position for a day characterizes the distribution of nighttime auroras, which naturally differs from the oval.

4. The auroral oval is the region in which auroras most frequently occur in the zenith at a fixed UT instant, i.e., above the Earth's surface in the region oriented in a certain manner relative to the direction toward the sun. Indeed, the Φ'–MLT dependence is represented by straight line segments in the Cartesian coordinate system. We translate these segments into the polar coordinate system with the geomagnetic pole as a pole; MLT as an azimuthal angle (t_m); and colatitudes, polar angles (Θ), and an addition to 90° of the Φ' value along straight line segments as radii. Each segment is described by the equation: $\Theta = \Theta_0 + ct_m$. The distance S from the pole to the point with colatitudes Θ can be represented as: $S = R\Theta = R\Theta_0 + cR[\mathrm{UT} + (\Lambda - 69°)/15] = C + D(\Lambda/15 + \mathrm{UT})$, where R is the Earth's radius and Λ is the geomagnetic longitude. At fixed UT, we have the spiral equation: $S = E + F\Lambda$. UT variations will be accompanied by variations in spirals.

5. The oval concept substantially differed from the concepts of aurora spatial distribution that predominated for almost a century. By that time, rocket launches into auroras (McIlwain, 1960) indicated that auroras occur as a result of the precipitation of electrons with $E < 10$ keV.

In the early 1960s, energetic electron ($E > 40$ keV) counter readings on the Cosmos-3 satellite were processed by E.V. Gorchakov at NIIYaF. By that time, I knew that the nighttime auroral zone was located at Φ' ~ 67° and that the oval is characterized by diurnal variations in the aurora location in the zenith from midnight to noon by ~10°. Therefore, I asked Gorchakov to use the Cosmos-3 satellite data in order to reveal the correlation between the aurora observations and the location of the outer radiation belt (Gorchakov, 1961a, 1961b). The conclusion was negative: the intensity maximum in the outer radiation belt is located at Φ' ~ 55°, i.e., much more equatorward of the auroral zone. Diurnal latitudinal variations in the location of the outer radiation belt maximum were not registered. It was simultaneously indicated (Gorchakov, 1961b) that the radiation belt outer boundary is located at Φ' ~ 69° at altitudes where auroras are observed, almost coinciding with the nighttime auroral occurrence frequency maximum. Thus, direct measurements of electron fluxes indicated that auroras near the zone of their maximum cannot be caused by electron precipitation into the atmosphere from the outer radiation belt, where the average electron energy was ~100 keV. The total electron energy in the radiation belts was subsequently decreased by several orders of magnitude. It turned out that this energy can maintain aurora with an average intensity during less than an hour, but the main "range of radiation belt particles certainly disagrees with auroras" ((Krassovsky, 1967). The report at the session of the General and Applied Physics Branch, Academy of Sciences of the USSR, on April 27, 1967). O'Brien (1963) indicated that the position of the outer boundary of the region with $E >$ 40 keV electrons trapped by the geomagnetic field, which is located closer to the pole in the daytime than at night by 4°–8°, strongly varies during a day. Using the Injun-5 satellite data, Frank et al. (1964) constructed isolines for the fluxes of energetic ($E > 40$ keV) precipitating electrons and electrons trapped by the geomagnetic field in Φ–MLT coordinates. The auroral oval according to (Feldstein, 1963a), which was called the Feldstein oval (Akasofu, 1968), was subsequently plotted on the isolines. The oval was located at the boundary of outer radiation belt energetic electron trapping. The auroral oval position in the large-scale magnetospheric plasma structure was thereby established, which initiated numerous studies of the relation between the oval boundary dynamics and the magnetospheric plasma domains.

6. The auroral oval is the region where auroras most frequently appear in the zenith. If extensive forms (arcs and bands) are located along the oval, their orientation (the azimuth relative to the direction toward the geographic or geomagnetic poles) should vary during a day. Such variations actually exist. According to the data from four stations at the oval latitudes, arcs follow approximately from east to west, and their azimuth decreases from dusk to dawn hours within 20°–70°. Such a diurnal variation in the azimuths of extensive forms is qualitatively explained by the fact that the evening (nighttime) spiral has azimuths larger than the morning one.

7. The location of the region where auroras most frequently appear in the zenith, which has the shape of an oval shifted toward the nightside, was related to the geomagnetic field deformation by incoming corpuscular fluxes. Such an interpretation apparently withstood the test of time.

8. We should not go from the distribution in the form of two spirals to the auroral oval because the oval is composed of two spirals. In the paper the oval was already described as a region with zenith auroral forms located asymmetrically relative to the geomagnetic pole. However, to finally confirm the auroral oval concept, it was necessary to indicate that discrete auroras appear in the zenith along the oval most frequently and almost constantly. Such a situation was considered in (Feldstein, 1963a), where isoauroras in Φ'–MLT coordinates were presented and the auroral oval region was identified. In subsequent papers, references to the existence of the oval always simultaneously included two publications: (Feldstein 1960, 1963a).

Based on an analysis of the diurnal variations in magnetic activity at high-latitude magnetic observatories, Nikol'skii (1956) concluded that the second zone with an increased occurrence frequency and magnetic disturbance intensity exists near the pole. Assuming that morning magnetic disturbances correlate with auroras, it was stated that this zone is also the second zone of maximal recurrence for auroras. According to Nikol'skii, the second zone has the shape of two spirals turning in opposite directions in the polar cap from the geomagnetic pole. The number of the observational sites near the second zone was extremely small. It is unclear whether a rather complex zone spiral shape is justified by observations or results from a researcher's interpretation.

We determined the position of the second and the main auroral zones on the Earth's surface (Feldstein and Solomatina, 1961a). This position is shown in Fig. 2. We took into account the aurora occurrence probability during the morning (08–10 MLT) and nighttime (22–24 MLT) maximums and the aurora distribution over the sky during these periods. During the Earth rotation, the second and the main zones in Fig. 2 are outlined on the Earth's surface by the morning and nighttime maximums, respectively. Both zones are located around the geomagnetic pole.

At first, all auroral occurrence frequency latitudinal distributions in the zenith were sometimes constructed with the use of observations during all darkness hours. This can be illustrated by the distributions on magnetically quiet and disturbed days presented in (Feldstein, 1960) and presented again at the symposium in Japan in 1961 (Feldstein et al., 1962). In all cases zenith auroras most frequently exist at latitudes of the nightside zone. On all days the aurora occurrence frequency monotonically decreases with increasing latitude. A monotonous decrease toward higher latitudes is disturbed on magnetically quiet days. An incipient maximum was interpreted as an appearance of the second auroral zone, but only under certain conditions. This could actually result from a decrease in the number of observations, a considerable spread in the occurrence frequency values at adjacent stations, and the usage of all darkness hours.

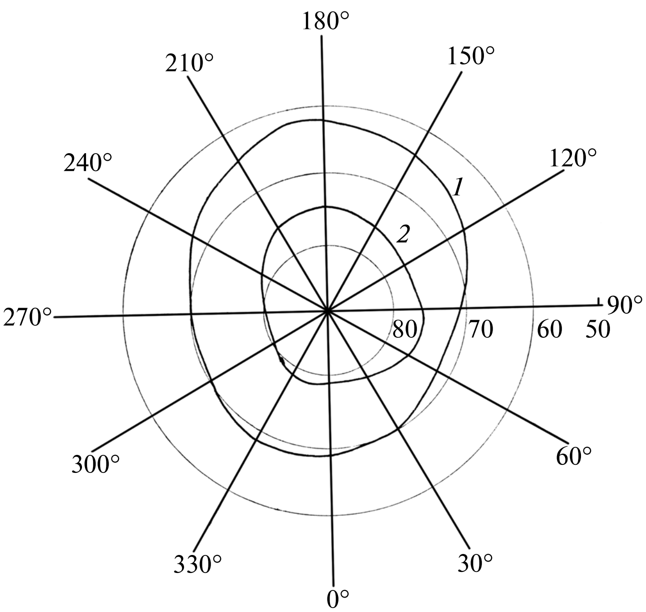

Fig. 2. Position of the auroral zones in the Northern Hemisphere in winter 1957/1958 during the nighttime (*1*) and morning (*2*) maximums in geomagnetic coordinates (Feldstein and Solomatina, 1961a).

For a long time, a popular Nikol'skii idea consisted in that maximums observed in the magnetic activity diurnal variations was interpreted based on the Störmer calculations (Störmer, 1955). The Störmer spiral includes four condensations of the solar proton trajectories at 02, 08–09, 14, and 20 LT. The Earth rotates below the spiral, and the condensation regions outline four auroral zones in the corresponding LT hours on the Earth's surface according to (Nikol'skii, 1960). At 14 LT, the auroral zone descends along the spiral from subauroral latitudes above the American continent to equatorial latitudes above India; at the same time, the zones descend to midlatitudes at 02 and 20 LT. An analysis of the auroral luminosity occurrence performed based on ascaplots did not reveal any suggestion that the auroral zone appears above midlatitude stations (Feldstein et al., 2012). The concept of the existence of four auroral zones that extend from subauroral to middle and even low latitudes proved to be far from real observations.

3. SUBSEQUENT JUSTIFICATION OF THE AURORAL OVAL CONCEPT

By the end of 1960, the compilation of ascaplots at MGU was completed, and ascaplots of the planetary network were published in 1962 (*Auroral ascaplots*, 1962). Researchers continued compiling ascaplots at IZMIRAN. From spring 1961 to March 1962, an expedition was organized, and the auroral luminosity was observed in the conjugate regions: Kerguelen Island in the Indian Ocean–the Archangelsk region (Yarensk), where the

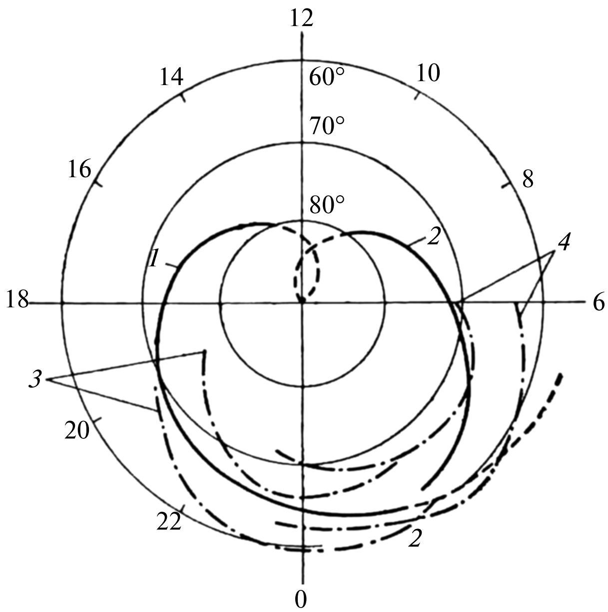

Fig. 3. Nighttime (*1*) and morning (*2*) segments of spirals composing the auroral oval. Spiral segments outside the oval are marked by dashes. Dot-and-dash lines show the auroral luminosity band boundaries according to Khorosheva (1961) at 15–16 UT (*3*) and 20 UT (*4*) on February 13, 1958 (Feldstein, 1963a).

author of this paper actively participated as a supervisor. The expedition was successful, and all data were transmitted to the Polar Geophysical Institute (PGI) for processing.

At that time, Ol'ga Bonifat'evna Khorosheva also studied the spatial–temporal distribution of auroras based on ascafilms. An analysis of the ascafilms for 17 nights at the stations in the 60°–180° longitudinal interval allowed Khorosheva (Khorosheva, 1961) to determine that auroras simultaneously observed at different longitudes compose a physically-bounded band, which synchronously changes its brightness and width along the entire its length. The band shifts polewards in the morning and evening hours. Figure 3 from (Feldstein, 1963a) shows the locations of the auroral band in the nightside sector obtained in (Khorosheva, 1961) compared with the position of spirals. The auroral band was in rather good agreement with the position of the aurora oval, which reflects the averaged position of zenith auroral forms. It is evident that the aurora position can sometimes slightly differ from the averaged distribution.

The distribution of zenith auroras on the dayside was determined from the data published in (Feldstein, 1960). We cite this situation according to Khorosheva (1961): "No wonder that Feldstein (1960) found that the diurnal variation in the aurora occurrence frequency in the zenith is characterized by two maximums (the morning and nighttime ones) north of the main zone. In this case the morning maximum shifts to daylight hours and the nighttime maximum is first displaced to evening hours and then to daylight hours of local time with increasing distance from the zone." In the same work, it is also indicated that one maximum is observed at geomagnetic latitudes about 80° but in daylight hours. It is easy to show that precisely such a pattern will be observed due to the daily motion of the auroral band. The latitudinal dependence of the number of maximums and the maximum appearance local time in the diurnal variation in the zenith aurora occurrence frequency, as established by Feldstein (1960), is repeated again in (Khorosheva, 1962). However, the citation that the same diurnal variations allowed Feldstein (1960) to propose the concept that zenith auroral forms are distributed in the form of the auroral oval was absent in this case. The concept of the auroral band in the form of a ring (Khorosheva, 1961–1963) essentially agrees with the auroral oval concept proposed previously (Feldstein, 1960).

Auroras are observed not only on the nightside of the Earth but also encircle the entire Earth in the form of an oval (or a ring). The auroral ring is actually a certain oval, most elongated on the nightside, rather than a circle (Khorosheva, 1962). According to Khorosheva (1961–1963), the existence of a continuous auroral band, which simultaneously occupies the dayside and nightside of the Earth, indicates that auroras are directly related to the outer radiation belt. Both rayed and homogeneous arcs can extend about 5000 km and can be observed on magnetically disturbed and quiet days (Khorosheva, 1963). Extensive arcs are located along the ring, which is actually a certain oval most elongated on the nightside rather than a circle. We should note that it is very difficult to trace the existence of extensive arcs based on simultaneous observations at several stations instantaneously. According to all publications, extensive arcs existed only in six cases. A sharp lower edge of these arcs was projected onto the Earth's surface. In all cases observations were performed during the daytime or at night since only ascafilms from the stations in the Soviet Arctic were used. There was insufficient data for us to close the ring by auroral observations at all longitudes at the same UT instant.

An auroral oval in the form of two spirals was obtained when the aurora occurrence frequency was studied statistically (Feldstein, 1960; Feldstein and Solomatina, 1961b). It would be extremely important to confirm that extensive auroral forms are located along the oval in specific situations, rather than along the generally accepted auroral zone (Fritz, 1881; Vestine, 1944). The auroral oval in the form of two spirals according to Feldstein or a weakly deformed ring according to Khorosheva did not make it possible to answer how often auroras appear along spirals or a ring. To convince the scientific community that it is necessary to use the auroral oval concept instead of the generally accepted Fritz–Vestine concept of the auroral zone, we had to indicate that the aurora occurrence frequency in the zenith is maximal along the oval rather than along the Fritz–Vestine auroral zone at ~67° geomagnetic latitude, which was generally accepted at that time. This was performed in (Feldstein, 1963a) based on the ascaplots from the planetary network of cameras. Figure 4 shows isoauroras as boundaries of the regions where the zenith aurora occurrence frequency is equal. Numerals within the region indicate the aurora occurrence frequency in the zenith. Isoauroras are actually located at lower latitudes on the nightside and at higher latitudes on the dayside. The region where the aurora occurrence frequency is higher than 75% (the dashed region in Fig. 4), which moves from Φ' ~ 68° on the nightside to Φ' ~ 78° on the dayside, is the auroral oval.

This is the first representation of the auroral oval in Φ'–MLT coordinates with the zenith aurora occurrence frequency indicated. Auroral luminosity almost constantly exists within the oval. The concept of the oval became widely known since references to (Feldstein, 1963a) were numerous. Based on the same initial data (ascaplots), Khorosheva presented a similar result only four years later (Khorosheva, 1967). The report invited to the COSPAR/IQSY joint symposium in London in 1967 was presented by Y.I. Feldstein, S.I. Isaev and A.I. Lebedinsky (Feldstein et al., 1969). The existence of the oval becomes the paradigm of solar–terrestrial physics.

Before IGY, Chapman (1957) indicated that it is necessary to construct maps similar to isochasms but for the aurora occurrence frequency in the zenith (isoauroras). Such maps for IGY were constructed in (Feldstein, 1963b) and are presented in Fig. 5. Since auroras most frequently appear in the zenith along the auroral oval, their spatial distribution over the Earth's surface is different for the daytime and nighttime. In Fig. 5 we for the first time present the systems of isoauroras separately for the daytime and nighttime in the Northern and Southern Hemispheres. The isoaurora maps complete the works on the study of the occurrence frequency of auroras as a geophysical phenomenon, which were performed for more than a century. For the Northern Hemisphere, the position of 0.5% equatorial isoaurora is plotted based on the visual observations of auroras (Feldstein and Shevnina, 1963). The isoauroras of the most frequent appearance of auroras in the zenith are marked by thickened lines. This is the auroral zone at Φ' ~ 67° in the nighttime and the second (circumpolar) zone at Φ' ~ 78° in the daytime. Two auroral zones result from the Earth's rotation below the auroral oval. The shape of isoauroras in two hemispheres is different: for the nighttime, it is similar to an ellipse with an axial ratio of ~1.2 in the Northern Hemisphere and to circle in the Southern Hemisphere. Hultqvist (1958) indicated that the maximal nighttime isoaurora is close to the corrected geomagnetic parallel. The deviation of the geomagnetic field from dipole during the field spherical harmonic expansion to the fifth term is taken into account when this isoaurora is determined.

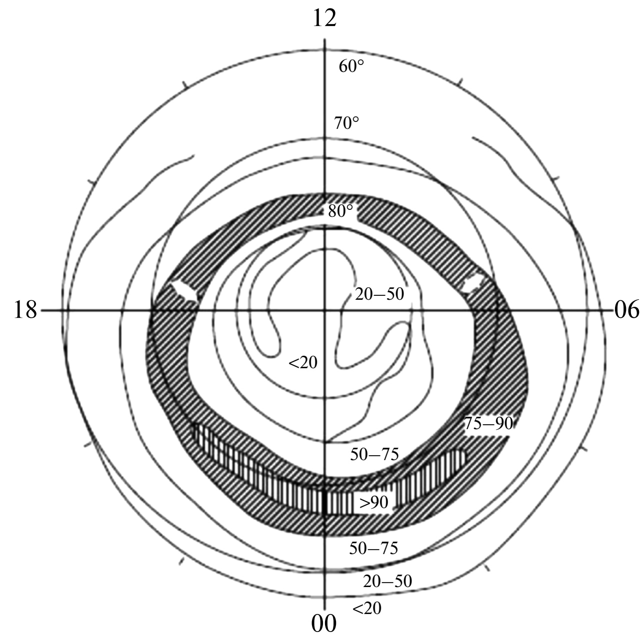

Fig. 4. Zenith aurora occurrence frequency in percent (P) in corrected geomagnetic latitude–MLT coordinates in the Northern Hemisphere. The region with P > 75% is shaded (Feldstein, 1963a).

In the mid-1960s, there remained two problems to be solved: (1) the dynamics of the auroral oval boundaries related to a change in the disturbance level in the magnetosphere; (2) the reconstruction of the auroral oval position based on the orientation of extensive auroral forms.

Since 1966, G.V. Starkov started participating in the studies of the aurora spatial–temporal distribution, first as an IZMIRAN PhD student guided by the author of this paper. It was easy to work with him, because he immediately understood the essence of a problem and could offer his own proposals in order to solve this problem. Starkov was a talented ripe scholar who could solve originated scientific problems. Our close scientific cooperation continued until his death in 2006.

We solved both problems simultaneously. What were the difficulties? Magnetic activity indices are as a rule used to estimate the disturbance level. The 3-h index (*Kp*) was most popular. However, this index is insufficiently informative as applied to auroras. The 15-min *Q* index, which ws proposed by the beginning of IGY (Bartels and Fukushima, 1956), was the only index with a rather high time resolution. It was precisely this index that was taken as an activity measure, but researchers had to determine the index values directly from magnetograms. At the same time, it is rather difficult to determine the *Q* indices and extreme positions of the auroral oval boundaries from ascafilms

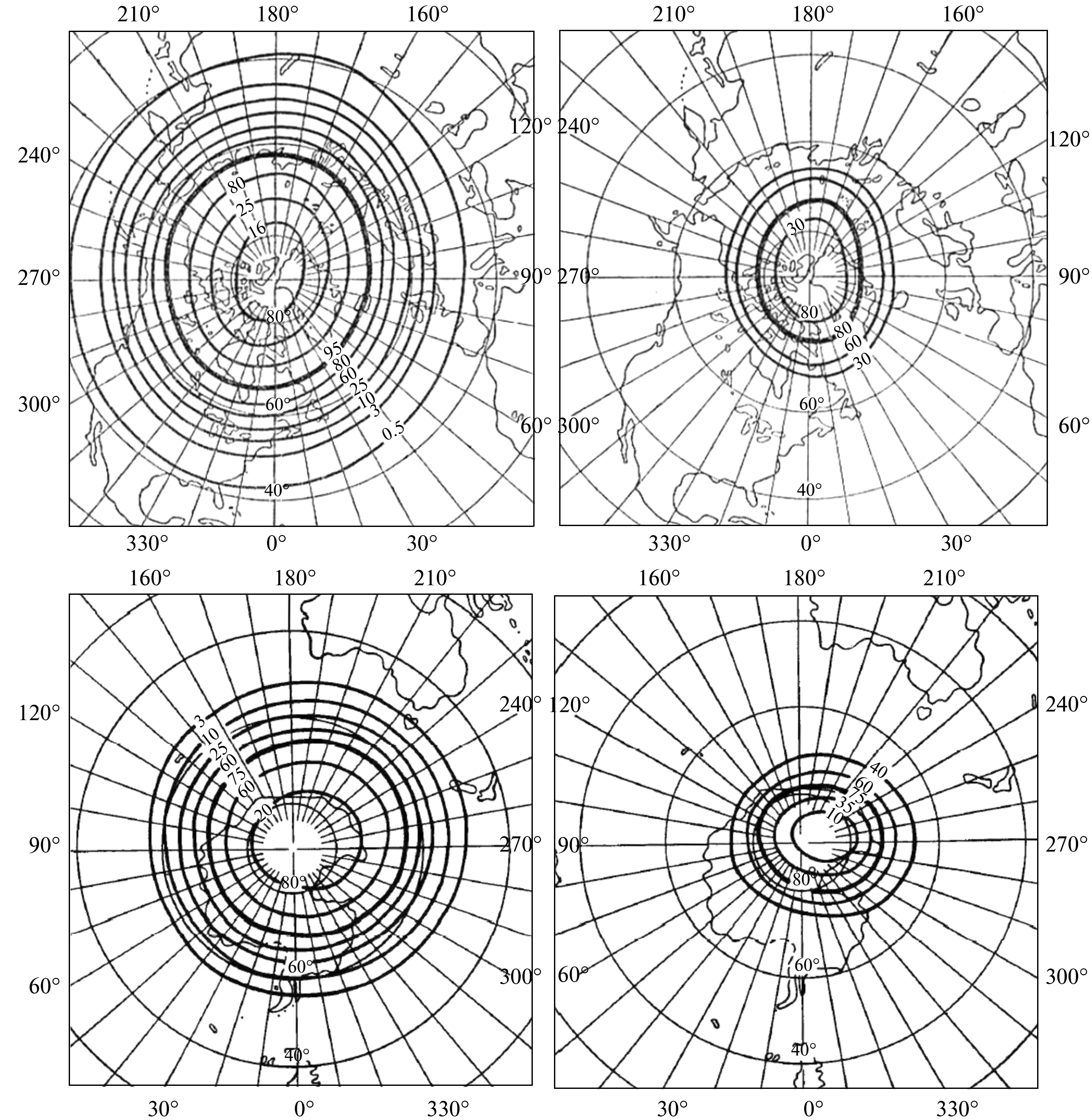

Fig. 5. Isoaurora systems for the Northern (top) and Southern (bottom) hemispheres during IGY in the nighttime (left) and daytime (right) hours. A thickened isoaurora shows the projection of the auroral daytime and nighttime sectors on the Earth's surface during the Earth daily rotation (Feldstein, 1963b).

during 15 min. To reconstruct the auroral oval position from observations of the extensive aurora orientation, it was necessary to have aurora azimuths in all LT hours. To meet such a requirement, it was necessary to extend available data to daylight hours for stations where auroras were registered round-the-clock.

Figure 6 presents the auroral oval variations from the magnetically quiet ($Q = 0$) situation to moderately disturbed conditions ($Q = 7$) published in (Feldstein and Starkov, 1967; Starkov and Feldstein, 1968). The established relation of the oval location and dimensions to the disturbance level made it possible to relate different geophysical phenomena to the domains where plasma with auroral energies penetrates into the upper atmospheric layers and, finally, to the dynamics of the large-scale magnetospheric plasma structure upon determining the interrelation between the oval boundaries and the plasma domain boundaries in the magnetosphere. Numerous researchers were interested in the data obtained by us, and they repeatedly

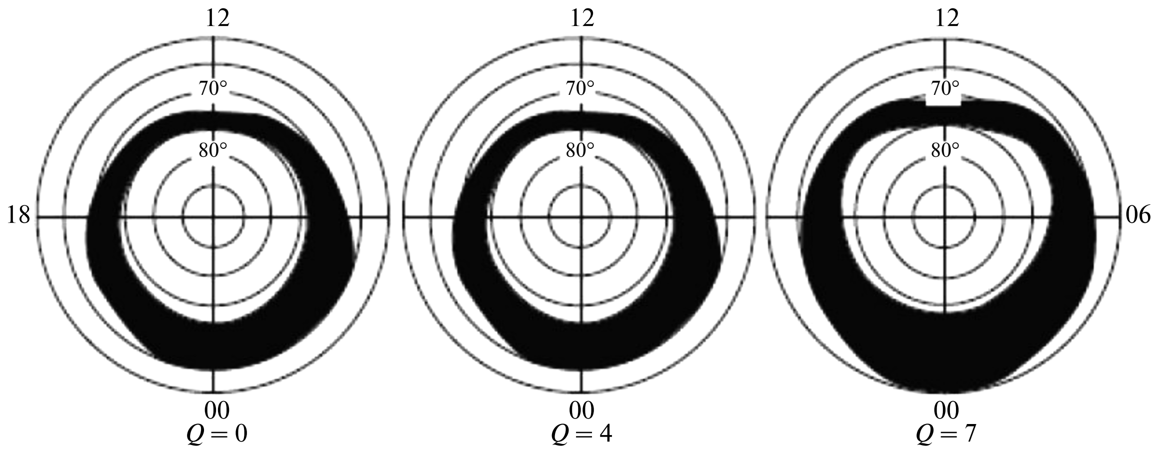

Fig. 6. Auroral ovals at $Q = 0$, 4, and 7 according to (Feldstein and Starkov, 1967; Starkov and Feldstein, 1968).

cited our works. The American Science Information Institute (Philadelphia), which keeps a record of citing publications in basic scientific journals, considered this paper among "Cited Classics" (*Citation Classics*, 1980). These conclusions gained international recognition, because they represented the most complete determination of the auroral oval dynamics for all MLT hours at a change in the activity level. Such a comprehensive study of the behavior of zenith auroral forms depending on magnetic disturbance in all LT hours was performed for the first time. The auroral oval representation, shown in Fig. 6 as a continuous band, does not mean that the same auroral form exists at all longitudes and luminosity fills the entire oval. Discontinuities can exist along the band, especially in the dawn and dusk hours. The problem of existence of discontinuities in a luminous band was discussed in several our works published together with Starkov, e.g., in (Feldstein and Starkov, 1967). The ground-based observations during IGY indicated that discrete auroral forms exist in the daytime and nighttime hours even in exclusively magnetically quiet intervals. The generalized schematic distribution of auroras during such periods is presented in Fig. 7. The model covers all longitudes. Different auroral forms and structures are located along the auroral oval depending on LT: rays, homogeneous arcs, and rayed arcs and bands in the prenoon and dusk sectors and in the nighttime and morning hours, respectively. The appearance of different auroral forms and structures along the oval is a more typical phenomenon than the existence of one extensive auroral form. The synoptic maps with auroras during quiet periods (Feldstein, 1967) confirm the distribution of auroras shown in Fig. 7.

The auroral oval is not only the region where zenith auroral forms appear most frequently. Extensive forms, i.e., arcs and bands, are located along the oval. The photographic observations of auroras processed during IGY indicated that the aurora spatial orientation regularly vary during a day (Lassen, 1959, 1961; Starkov and Feldstein, 1960; Hultqvist et al., 1961). Generalization of the experimental data made it possible to reveal the main regularities in these variations (Hultqvist, 1962; Feldstein, 1963a). At the latitudes of the oval, the azimuths of extensive forms decrease from the evening hours to the morning ones, and the variation amplitude increases with increasing latitude from 20° to 70°. Azimuth variations are explained by the location of auroras according to the Alfvén theory (Hultqvist, 1962) or by the existence of the auroral oval (Feldstein, 1960; Khorosheva, 1962). According

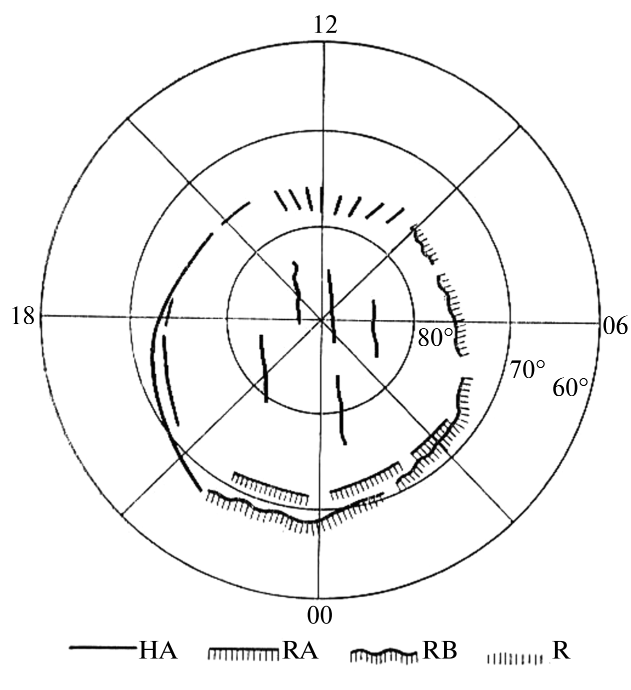

Fig. 7. Position of different auroral forms during exclusively magnetically quiet periods according to (Feldstein, 1966, 1967): (HA) homogeneous arcs, (RA) rayed arcs, (RB) rayed bands, and (R) isolated rays.

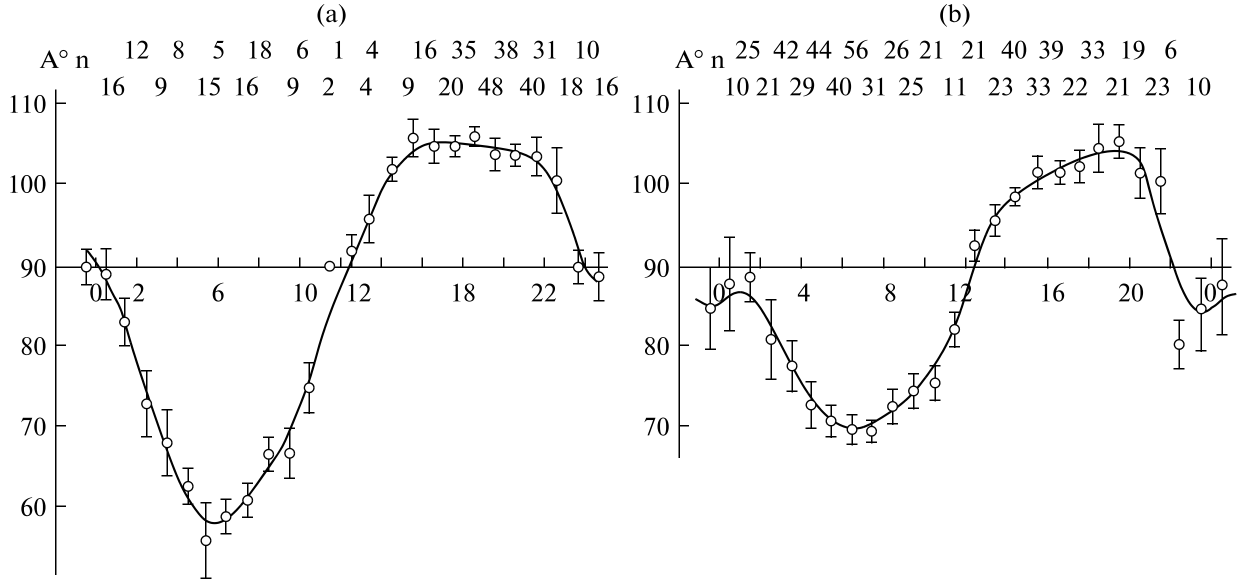

Fig. 8. Diurnal variations in the azimuths of extensive auroral forms according to MLT at (a) Cape Chelyuskin and (b) Piramida (Spitsbergen) stations. Numerals at the top show the number of arcs in the corresponding hour according to (Starkov and Feldstein, 1968; Feldstein and Starkov, 1967).

to the Alfvén theory, a 30° jump was found in the morning hours (Lassen, 1959; Hultqvist et al., 1961), but the existence or absence of the jump in arc azimuths was the problem to be solved. To reconstruct the oval location based on the orientation of extensive forms and elucidate the existence of the jump, Starkov and Feldstein (1967) used round-the-clock azimuth observations at Cape Chelyuskin and Piramida stations presented in Figs. 8a and b. The azimuth diurnal variations at two stations are approximately sinusoidal and have an amplitude of ~20°. Figure 8 indicates that an abrupt change in azimuths is absent at 06–08 MLT. Azimuths start increasing from 06 MLT (Figs. 8a, b), and this increase was interpreted as a jump at certain stations since the number of observations was small.

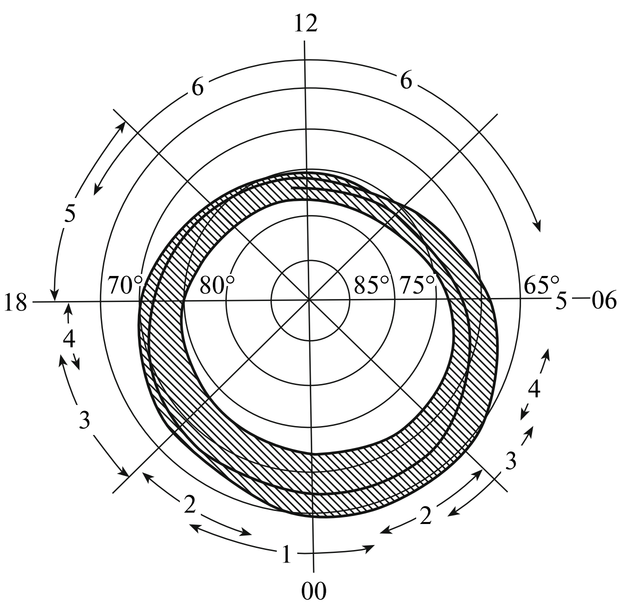

Fig. 9. Auroral oval in the form of a line obtained from the observations of the extensive aurora orientation at Dixon Island (*1*), Point Barrow (*2*), Fort Churchill (*3*), Cape Chelyuskin (*4*), Vize Island (*5*), and Piramida (Spitsbergen) (*6*). The auroral oval position for $Q = 3$ is dashed. Numerals (*1*)–(*6*) mark the LT intervals in which the observations of the azimuths of the corresponding stations were used to construct the auroral oval according to the data from (Starkov and Feldstein, 1968; Feldstein and Starkov, 1967).

The auroral oval location was determined based on the orientation of aurora extensive forms at many stations. The method for determining the auroral zone position by observations at one station was for the first time proposed by Alfvén (1950) and was used in (Hultqvist et al., 1961). Starkov and Feldstein (1967) used the observations at five stations at different latitudes, which made it possible to determine more accurately the auroral oval position fixed relative to the Sun (see Fig. 9). Such a determination, which was based on the observations of the orientation of extensive auroral forms, was performed for the first time. Gustafsson et al. (1969) continued a similar oval determination using the data on the arc orientation during the IQSY period.

The main studies concerning the aurora planetary distribution in the presatellite era and the determination of the auroral oval existence and the dynamics of its boundaries were performed in the 1960s. The oval geometry and boundaries were determined when considerable data sets were statistically averaged. The oval is oriented relative to the direction toward the Sun and

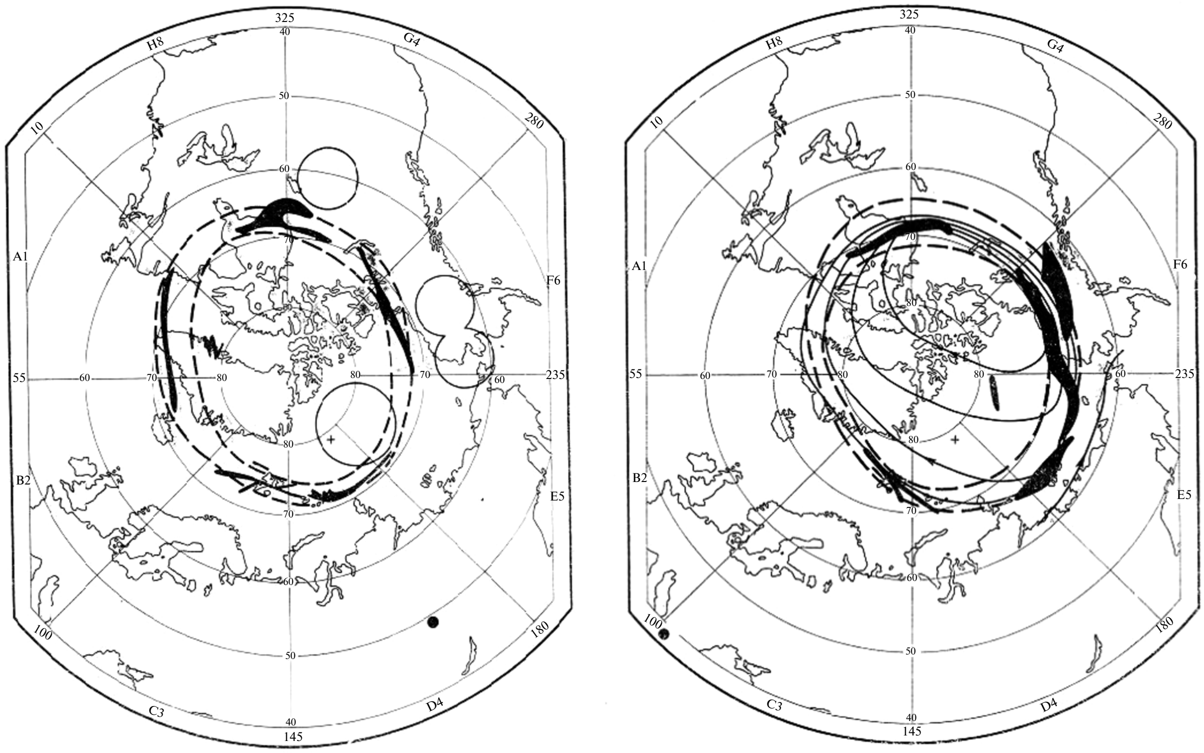

Fig. 10. (a) Instantaneous distribution of auroras according to the photographs from the camera planetary network at 0500 UT on December 19, 1957, at $Q = 1$. (b) Instantaneous distribution of auroras according to the photographs from the camera planetary network at 1030 UT on December 8, 1957, at $Q = 2$ according to (Starkov and Feldstein, 1970). Auroral ovals at corresponding disturbance levels are shown by dashes. The filled circle at the edge of the map shows the position of the Sun. The equivalent current system between the 15000 A current lines is shown by thin lines. The open circles show the all-sky camera fields of view without auroras.

is suspended over the rotating Earth. At each fixed UT instant, the oval is projected onto a certain region on the Earth's surface and is assumed to be fixed in this respect. The same oval will be over another region at the next instant. The degree of the oval similarity to the aurora distribution for the next each instant will depend on the oval determination method. Two spirals is the first approximation; an oval in Φ'–MLT coordinates is the second approximation; and an oval with boundaries depending on magnetic disturbance indices is the third approximation. The highest approximation will correspond to the instantaneous distribution of auroras over the sky.

Such instantaneous distributions are often used to demonstrate the discrete aurora location and dynamics during quiet and disturbed periods. Thus, Feldstein (1966) presents synoptic maps with the aurora planetary distributions at 0835 and 1600 UT on December 13, 1957, and at 0505 and 1322 UT on December 23, 1957. The observed auroral forms are shown by symbols within the camera view fields. These maps indicate that auroras are located along the auroral ovals and an auroral arc at the oval poleward boundary on the nightside moves to the North Pole station zenith (Φ' ~ 81°) during a disturbance. The high-latitude region is incompletely observed by the network of cameras. Rather wide areas are not observed.

Instantaneous planetary distributions are illustrated in Figs. 10a and b by the synoptic maps according to Starkov and Feldstein (1970) for two instants in December 1957 and December 1958, when observations covered a considerable part of the high-latitude region. The auroral luminosity is located within the oval on December 19, 1957 (Fig. 10a), when the magnetic field was quiet. Discontinuities in the luminosity band are caused by the fact that observations were absent at the corresponding latitudes. The photographs of auroras at different longitudes along the band correspond to the forms consistent with the scheme presented in Fig. 7. On December 8, 1958 (Fig. 10b), auroras were instantaneously distributed over a considerable part of the oval and were rather intense on the nightside. The westward electrojet flows along the nightside sector. Lazutin (2015) assumed that the instantaneous distributions in the form of rings were constructed by Khorosheva based on simultaneous photographs of auroras. However, she actually constructed such distributions using ascaplots.

Entitling the paper with the statement that the oval is an archaic paradigm, L.L. Lazutin uses this outdated paradigm in order to interpret relatively recent satellite observations (Lazutin, 2015; p. 26). He writes: "Thus, the satellite studies demonstrated that the auroral oval "breathes": as disturbances intensify, the nightside part of the oval expands poleward and equatorward and the dayside part moves equatorward." However, this result was achieved earlier, when the auroral oval boundary dynamics during magnetic disturbances was studied (Starkov and Feldstein, 1968). The introduction of the oval concept is so evidently profitable that Lazutin repeatedly uses this concept in the conclusive sections of his paper.

According to this statement (Lazutin, 2015; p. 26), small-scale processes during magnetospheric substorms can also be studied ignoring the auroral oval concept. However, the auroral oval term and concept are extremely efficient when the types and large-scale structure of auroral precipitation into the upper atmosphere are described and their correlation with magnetospheric plasma domains is revealed, as well as in several other studies (e.g., (Vorobjev et al., 2000; Starkov et al., 2002, 2003)).

4. CONCLUSIONS

The existence of the auroral oval is still the paradigm in solar–terrestrial physics. We list some of the presumably most typical scientific fields in which the auroral oval or simply oval concept was and is the paradigm:

—the description of the luminosity of the Earth and the Solar System planets with the intrinsic magnetic fields from space;

—the description of auroras as a natural geophysical phenomenon in the Earth's atmosphere;

—the auroral oval as a natural coordinate separating the regions with different geophysical phenomena;

—the auroral oval as a region in which the maximal flux of the corpuscular energy enters into the upper atmosphere;

—the consideration of planetary regularities in the spatial–temporal distribution of discrete auroras;

—the interpretation of geophysical observations of the high-latitude station meridional chains crossing the high-latitude region along geomagnetic latitudes and longitudes as well as satellite observations of plasma structures in the nightside magnetosphere, mapping along magnetic field lines on the different auroral luminosity types in the upper atmosphere;

—the auroral oval and auroral substorm concepts are used for different time and spatial scales of the studied phenomena. These concepts can complement each other. Thus, when the substorm onset zone is studied, the data on auroras (oval) and energetic electrons coincide: the process starts deep in the magnetosphere on closed magnetic field lines in the region of the equatorial auroral arc;

—the paradigm of the auroral oval was put as the basis for the generally accepted at present time the large-scale structure of plasma domains in the nightside magnetosphere and for the relation between this structure and different auroral luminosity types in the upper atmosphere. Such correspondence is presented in (Galperin and Feldstein, 1996).

The auroral oval concept was published for the first time in (Feldstein, 1960). The author for the first time introduced the term "auroral oval" in geophysics; for the first time proposed the concept of the auroral oval as a region with zenith auroral forms shifted onto the nightside relative to the geomagnetic pole; for the first time presented the pattern of isoauroras in geomagnetic latitude–MLT coordinates with the region where auroras almost constantly exist in the zenith (the auroral oval); and for the first time isoaurora maps were constructed for the daytime and nighttime hours in the Northern and Southern Hemispheres. The author, together with G.V. Starkov, for the first time investigated the auroral oval boundary dynamics for all LT hours under geomagnetic conditions from quiet to strongly disturbed.

All this justifies the indisputable priority of the paper's author in the establishment of the auroral oval paradigm.

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