The Phenomenology and Morphology of Aurorae

Ya. I. Feldstein, S. I. Isaev†, and the late A. I. Lebedinsky§*

* *IZMIRAN, Akademgorodok, Moscow, USSR*
† *Polar Geophysical Institute, Murmansk, USSR*
§ *Moscow State University, Moscow, USSR*

Abstract

The space–time distribution of the discrete aurorae in the polar cap and of the zone aurorae is discussed. Special attention is paid to the dynamics of the association of aurorae with polar magnetic disturbances and ring currents in the magnetosphere. A scheme of the dynamical morphology of aurorae including the observed regularities in their movement accompanied by the appearance, development, and extinction of polar magnetic disturbances is presented for the northern hemisphere.

The morphological and phenomenological features of aurorae during the solar maximum (IGY) and minimum (IQSY) are compared.

1 Introduction

Aurorae are the luminescence of the upper rarefied atmospheric layers. Earlier Birkeland (1908) showed that aurorae were possibly due to the intrusion of energetic charged particles from space.

It is usually assumed that the discrete pronounced visual forms of aurorae are due to atomic and molecular excitation under the influence of energetic electrons for which $E \leqslant 10$ keV. This was confirmed by direct rocket measurements (McIlwain 1960, Davis, Berg, and Meredith 1960). It is usually assumed that these electrons intrude into the atmosphere from the geomagnetosphere or from the region of the neutral line on the day side of the earth (Piddington 1965, Shabansky 1968, Axford, Petschek, and Siscoe 1965, Dessler and Juday 1965, Dungey 1968, Pletnev *et al.* 1965, Ponomarev 1966, Akasofu 1966b, Omholt 1963). However, the discrete structures in aurorae are likely to be due to the ionospheric electric discharge accompanied by the appearance of energetic electrons in the ionosphere (Lebedinsky 1952, 1956). Proton intrusions do not result in the appearance of pronounced structural formations but form vast regions of homogeneous diffuse glow.

Aurorae differ from the weak and relatively stable airglow by a high ratio of the intensity of the 3914 Å line of the N_2^+ First Negative band to that of the 5577 Å OI line (Dalgarno 1965, Cummings *et al.* 1966) and also by close correlation of the auroral morphology with the geomagnetic field.

A historical review of the development of ideas about the aurorae before the IGY was given by Chapman and Akasofu (1964) and the morphology of aurorae has been surveyed by many workers (Harang 1951, Störmer 1955, Chamberlain 1961, Elvey 1964, Paton and Evans 1964, Bates 1960, Hultqvist 1964, Khvostikov 1963, Schneider 1964). On the basis of the results of visual observations of aurorae for a number of centuries, Fritz (1881) plotted a map of the isochasms of equal average frequency of auroral visibility. Vestine (1944) prepared a subsequent map of isochasms from visual observations during the First and Second International Polar Years (1882–1883, 1932–1933) and data on magnetic disturbances. The peak isochasm along which the aurorae are observed practically every clear night, i.e. with 100 per cent frequency, is located along the so-called corrected geomagnetic latitude $\Phi' = 67°$ (Hultqvist 1958); the approximate position of the peak isochasm in the southern hemisphere has been determined by White and Geddes (1939) and Vestine and Snyder (1945).

The latitude range in which aurorae are most frequently observed has been named the auroral zone; its boundaries are the isochasms with a definite probability of auroral occurrence. This zone is customarily called the Fritz zone. Instead of isochasms, the auroral zone may be defined by isoaurores (lines of equal average frequency of occurrence of overhead aurorae), and the location of the auroral zone is determined from statistical data based on the probability of auroral occurrences in excess of a certain given value, for example, 0.1 (Davis 1950, Malko 1966) or 0.6 (Sandford 1964, Feldstein 1966b).

In investigating the morphology of aurorae one has often to discuss the boundaries of the region in which at a particular instant aurorae are overhead. We shall call this region the auroral belt. The notion of the zone appears as a result of the statistical averaging of the instantaneous patterns of aurorae. Such an averaging may be made both for definite geophysical conditions evaluated by the geomagnetic activity indices and for definite periods of time.

Ideas about the location of the auroral zone were significantly altered as a result of the analysis of the IGY–IGC observational material (*Ann. IGY* 1962, 1964). It appears that distinct forms of aurora exist practically continuously during the near-midnight hours at geomagnetic latitude $\Phi' \sim 67°$. During the evening and morning hours such forms are observed predominantly at higher latitudes and near midday they are observed at $\Phi' \sim 76–77°$. The region of overhead aurorae is located eccentrically with respect to the geomagnetic pole: in the day-time this region is 10° closer to the pole than at night-time. This eccentrically located region is called the auroral oval. To a rough approximation, one may assume that the auroral oval is fixed in space with respect to the sun, and the earth is rotating below it, i.e. the luminescence region hangs permanently over the rotating earth. The Fritz zone in such a model is a region on the earth's surface over which the near-midnight portion of the oval is passing. In this approximation, three regions should be distinguished: the polar cap, the auroral oval, and subauroral latitudes. The region inside the auroral oval is related to the polar cap and that at the equatorial oval is related to the subauroral zone. Depending on the local time, one and the same station may be located (during a 24-hour period) in different regions: in the polar cap, in the auroral oval, and in the subauroral latitudes. The form and the width of the auroral oval depend on the intensity of the polar magnetic disturbances DP and ring current DR.

Depending on the nature of the exciting agent (electrons or protons), the energies of the charged particles, and locality, the aurorae may be divided into several groups:

1. Polar-glow aurorae. The main exciting agents are the low-energy protons and alpha particles of the solar cosmic rays in the energy range from 100 keV to several MeV, and, probably, protons of even lower energies.

These particles are generated in the solar flares. A description of the polar-glow aurorae is given by Sandford (1967b).

2. Hydrogen luminescence along the auroral oval due to protons with energies of 1–10 keV (Chamberlain 1961, Galperin *et al.* 1966) and according to some determinations up to 100 keV (Evlashin 1964, Murcray 1966). This luminescence, which is due mainly to the proton intrusion, was called by Omholt (1963) the hydrogen aurora. The protons intrude as a band of size from several hundreds to thousands of kilometres (Galperin 1959, Vallance Jones 1965, Evlashin 1963, Eather and Sandford 1966, Krasovskii 1961).

The hydrogen emission band undergoes a systematic drift towards the equator during the evening hours and towards the pole during the morning hours (Galperin 1959, Rees and Reid 1959, Montbriand and Vallance Jones 1962). The occurrence of hydrogen emission in the evening at a station at $\Phi \sim 65°$ precedes the occurrence of electron aurorae (Galperin 1959, Romick and Elvey 1959). Stoffregen and Derblom (1962) consider that in the evening the proton aurora is located nearer the equator than are the structured auroral forms, and in the morning closer to the pole. These results are confirmed by Vallance Jones (1965) and Evlashin (1969) but disagree with the data of Galperin (1959) and Eather and Sandford (1966) according to which proton aurorae are always located nearer to the equator than electron aurorae. According to Krasovskii (1967), Eather and Jacka (1966), and Omholt *et al.* (1962) hydrogen luminescence is observed in the diffuse forms but not in bright electron aurorae. However, an increase in the hydrogen emission in the bright structural formations has been found by Chamberlain (1958).

3. Discrete aurorae in the polar cap characterized by pronounced forms. The occurrence of such aurorae is restricted within the region of magnetic lines of force forming the magnetospheric tail. The exciting agent is electrons, probably with energies which do not as a rule exceed 500 eV.
4. The oval zone aurorae. The exciting agent is electrons probably with energies of several keV. These aurorae are easily visible as pronounced forms bordering the near-polar region.

In the morning and evening Sandford (1964) observed subvisual glow at a latitude nearer the equator than the auroral oval; this he has called "mantle aurora." Piddington (1965) and Hartz and Brice (1967) associate the occurrence of the mantle aurora with quite a number of geophysical events and assume that it is due to the $E > 20$ keV electrons.

A stable red luminescence in the form of arcs at middle latitudes during the intense magnetic storms was found by Barbier (1958). This luminescence is produced at altitudes of the order of 300 km. A detailed review of the results observed is given by Roach and Roach (1963). Mechanisms for the excitation of the oxygen atoms are proposed by Megill and Carleton (1964) and Cole (1965).

2 Classification

During the last decades, the forms and structures of electron aurorae have been classified according to Störmer's recommendations (1930).

To unify the visual observations of aurorae from the world-wide network of stations, the *IQSY Instruction Manual* (Jacka and Paton 1963) and the *International Auroral Atlas* (1963) have been issued in conformity with the International Association of Geomagnetism and Aeronomy decisions. The phenomenology introduced by these documents is briefly summarized as follows.

The whole variety of the luminescence regions observed visually is described by six parameters:

1. The auroral forms are divided into three groups: band-like (arcs and bands), diffuse (patch and veil), rays.
2. The structure is analysed into three kinds: homogeneous, striated, rayed.
3. The structure is qualified as multiple, fragmentary, or coronal.
4. The state of activity characterizes the behaviour of a single form or of the whole display and is subdivided into quiet, active, pulsing.
5. The brightness of the aurorae observed visually is evaluated according to the scale of International Brightness Coefficients. Seaton (1954) and Hunten (1955) associated this scale with the absolute intensity of the 5577 Å emission. In this case, the unit of measurement was the kilorayleigh, i.e. 10^9 photon cm^{-2} s^{-1}. As calculations have shown (for example, Dalgarno 1965), a flux of energetic particles of about 3 erg cm^{-2} s^{-1} is

necessary to excite a weak luminescence of intensity 1 kilorayleigh, i.e. 0.2 per cent of the particle energy is transferred to the visible radiation.

These results agree well with the rocket and satellite data (McIlwain 1960, O'Brien and Taylor 1964). On the basis of the data on the vertical distribution of the luminescence intensity of the 3914 Å line, Belon *et al.* (1966) showed that the 1–4 keV primary electrons dominated in the arcs and that the $E > 30$ keV electrons were of little importance in the excitation of aurorae. The total electron flux in 16 arcs was changed from 2.9×10^9 to 1.10×10^{11} electrons $cm^{-2} s^{-1}$ and the total energy flux varied between 28 and 590 erg $cm^{-2} s^{-1}$. Electron energy fluxes of about 360 erg $cm^{-2} s^{-1} sr^{-1}$ (Krasovskii *et al.* 1961) or 400 erg $cm^{-2} s^{-1} sr^{-1}$ (O'Brien and Laughlin 1962) are sometimes found.

6. The colour of aurorae is notable for its considerable variety. Spectroscopic observations have shown (Krasovskii 1961) that the type of spectrum, and hence the colour of the luminous formation, is explained by the depth to which the excitation agent penetrates into the atmosphere.

3 The Characteristics of the Auroral Forms

Detailed investigations of the time regularities in the occurrence of the auroral forms have been carried out by Heppner (1954) (see also Meek 1953, Oguti 1963, and others). The sequence in the occurrence of the forms observed at $\Phi \sim 65°$ depends on local time and on magnetic disturbance. The sporadic occurrence of the polar geomagnetic disturbances results in the activation of the whole auroral pattern (Akasofu 1964b, 1965) and therefore the observed sequence of the form on a specific day may be somewhat different. The systematic change in auroral forms is not observed in the polar cap.

The predominant latitude distribution of individual auroral forms has been studied statistically. According to Dzyubenko (1964a), the rayed arcs and rays are located, as a rule, closer to the pole than the homogeneous forms, and the pulsating spots are observed even nearer to the equator; according to Gartlein (1958) and Nadoubovich (1967), however, rays are located 2° to the south of homogeneous arcs.

Jorjio has shown (1959) that only a small portion of the radiation which increases with increase in geomagnetic activity is concentrated in the pronounced bright formations (Sandford 1964).

Homogeneous arcs and bands extend over thousands of kilometres in magnetically quiet periods (Khorosheva 1963b, Akasofu 1963b); in exceptional cases they can extend about 10,000 km. During magnetic disturbances the length of the arcs is greatly decreased and their regular structure is distorted. According to the measurements of Kim and Volkman (1963, 1965) the thickness of the arcs at Churchill is on the average 9.1 km, that in Alaska is 8.8 km and it increases with geomagnetic activity. Bands of less than 1 km thickness are reported (Akasofu 1961). The vertical extent of homogeneous arcs and bands according to Currie and Weaver (1955) is on the average 25–29 km, and according to Andrienko (1965b) 28.5 km. The lower boundary is located at altitudes of 100–110 km (Vegard and Krogness 1920); in the IQSY period it was at 111.5 km (Andrienko 1965a). The distance between the homogeneous arcs is 30–40 km (Akasofu *et al.* 1966). When photographed with an exposure of $\frac{1}{60}$ second the homogeneous arcs look like the superposition of elements extended horizontally along the arc direction and having a size of 100–1000 m (Davis 1966).

Nadoubovich and Starkov (1961) and Dzyubenko (1965) studied the striated structure of arcs and bands. Dark bands of minimum width 150 m and length of the order of 20 km are most frequently observed in the morning and persist for several minutes.

The lower altitude of the rayed forms is 106.6 km (Andrienko 1965a). The rays are located along the line of the magnetic field (Vegard and Krogness 1920) and reach a length of thousands of kilometres (Störmer 1955). According to Vegard (1912) the cross sections of the rays are several hundreds of metres. In the years of maximum solar activity the rayed forms are of greater length than in the years of solar minimum. The altitude of the lower boundary also changes with the solar activity cycle (Elvey 1957) but correlation with solar activity is absent (Egeland and Omholt 1966).

Hill (1965) measured the altitudes of aurorae over Churchill in 1963 and 1965. The altitude of the lower border was most frequently 110 and 120 km as compared with 101 and 107 km during the IGY period (McEwan and Montalbetti 1958). Parallactic measurements of auroral altitudes in the Antarctic (Kinsey 1965, Aitken 1965) gave values between 100 and 110 km for most of the altitudes.

According to Harang's observations in Tromsö (1944), those by Andrienko in Tixie (1966), and those by McEwan and Montalbetti in Canada (1958), the altitudes of the lower border of aurorae decrease with increase in intensity.

Aurorae have minimum altitude and maximum brightness at the latitudes of the peak isochasm (Störmer 1955, Malko and Starkov 1965, Khorosheva 1960) and it has been shown by Egeland and Omholt (1966) that the altitude systematically decreases from $\Phi = 70°$ to $\Phi = 60°$ and depends on local time, decreasing towards the morning hours.

The aurorae with the green line intensity of up to 11.5 kR occur most frequently at $\Phi \sim 65°$ (in 80 per cent of cases). The intensity was above 100 kR only during 0.4 per cent of the time (Roach and Rees 1960).

Akasofu and Kimball (1964) believe that the quiet homogeneous arc is the main stable luminous form and that other forms are produced from it and that, as the intensity increases, these are arranged in the following order: rayed arc, homogeneous band, rayed band, rays, patches. This may be valid, but not for all latitudes. Thus, at $\Phi' \sim 75°$ in the day-time, the activation has the opposite sequence: from rays to the rayed arcs (Feldstein and Starkov 1967).

The data on the forms and location of aurorae for the period July 1957–December 1959 have been published as visoplots (*Ann. IGY* 1964, Gartlein *et al.* 1965, Lassen *et al.* 1964). Synoptic maps of the auroral distribution for individual days of the IGY period are given by Akasofu (1963a) and by Gartlein (1966). Similar maps for each hour UT of the IQSY period are being plotted at the World Data Centres. The planetary distribution of aurorae according to data from all-sky cameras may be determined from ascaplots (*Ann. IGY* 1962) which provide information on the occurrence of aurorae in three regions of the sky — zenith, north, and south — and at half-hourly intervals. Ascaplots are also being prepared from all-sky cameras for the IQSY period.

4 Discrete Aurorae in the Polar Cap

The aurorae observed in the polar cap are, as a rule, of the form of single or multiple arcs with a diffuse rayed structure. The brightness of such aurorae is inconsiderable. These aurorae persist for only short periods. The period of existence of a single form is of the order of several minutes.

4.1 Alignments of Aurorae

It has been known since 1920 (Vegard and Krogness 1920) that in the near-polar region the arcs were not in any predominant alignment, and the rotation of the arcs through 360° during a day with the predominant direction towards the sun was noted by Mawson (1925). Observations during IGY have confirmed the rotation of arcs through 360° in the polar cap (Weill 1958, Davis 1960, 1962b, Feldstein 1960, Denholm and Bond 1961).

Figure 1*a* shows the changes in azimuth according to Feldstein (1960), Denholm and Bond (1961), and Davis (1962b). At midday and midnight the arcs were oriented approximately in the direction of the geomagnetic pole and their azimuths changed during a day by 360°.

Aurorae roughly aligned in the direction of the sun are observed at night up to the latitudes of about 75° (Starkov and Feldstein 1967a).

Figure 1*b* shows the data from the near-polar station Vostok for 1965 (Belousov *et al.* 1968a). During the IQSY period, aurorae in the near-polar region were also aligned in the direction of the sun within $\pm 25°$. In very rare cases during intense magnetic disturbances at $\Phi' > 80°$ aurorae occurred which were aligned at an angle of about 90° to those usually observed. Figure 1*b* shows the azimuths of two such aurorae which were oval zone aurorae.

4.2 Aurorae and Magnetic Activity

Attention was drawn by Lassen (1959), Feldstein (1960), and Hatherton and Midwinter (1960) to the absence of correlation between the intensity of

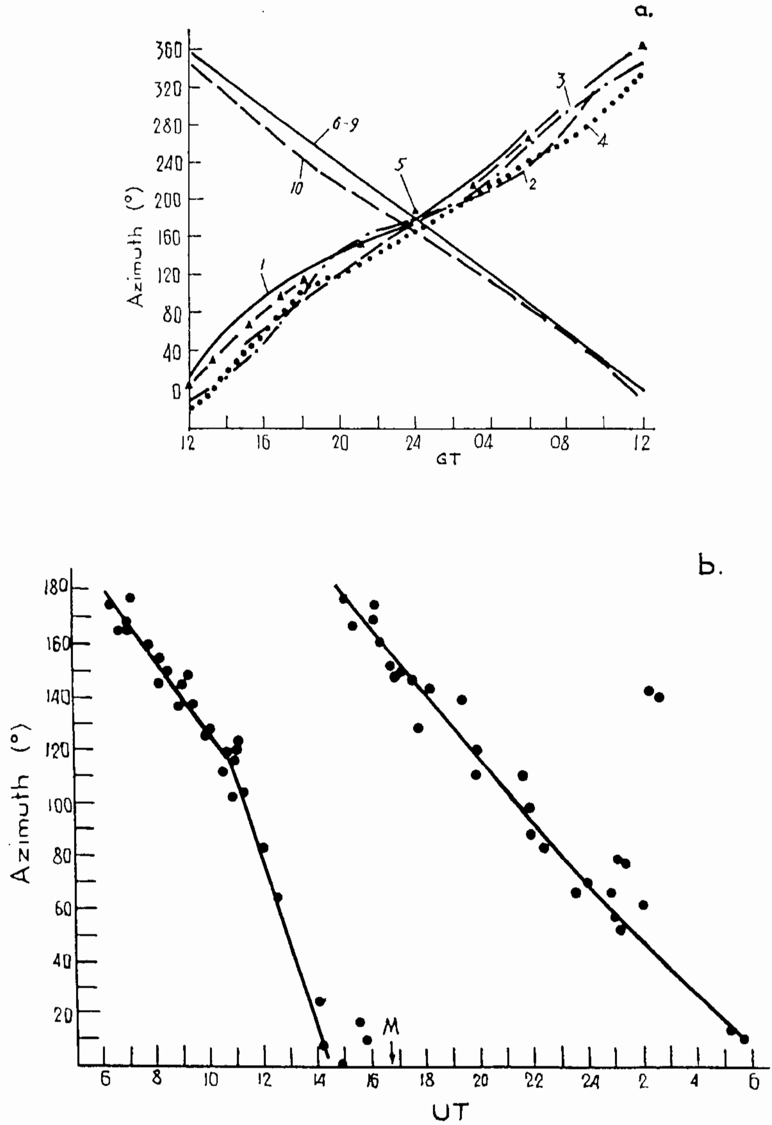


Fig. 1 *a.* Variation of azimuths of auroral arcs in the near-polar region (data from Feldstein 1960, Denholm and Bond 1961, Davis 1962b).

1 Resolute Bay
2 Thule
3 Alert
4 Arctica II (1957–1958)
5 Arctica II (1958–1959)
6–9 Wilkes, Dumont d'Urville, Scott, Hallett
10 Vostok

Geomagnetic time. The azimuth is calculated eastwards from the direction of the geomagnetic pole.

b. Variations of azimuths of auroral arcs at Vostok in 1965 (Belousov *et al.* 1968a). Time in UT, the arrow indicates local midnight, the azimuth is calculated eastwards from geographical north.

Table I Percentage Occurrence P of Overhead Aurorae

Station	College	Dixon	Murchison Bay	Arctica I 1958–1959	Arctica II 1957–1958	Arctica II 1958–1959	Resolute Bay	Thule
Q	$\Phi' = 64.9°$	$\Phi' = 68.0°$	$\Phi' = 76.0°$	$\Phi' = 78.4°$	$\Phi' = 80.8°$	$\Phi' = 84.7°$	$\Phi' = 84.3°$	$\Phi' = 87.7°$
0	—	—	—	—	10	27	—	—
1	9	20	60	31	24	11	67	22
2	19	33	76	51	23	8	45	20
3	62	62	72	34	14	9	37	14
4	82	72	65	43	12	6	14	13
5	95	95	57	20	6	—	3	12
6	97	98	62	—	15	—	—	—
7	98	100	—	—	—	—	—	—
> 7	100	100	—	—	—	—	—	—
$\bar{P}$	74	74	70	41	17	10	27	17

$\bar{P}$, mean frequency of occurrence of aurora.
Φ', corrected geomagnetic latitude according to Hultqvist (1958).

magnetic activity and the occurrence of aurorae at a number of high-latitude stations. Lassen (1961a, b, 1963), Feldstein (1961, 1962b), and Davis (1963) have examined in detail the association of aurorae with magnetic disturbances at high latitudes.

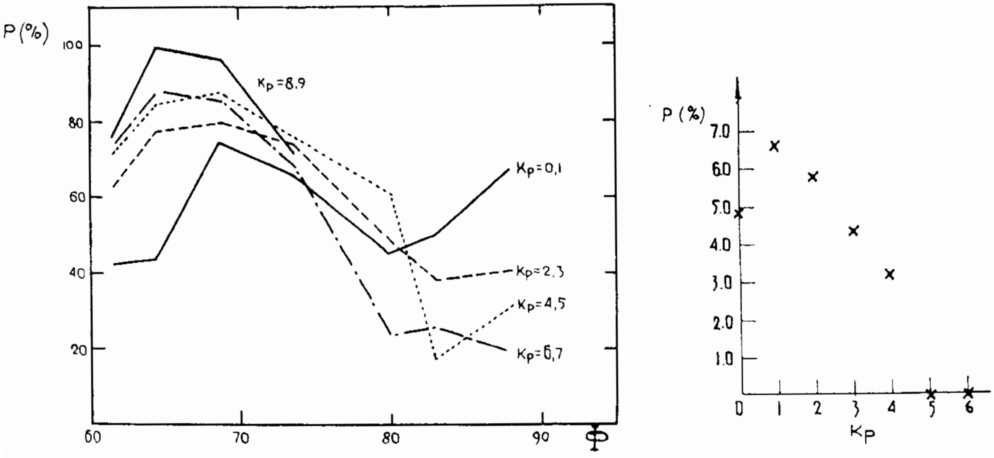
Table 1 shows the percentage occurrence P of aurorae in the zenith according to Feldstein (1961, 1962b) for various values of the magnetic activity index Q. As Q increases, P also increases at latitudes $\Phi' < 70^\circ$ and decreases at latitudes $\Phi' > 80^\circ$.

Figure 2*a* shows the latitude changes in P for various Kp obtained by Davis (1963). At $\Phi > 80^\circ$ the occurrence of visual aurorae is in anti-correlation with Kp; for $\Phi < 70^\circ$ the correlation is positive. The presence of the negative correlation of visual aurorae and magnetic disturbances in the near-polar region is confirmed by Sandford (1964) and Akasofu (1964b).

According to Fig. 2*b*, the negative correlation of P and magnetic activity is also maintained during the IQSY period (Belousov *et al.* 1968b). The number of auroral forms also decreases with increasing Kp according to Stringer and Belon (1967). The negative correlation of P with Kp explains a more frequent occurrence of aurorae in the near-polar region in the years of solar minimum (Davis 1950).

The indices K, Q, $r_H{}^{\gamma}$ characterize the intensity of geomagnetic disturbance. It has been shown by Evlashin and Maltseva (1965) and Zhigalov (1966) that the occurrence of aurorae in the near-polar regions is usually accompanied by irregular short-period pulsations of the small-amplitude electromagnetic field.

The red luminescence of oxygen in the near-polar region described by Sandford (1964), Weill *et al.* (1965), and Evlashin (1961) cannot be observed



a *b*

Fig. 2 *a*. Variations of $P(\%)$ with latitude at different Kp by Davis (1963) in 1957–1958.
b. Variations of $P(\%)$ at Vostok at different Kp in 1965 (Belousov *et al.* 1968b).

visually or using all-sky cameras. It is likely that the nature of this luminescence (as was noted by Cole (1966) and Krasovskii (1967)) is different in principle from that caused by the excitation of energetic particles. Taylor and Hones (1965) explain the existence of the negative correlation of Kp and P in the near-polar region by the extension and rupture of the geomagnetic field lines in the magnetospheric tail at large Kp.

4.3 Altitudes of Aurorae

Starkov has found from the ascafilms that during the IGY period the altitude distribution of aurorae had a peak at altitudes of 150–175 km at $\Phi' \sim 76°$. Aurorae were often observed at altitudes of about 300 km. As the brightness of aurorae increased from 10^{-7} to 10^{-6} stilb, the altitude decreased from 200 to 150 km. Evaluation of the energy of the monochromatic electron flux penetrating down to the observed altitudes gives $E < 500$ eV (Rees 1963) for aurorae at altitudes above 175 km. The high altitude of aurorae explains the absence of the connection between DP which is due to currents in the ionospheric E layer and the frequency of occurrence of aurorae.

The depth of the penetration of the corpuscular streams into the ionosphere may be judged from the data of the vertical soundings of the ionosphere. At $\Phi \sim 65°$ the occurrence of overhead aurorae is accompanied, as a rule, by sporadic formations in the E region at altitudes of 100 km (Heppner *et al.* 1952), etc. In 1957–1958 and 1958–1959 at Arctica II station overhead aurorae were not accompanied by the regular formation of Es at altitudes of 100–110 km (Feldstein 1961). Additional ionization produced in the near-polar region when aurorae occur is located at the altitudes of the upper part of the dynamo region (>120 km).

A higher altitude of aurorae inside the auroral oval follows also from the analysis of the spectra obtained in 1958–1959 using patrol spectrographs with exposures of 2 and 8 minutes (Evlashin 1961). It appears that at $\Phi \sim 75°$ in 42–48 per cent of all recorded spectra and at $\Phi \sim 65°$ in only 3.5 per cent of all spectra, the 6300 Å line is more than 1.5 times more intense than the 5577 Å line.

5 Aurorae of the Auroral Oval Zone

5.1 The Space–Time Distribution during the IGY Period

The most detailed data on auroral distribution before the IGY are given by Vestine (1944), White and Geddes (1939), Vestine and Snyder (1945), and Isaev (1958) who evaluate the frequency of occurrence of aurorae on the basis of the number of nights when aurorae occurred in every portion of the sky. Before the beginning of the IGY, Chapman (1957) noted the necessity of plotting maps of the frequency of occurrence of overhead aurorae.

The frequency of occurrence of overhead aurorae P is a function of latitude and local time $P = P(\Phi, t)$. In the cycle of experiments carried out independently in 1960–1963, Feldstein and Khorosheva put forward the idea of the existence of the auroral oval (Feldstein 1960, 1963a, b, Khorosheva 1961a, b, 1962, 1963a, Feldstein and Solomatina 1961b).

To obtain the function $P(\Phi, t)$ it is necessary to examine separately the variations in $P(t)$ for constant Φ and the variations in $P(\Phi)$ for constant t. Figure 3 shows the former for 1957–1959. For $\Phi' < 68°$ overhead aurorae occur most frequently at near-midnight hours. For $71° \leqslant \Phi' \leqslant 75°$ the peak is divided into two and both peaks move further away from midnight with increasing Φ'. For $\Phi' \leqslant 77°$, the aurorae are observed predominantly in day-time. For Φ' between 66° and 77°, the value of P reaches 80 per cent or more; at lower latitudes it is less than 80 per cent, and in the near-polar region aurorae occur much more seldom. The diurnal variations described above are confirmed by the data from the overwhelming majority of stations at which aurorae were photographed during the IGY–IGC period (*Ann. IGY* 1962).

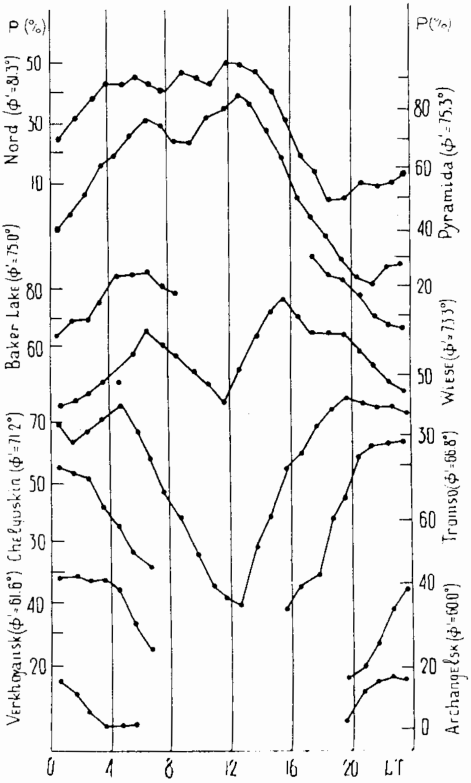


Fig. 3 Daily variations of $P(\%)$ for the period 1957–1959 at stations in the northern hemisphere.

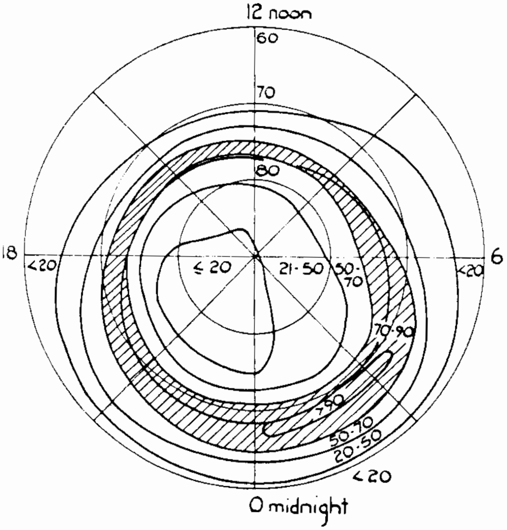


Fig. 4 The frequency of occurrence of overhead aurorae in coordinates Φ' and local time for the period 1957–1959 in the northern hemisphere (Feldstein 1966b). The figures indicate the percentage frequency of aurorae. The solid line shows the boundary of the trapped electron stream $E > 40$ keV of intensity 3×10^3 cm^{-2} s^{-1} (Frank *et al.* 1964).

When $P(t)$ is available, the dependence of P on Φ', $P(\Phi')$, at constant t and the isoaurores of the frequency of occurrence of aurorae may be plotted. The isoaurores for the northern hemisphere are shown in Fig. 4; those for the southern hemisphere are given by Sandford (1964) and Feldstein (1964). The region where P is highest is hatched. This region is located asymmetrically with respect to the geomagnetic pole in the plane of the midday–midnight meridian and is of oval shape. It is this region that is the auroral oval zone. The characteristic feature of the oval zone is the fact that on the day side this zone is less widespread latitudinally than on the night side. Also plotted in Fig. 4 are the data on the boundaries of the $E > 40$ keV electron trapping according to the data from the Injun 3 satellite (Frank *et al.* 1964). The boundary agrees quite well with the position of the oval zone. Some of the discrepancy can be attributed both to the difference in the periods of observation and to the intensity of geomagnetic disturbance which affects substantially the position of the oval zone and the boundaries of the trapping zone (Maehlum and O'Brien 1963). Injun 3 observed also the brightest aurorae along the high-latitude boundary of the trapped electrons (O'Brien and Taylor 1964). In somewhat idealized form the oval may be represented by the ring located on $\Phi' \sim 67°$ at night-time and on $\Phi' \sim 77°$ in the day-time and having mean radius approximately 19°. It can be seen from Fig. 5 that the location of the extended forms of aurorae at fixed moments of universal time coincides well with the auroral ring both on the day side of the earth (19 December) and

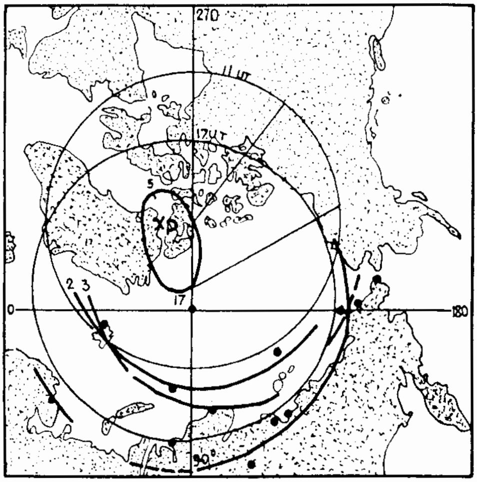


Fig. 5 The projection on the earth's surface of the extended auroral forms:

1, a diffuse band at 1718 UT, 16 February 1958;
2, a rayed arc at 0730 UT, 19 December 1957;
3, a rayed arc at 1050 UT, 19 December 1957.

Thin circles show the location of an auroral ring at 1100 UT and 1700 UT. The ring radius = 19°, the centre is located in the closed thick curve near the geomagnetic pole. The points indicate the stations at which the aurorae were photographed (Khorosheva 1963b).

on the night side (16 February); this is confirmed by Akasofu (1964b). The oval zone for the southern hemisphere is shown in Fig. 6; the position of the hydrogen auroral zone according to Evlashin (1963), Eather and Sandford (1966), and Montalbetti and McEwan (1962) is also shown. The proton auroral zone is located near the auroral oval.

The data on the diurnal variations in P(per cent) at a great number of points of the northern and southern hemispheres agree with the idea of the oval zone. It is known from the observations carried out before the IGY (Hultqvist 1964, Heppner 1954, and others) that $P(t)$ at $\Phi' \leqslant 68°–70°$ is maximum near midnight; for $70° \leqslant \Phi' \leqslant 78°$ an additional peak is observed in the morning; at $\Phi' > 78°$ the characteristic diurnal variations are absent. During the IGY period, one night peak was observed at $\Phi' = 62.6°$ (Malville 1959) and two peaks were observed at $\Phi' = 74.7°$ (Malville 1959, Morozumi 1963). Near midnight aurorae occur most frequently at $\Phi' = 55–58°$ (Lassen *et al.* 1964), $\Phi' \sim 65°$ (Malko 1967, Dzyubenko 1963b), $\Phi' \sim 70°$ (Davis and Dewitt 1963), and $\Phi' \sim 69°$ (Davis 1962a). At $\Phi' > 70°$ in the Antarctic $P(t)$ is maximum not at midnight but in the morning and evening (Hatherton and Midwinter 1959). In the day-time, aurorae occurred predominantly at Nord station (Lassen 1961a) and at the drifting stations (Belousov and Moisseev 1960). The number of peaks at Baker Lake is different according to Davis (1962a) and Feldstein and Solomatina (1961a). The time of occurrence of peaks in $P(t)$ for the Greenland stations is represented by two sections of spiral, clockwise and counterclockwise (Lassen 1963). For $67° \leqslant \Phi' \leqslant 77°$ these sections coincide with the auroral oval. This spiral form of the variation of $P(t)$ has been studied by Lassen (1963), Feldstein (1964), Malville (1959, 1964) and Korotin (1965) and of the variation of magnetic activity by Burdo (1960).

When the earth rotates beneath the oval, the night portion of the oval traces a band on the earth's surface whose distance from the geomagnetic pole is essentially greater than that for day-time aurorae. The maximum isoaurore is located at $\Phi' \sim 67°$ at night and at $\Phi' \sim 77°$ in the day-time. Thus, the maps of isochasms (isoaurores) and the position of the maximum isochasm (isoaurore) given for the northern hemisphere by Fritz (1881), Vestine (1944), and Feldstein (1960) and for the southern hemisphere by White and Geddes (1939), Vestine and Snyder (1945), Feldstein and Solomatina (1961b), and Bond and Jacka (1962, 1963) reflect the distribution of night aurorae. Day aurorae occur most frequently at the latitudes of the inner auroral zone (Nikolsky 1956, Alfvén 1955, Lassen 1959, Feldstein and Solomatina 1961a).

Several theoretical interpretations of the position of the peak isoaurore were proposed. Gartlein and Sprague (1960) believe that this isoaurore follows the isocline of the real magnetic field $I = 76°$. Hultqvist (1958, 1961) explains the deviation of the peak isoaurore from the geomagnetic parallel by the distortion of the path of the penetrating particles due to the distortion of the geomagnetic dipole field near the earth's surface. Vestine and Sibley (1959) have shown that the peak isoaurore corresponds to the line of equal value of the integral invariant of the movement of the particle along the geomagnetic lines of force between conjugate points. The auroral oval which gives the aurora distribution in (Φ', t) coordinates is essentially different from the theoretical curves described above. The theoretical explanation of the existence of the auroral oval should be sought in the day–night side asymmetry of the geomagnetosphere constricted by the solar wind. In this case, the outer boundary of the trapped electrons lies at higher latitudes on the day side than on the night side. The calculations of Malville (1960), Hones (1963), Fairfield (1964), Shabansky (1965), and Tverskoy (1964) have shown that the magnitude of the asymmetry in the position of the boundary depends on the model accepted for the geomagnetic field. According to Williams and Mead (1965) the observed asymmetry is in agreement with the theoretical calculations which include the constriction of the field on the day side and the formation of the geomagnetic tail on the night side.

5.2 The Alignment of Extended Forms in Aurorae

At the latitudes of the auroral oval, auroral arcs and bands are extended from east to west (Vegard and Krogness 1920) and the deviation of the mean azimuth from the geomagnetic parallel is due, according to Hultqvist (1958), to the difference of the geomagnetic field from the dipole field. Because extended forms in aurorae are located along the oval one would expect diurnal variation in the azimuth of the arcs and bands. Before the IGY such variations were described by Harang (1945) and Currie and Jones (1941), and their existence was confirmed in a great number of studies during the IGY (Evans and Thomas 1959, Feldstein 1960, Denholm and Bond 1961, Lassen 1961b, 1963, Starkov 1961, Denholm 1961, Hultqvist 1962, Khorosheva 1962, 1967, Davis 1962b, Dzyubenko 1964b, Lassen *et al.* 1964, Starkov and Feldstein 1967a).

The following main regularities in the variations of the azimuths have been found: (*a*) the amplitude of variation increases as the latitude increases and is about 20° at $\Phi' \sim 65°$ and about 60° at $\Phi' \sim 75°$; (*b*) the arcs rotate in the direction opposite to the changes in azimuth in the polar cap.

Fig. 6

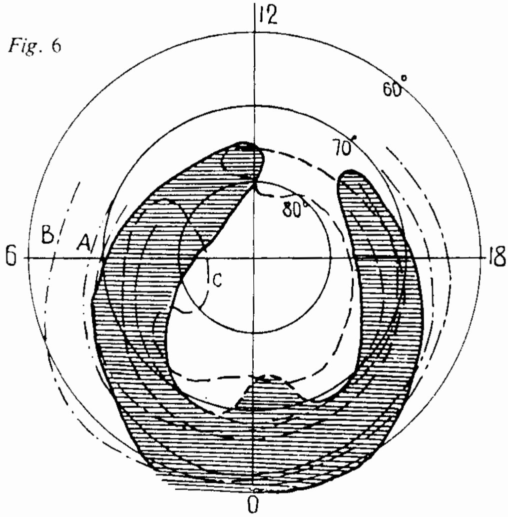


Fig. 7

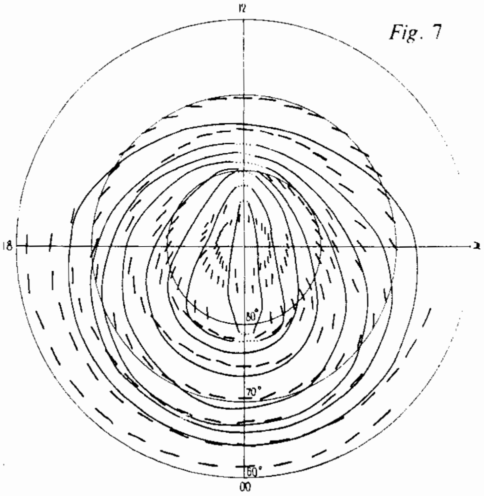


Fig. 6 The zone of hydrogen emission in the southern hemisphere as a function of latitude and eccentric dipole time (Eather and Sandford 1966). A, B, the conjugate zone of hydrogen emission in the northern hemisphere: A, Montalbetti and McEwan (1962); B, Evlashin (1963); C, the auroral oval zone (Sandford 1964).

Fig. 7 The polar diagram of the observed alignment of auroral arcs in coordinates of corrected geomagnetic latitude and time (Gustafsson 1967).

Gustafsson (1967) has obtained the smoothed mean diurnal variations of the azimuths in the 61–90° latitude range during the IGY period; a polar diagram showing the alignment of the arcs is given in Fig. 7. The solid lines show eight ovals along which the auroral arcs are located, obtained by graphical integration. Comparison of the oval curves calculated from the variations in arc azimuths with the position of the auroral oval determined by Starkov and Feldstein (1967a) and Gustafsson (1967) shows good agreement.

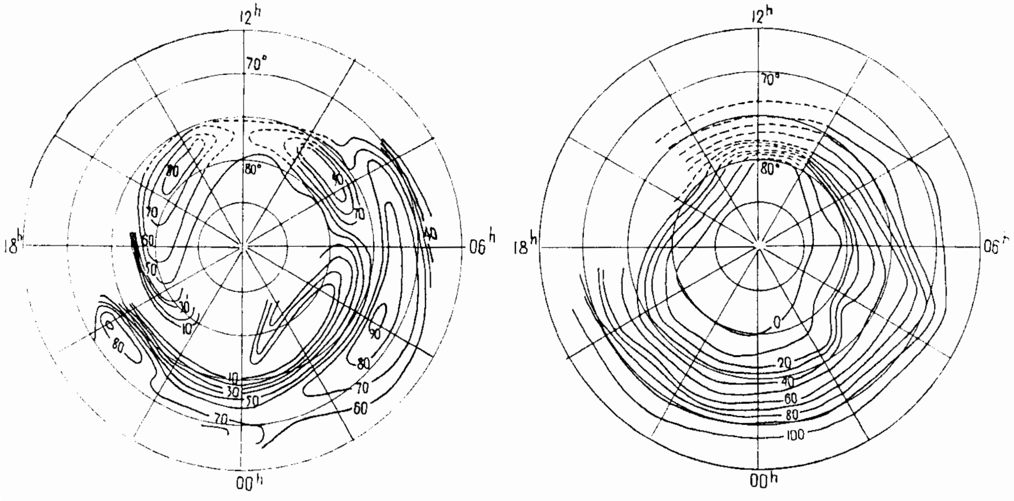
The agreement of the oval curves and the auroral oval testifies to the fact that the observed diurnal variations in the arc azimuths are due to the existence of an auroral zone located eccentrically relative to the geomagnetic pole. Evans and Thomas (1959) also explained the variations in the arc azimuths at Halley Bay station by the eccentric location of the auroral zone shifted by 2° from the geomagnetic pole towards the two-hour meridian.

5.3 The Change in the Space–Time Distribution of Aurorae

The auroral distribution presented in Fig. 4 for the IGY period changes with the intensity of DP and DR. Gartlein, Gartlein, and Sprague (1960) have found that over North America the peak isoaurore at $\Phi < 70°$ is displaced to lower latitudes as K and Kp are increased. According to Davis (1962a) the position of the peak isoaurore is not changed. Bond and Jacka (1963) have found for the southern hemisphere that the 50 per cent isoaurore is located at a distance of 23.3° from the pole at $Kp = 1$ and 28.8° at $Kp = 5$. The equatorial displacement of the peak isoaurore on magnetically disturbed days with simultaneous increase in P at higher latitudes has been noted by Feldstein (1960), Feldstein and Solomatina (1961b), and in the Antarctic Atlas (1966).

Figure 8 shows the overhead auroral distribution on quiet and disturbed days according to Lassen (1963). The location of the isoaurores indicates the formation of at least two regions of most frequent occurrence of aurorae in the quiet periods: at 76–78° in the morning hours and at 69–72° on the night side. On magnetically disturbed days, the isoaurores form a single region which is similar to the oval zone in Fig. 4. The absence of the single oval zone in magnetically quiet periods is reported also by Feldstein and Starkov (1967) and Malko (1965). At low levels of geomagnetic activity, the oval zone is not always continuous. Before midday and in the evening, breaks in the oval or a decrease in auroral intensity below the sensitivity threshold of the camera are possible.

The equatorial edge of the auroral oval on the night side of the earth moves equatorwards with increase in geomagnetic disturbance (Meek 1953, Heppner 1954, Gartlein 1958, Bless *et al.* 1959, Bond 1960, Isaev 1962, Davis 1963, Lange-Hesse 1964b, Schröder 1965, Khorosheva 1967). Bless *et al.* (1959) and



a b

Fig. 8 Isoaurores (Lassen 1963) from the data for four Greenland stations in 1957–1958, using the magnetic coordinates of Mayaud (1960): *a*, international quiet days; *b*, international disturbed days.

Bond (1960) have shown that the displacement is practically linearly dependent on *Kp* and is similar in the northern and southern hemispheres.

The positions of the boundaries of the oval for all 24 hours of the day for various intensities of DP on the night side of the earth have been determined by Feldstein and Starkov (1967) (Fig. 9). Around midnight at $Q = 0$ the oval is located at $\Phi \sim 70$–$72°$. As the geomagnetic activity increases, the oval is displaced somewhat equatorwards and is markedly extended for $Q \geqslant 2$; the southern and northern boundaries are displaced equatorwards and polewards respectively. In the day-time, there is a gradual equatorward displacement of the whole oval as Q increases, which is in good agreement with the results of the theoretical calculations of Slutz and Winkelman (1964). The expansion of the oval during the night and its displacement during the day are in agreement with the findings of Davis (1963), Lassen (1963), Akasofu (1964b), and Feldstein (1966b). At low Q the oval seems to be a weakly deformed ring with its centre at a distance of 3° from the pole along the midnight meridian. The quantitative characteristics of the auroral oval asymmetry for the day–night and morning–evening hemispheres with changing Q are given by Feldstein and Starkov (1967). The asymmetry is present at any value of Q but the change in its character is fairly complicated.

A characteristic feature of magnetic storms is the occurrence of the ring current DR at a geocentric distance of 3 to 5 R_e. The *Dst* variation is the measure for DR. Akasofu and Chapman (1962, 1963) studied the influence of DR on the location of the auroral oval. Figure 10*a* (from Akasofu and

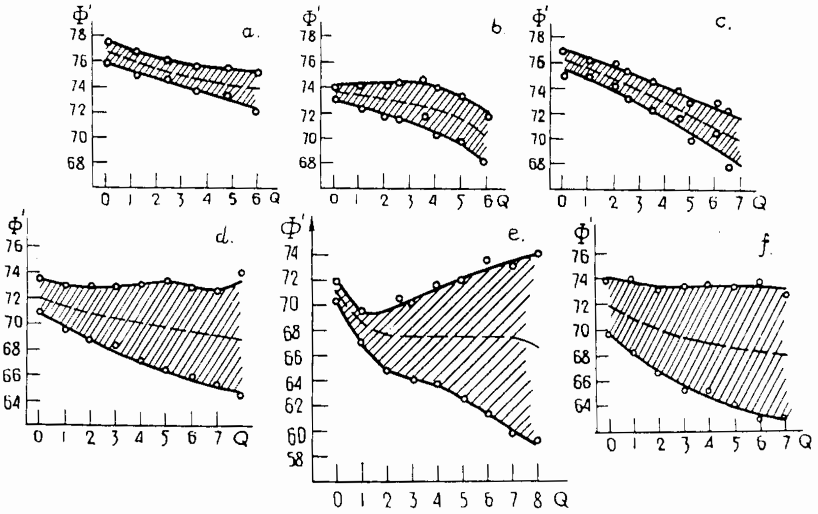


Fig. 9 The northern and southern edges of the auroral oval as a function of Q index in 1957–1959 (Feldstein and Starkov 1967). The broken line is the centre line of the auroral belt:

a, 10–14 h *b*, 6–10 h *c*, 14–18 h
d, 18–22 h *e*, 22–02 h *f*, 02–06 h

Chapman 1963) shows the dependence on *Dst* of the location of the southernmost quiet arcs during 16 magnetic storms in the IGY period. As DR increases, the arcs appear at even lower latitudes at night. Figure 10*b* shows the location of the northern and southern edges of the oval with changing *Dst* for Q constant at 3 and 5 according to Starkov and Feldstein (1969). An increase in the *Dst* variation results in the equatorward displacement of both edges of the oval. Thus, the influences of DR and DP on the location of the oval near midnight are quite different: the ring current displaces both edges equatorwards and the polar disturbances result in the poleward displacement of the northern edge and equatorward displacement of the southern edge. An increase in *Dst* results also in a small expansion of the oval. Thus, the occurrence of the ring current inside the magnetosphere results in a deformation of the geomagnetic field lines and hence in the change in the position of the auroral oval. This problem has been theoretically examined by Akasofu (1963c, 1966a).

Akasofu and Chapman (1962) consider the auroral pattern in two time intervals of the very severe storm of 11 February 1958. The use of additional observations enabled Starkov and Feldstein (1969) to show that the auroral belt is not located along the line L = constant (McIlwain 1961) over the whole longitude range but is displaced towards larger L in the evening hours compared with the night hours. The radius of the belt increases with increasing DR and for intense DR aurorae appear overhead at $\Phi \sim 60°$ in the evening and at $\Phi \sim 55°$ at night.

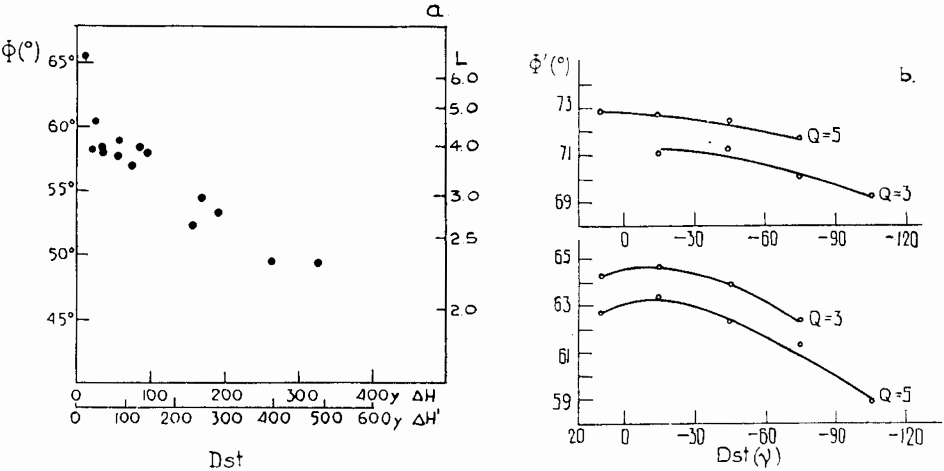


Fig. 10 *a.* Location of quiet arcs over North America and intensity of ring current during the IGY period (Akasofu and Chapman 1963).
b. Location of the northern and southern edges of the oval at $Q = 3$ and 5 near midnight during the IGY period plotted as a function of *Dst* (Starkov and Feldstein 1968).

5.4 The Comparison of the Auroral Distribution during the IGY and IQSY Periods

Information on the auroral distribution during the IQSY is very scanty and therefore the analysis is based predominantly on the material from the Soviet network of stations using data already published. Figure 11 shows the latitude changes in P at the near-midnight hours during the IGY and IQSY periods (Feldstein *et al.* 1966). Despite a very considerable decrease in solar activity, atmospheric glow exists practically continuously at $\Phi' = 68\text{–}71^\circ$ on the night side. The change in auroral intensity in the zone is also insignificant. Solar activity has little effect on the number of days with aurorae at the latitudes of the peak isochasm (Langē-Hesse 1964a), and at Byrd station the 3914 Å emission intensity at $K \geqslant 3$ was the same in 1959 and 1963 (Sandford 1967a). At $\Phi' \sim 65^\circ$ the mean auroral intensity was the same in the years of minimum and maximum (Ponomarev 1966, Dzyubenko 1964a) but aurorae occur less frequently overhead and move back to higher latitudes with decreasing solar activity (Malko 1967, Blundell 1967, Dzyubenko 1964a). The proportion of rayed forms steadily decreases and that of the diffuse forms is appreciably increased (Blundell 1967, Dzyubenko 1964c). The most appreciable effect of the cyclic changes shown in Fig. 11 is a more frequent occurrence of aurorae at subauroral latitudes during the IGY period. The latitude of the region with maximum overhead aurorae does not undergo appreciable cyclic displacements. During the IQSY period, the peak night isoaurora was located at $\Phi' \sim 69\text{–}70^\circ$ and during the IGY period at $\Phi' \sim 68^\circ$, if the middle

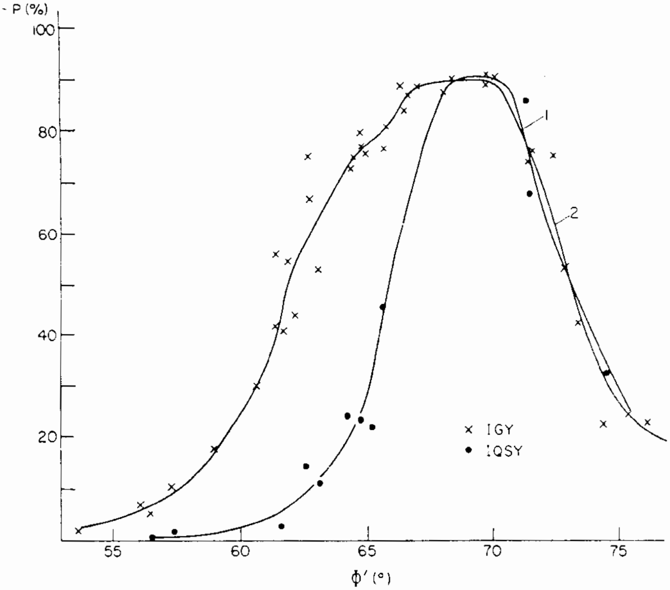


Fig. 11 Latitude distribution of P on all days during the six-hour period centred on local midnight (Feldstein *et al.* 1966).

of the interval in which the highest frequency of occurrence of aurorae was observed is taken as the position of the peak isoaurore. The satellite measurement in January–February 1963 (O'Brien and Taylor 1964) showed that the 3914 Å emission intensity was maximum over North America at $\Phi = 69 \pm 1°$. The smallness of the cyclic changes in the location of the zone agrees also with data published elsewhere (Davis 1950, Gartlein 1958, Sheret and Thomas 1961, Feldstein 1962a, Gustafsson 1964, Malko 1966, Sandford 1967b). In 1964, the number of nights with aurorae over Great Britain was less than in the minimum of the previous cycle (Paton 1965).

The number of days with aurorae at middle latitudes is a maximum 1–2 years after the peak spot formation (Meinel *et al.* 1954) or coincides with it (Lassen 1963). Ohl (1960) has shown that for four cycles near the maxima of the 90-year solar activity recurrence the number of aurorae increased at the end of the decrease branch (of the solar activity).

Figure 12 shows the frequency of occurrence of nights with hydrogen luminescence for the period 1957–1965 according to data from Eather and Sandford (1966) and Evlashin (1969). In the northern and southern hemispheres P at $\Phi \sim 65°$ and the frequency of occurrence of electron aurorae decrease throughout the cycle. The number of auroral forms observed at $\Phi = 60$–$70°$ during the IQSY period is markedly increased with increasing K and the latitude of the peak is displaced from $\Phi > 70°$ at $K = 0$ to $66.5°$ at $K > 5$ (Stringer and Belon 1967). However, the greatest number of aurorae

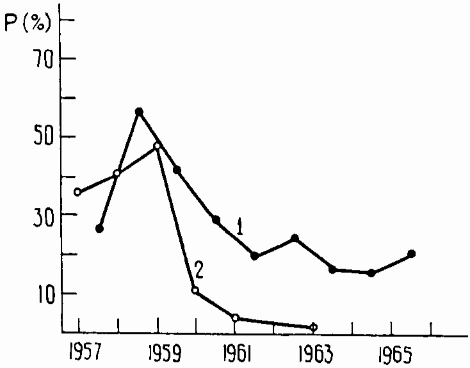


Fig. 12 Probability of appearance of hydrogen aurorae in the cycle of solar activity: 1, Murmansk (Evlashin 1969); 2, the southern hemisphere (Eather and Sandford 1966).

was observed at Φ = 66.5° in both the IGY and IQSY periods and only the shape of the latitude distribution was somewhat changed: during the IQSY period the southern boundary of the oval was displaced equatorwards with increasing *Kp*. It follows from Fig. 13*a* that for weak magnetic disturbances the boundary is located at the same latitudes in years of maximum and minimum. As *Kp* increases aurorae occur at even lower latitudes, but during the IGY for the same *Kp* the boundary of the oval was located farther from

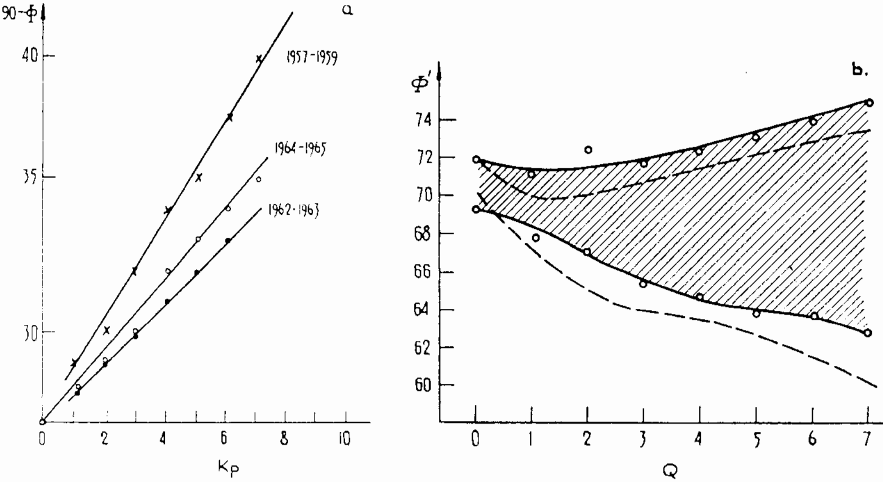


Fig. 13 *a.* The southern edge of the auroral oval from visual observations at longitudes 145–190° in 1957–1959 (Feldstein and Shevnina 1963), 1962–1963 (Malko 1966), and 1965–1966 (Shevnina and Feldstein).
b. Auroral oval near midnight during the period of IQSY (hatched) and IGY (broken line) as a function of the *Q* index (Starkov and Feldstein 1967c).

the pole. A similar result was obtained during the observations at Murmansk (Malko 1967) and at Sacramento Peak (Bellew and Silverman 1965). The comparison of the locations of the auroral oval during the IGY and IQSY periods (Fig. 13*b*) (Starkov and Feldstein 1967c) shows that, with exclusion of very quiet periods, both northern and southern boundaries were shifted equatorwards during the IGY and the width of the oval was practically the same. During the IGY and IQSY periods, the central line of the oval at $2 \leqslant Q \leqslant 6$ was located at $\Phi' = 67.5°$ and at $\Phi' = 69.0°$, respectively.

The cause of such cyclic variations is likely to be due to the change in the intensity of DR with the phase of solar activity for the same intensities of DP.

In December 1964, according to Bates *et al.* (1966), the aurorae existed even in absolutely magnetically quiet periods. In the day-time, the belt was located at $\Phi = 77$–$79°$ and by midnight was displaced to $\Phi = 65$–$70°$.

The auroral distribution in very quiet periods is given by Akasofu (1964a), Stringer *et al.* (1965), and Feldstein (1966a). During the IGY and IQSY periods the auroral belt near midnight on the days with $\Sigma\, Kp < 10$ was observed as a rule at $\Phi' \sim 70°$ for $K \leqslant 1$; this has been confirmed by radar data (Bates 1966). It appears that atmospheric luminescence occurs continuously irrespective of the intensity of the planetary magnetic disturbance. The eccentricity of the oval zone with respect to the geomagnetic pole is maintained even in the complete absence of planetary geomagnetic disturbances.

5.5 The Auroral Belt according to Radar Data

The intrusion of energetic corpuscular streams into the atmosphere results in the appearance of auroral radio reflections. The mechanism of scattering or reflection to explain the appearance of echoes has been examined theoretically by Booker (1960), Moorcroft (1961), and Pogorelov (1962), and in review papers by Hultqvist and Egeland (1964) and Leadabrand (1965); the spatial features of the radio reflections are discussed by Egeland (1962), Bagariatsky and Feldstein (1965), Unwin (1966), Brunnelli and Sandulenko (1961), and Bullough (1963).

Gadsden (1959) and Leonard (1962) have established the existence of a zone of maximum frequency of occurrence of radio reflections which embraces the geomagnetic pole. The peaks of diurnal variation in frequency of occurrence of radio reflections are located along three sections of spirals (Bagariatsky and Feldstein 1965, Unwin 1966), two of which are located along the oval zone. The use of multichannel radar at frequencies of 4–64 MHz enabled Bates (1965) to obtain reflections over the whole distance range from the zenith to 3000 km avoiding the limitation imposed by the condition of aspect sensitivity on the occurrence of the reflected signals. There is good agreement between the simultaneous optical and radio observations of the locations of the auroral belt and the scattering belt (Bates *et al.* 1966). From

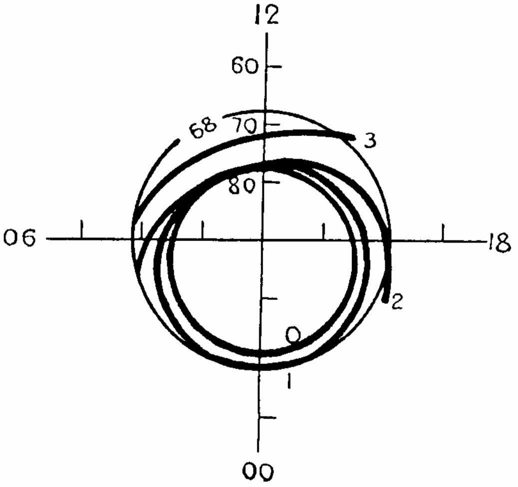


Fig. 14 The average geomagnetic latitude of the southern boundary of the scattering belt during 1965 plotted against geomagnetic time for the ranges of Kp indicated (*after* Bates 1966): 0, $Kp = 0$; 1, $Kp < 2$; 2, $1 < Kp < 4$; 3, $Kp > 3$. There are no data for $\Phi < 68°$.

the radio observations, the spatial and time variations in the auroral oval in the sunlit period of the day in summer could be determined. Figure 14 shows the results of statistical treatment of the location of the southern boundary of the scattering region (Bates 1966). For weakly disturbed days, the boundary is located 1500 km north of College during the day; in the evening the boundary approaches, and in the morning it moves away from College. Under identical magnetic conditions the boundary is located at approximately the same latitudes in summer and winter. In magnetically very quiet periods the southern boundary is always displaced to $\Phi \sim 70°$ near midnight. During winter, the scattering region was observed on the College meridian at the given hour for at least 85 per cent of the period, and for more than 55 per cent in summer.

5.6 Development of the Auroral Substorm and Movement of Aurorae

The change in auroral activity over the entire polar region seems to be a sequence of auroral substorms. Khorosheva (1961a, b, 1967) has concluded from the analysis of the substorms that the aurorae are observed simultaneously over a great longitude range and are a single, physically connected belt; the auroral intensity changes simultaneously at all longitudes (Khorosheva 1962). The change in the auroral activity has been studied by Davis (1962b), Akasofu (1963a, b), and Feldstein (1966b) by plotting synoptic maps.

Akasofu (1963a, 1964b, 1965) and Akasofu and Kimball (1965) have examined in detail the simultaneous changes in the forms, brightness, and movements of aurorae during substorms for the night side of the earth. For the day side, Akasofu's scheme is supplemented by Starkov and Feldstein (1967b), and Feldstein and Starkov (1967). The duration of an individual substorm was from tens of minutes to 2–3 hours. The development of aurorae varies considerably from case to case; the features which are characteristic of a great number of substorms have been taken as the basis of a schematic representation of their development.

According to Akasofu, the substorm appears first in the region of the midnight meridian and has two phases of development: the expansion phase and the recovery phase. In Fig. 15, which illustrates the development of an auroral substorm, the quiet phase corresponds to $T = 0$, the expansion phase to $T = 0$–5, 5–10, 10–30 min, and the recovery phase to $T =$ 30 min–1 h, 1–2 h.

At $T = 0$ one may distinguish three pronounced regions corresponding to various auroral forms: homogeneous arcs on the night side, rays on the day side, and the geomagnetic polar region with arcs aligned towards the sun. It is

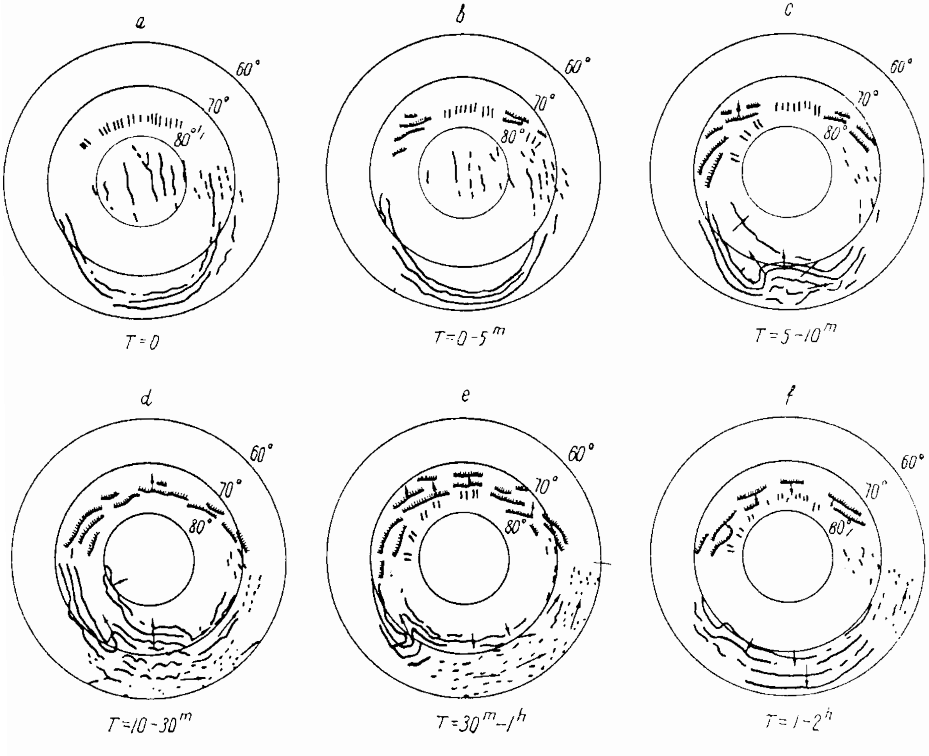


Fig. 15 Schematic diagram, illustrating the development of an auroral substorm. The north geomagnetic pole is at the centre of the concentric circles and the sun is at the top of the diagram (Akasofu 1964b, Feldstein and Starkov 1967).

likely that the night aurorae are associated with the electrons of the magnetospheric tail (Akasofu 1966b, Dungey 1968, Piddington 1967, Shabansky 1968) and the day aurorae with the electrons from the region between the magnetospheric boundary and the shock wave (Pletnev *et al.* 1965, Piddington 1967). A number of other geophysical events which are due to corpuscular agents also occur in different ways on both day and night sides (Morozumi 1966). The expansion phase shows itself as an increase in the brightness of the quiet arc around midnight and as the occurrence of rayed arcs around midday. During intense storms, the poleward movement of the arcs results in the appearance of a bulge in the midnight section (Fig. 15*c*) which propagates rapidly towards the pole, east, and west with a velocity of 10–100 km min^{-1}. Around midday the arcs become brighter and a southward movement with a velocity of 10–30 km s^{-1} begins. At the peak of the expansion phase (Fig. 15*d*) the bulge reaches its most northern position, being stopped at $\Phi \sim 80°$ by very intense substorms. In the evening the formation of the bulge is sometimes followed by the formation of enormous surges which propagate westwards along the existing arcs with a velocity of 10–100 km min^{-1}. After midnight the break-up of the arc with the formation of spots drifting eastwards is observed. In the morning hours, individual bands drift as a whole eastwards with a velocity of 18–30 km s^{-1}. On the day side the changes cover the near-midday hours where the rayed arcs moving equatorwards are formed. The aurorae cover all longitudes and form a single belt.

The recovery phase (Fig. 15*e*) is characterized by the southward movement of the northernmost active arcs and bands near midnight with a velocity of 6–15 km s^{-1}. The irregular westward-moving surges often assume the form of regular loops which drift in intense substorms up to distances of 2000 km from the midnight meridian with a velocity of 30 km min^{-1}. In the morning hours at $\Phi' = 60$–$70°$ the arcs are replaced by spots drifting eastwards with a velocity of 20 km s^{-1}. On the day side, the auroral brightness is increased, the width of the belt is a maximum, and equatorward movements predominate. In the second period of the recovery phase (Fig. 15*f*) homogeneous arcs are formed from the spot groups in the morning; on the night side, the aurorae move equatorwards and on the day side they move polewards; the intensity of aurorae is decreased.

The above described scheme of the development of the auroral substorm may be particularized for the positions of arcs in the night hours in the quiet period (at $\Phi' \sim 65$–$70°$ and not at 60–65°), for cases when equatorward movements are greater than poleward (Heppner 1954, Davis 1962a and Fig. 9*e*), and for the possibility of the onset of auroral activity not on the midnight meridian.

Akasofu and Kimball (1965) have illustrated the main features of the development of the auroral substorm by a great number of photographs of aurorae with all-sky cameras.

The general regularities of the meridional and longitudinal movements in aurorae have been established by Meinel and Schulte (1953), Kim and Currie (1958, 1960), Stoffregen (1961), Davis (1962b), Dzyubenko (1963a, 1964b), Akasofu (1964b), Malko (1965), and Feldstein, Shevnina, and Lukina (1967).

The meridional movement may be of several types. The equatorward and poleward drifts dominate in the evening and in the morning respectively, due to the earth's rotation beneath the oval. Such systematical drift was described by Störmer (1930), Harang (1951), Heppner (1954), and others. This drift, reaching 60 km min^{-1}, has been studied for a great number of stations by Malko (1965) and Dzyubenko (1963a) for the IGY period and by Feldstein, Shevnina, and Lukina (1967) for the IQSY period. Irregular motion due to substorm development is superposed on the regular diurnal drift. During the expansion phase, poleward movements, which exist for a short period, appear near the northern edge of the belt. The equatorward movements of aurorae appearing near the southern edge in the expansion phase or during withdrawal to the initial position at the northern edge in the recovery phase are observed more frequently.

The longitude movement is controlled by local time. At $\Phi \leqslant 67^\circ$ this movement is eastward in the morning and westward in the evening with a change in direction of drift near midnight. In the high latitude region, Davis (1962b) and Stoffregen (1961) have found eastward movement in the evening and westward movement in the morning. The velocity of the movement increases as magnetic disturbance increases (Unwin 1959, Kim and Currie 1960). The very active rays may move with velocities of up to 30 km s^{-1} (Omholt 1962) and extend vertically for tens or hundreds of kilometres without changing their form (Cole 1963). High-speed filming of the luminous formation has shown the presence of velocities of up to 125 km s^{-1} (Davis and Hicks 1964).

5.7 The Local Features of Auroral Distribution

The detailed study of the auroral distribution over comparatively small regions of the earth's surface has revealed a number of local effects. Nadoubovich (1967) has examined various aspects of a vast complex of events which are due to the dependence of auroral characteristics on the presence of the water–land interface (the coastal effect). It appears that the peak isoaurore of the homogeneous forms is a copy of the coastline, the extended auroral form being bent in specific cases along this line. Figure 16 shows the projection of auroral arcs on to the earth's surface near the East Siberian shore (Nadoubovich 1967) which illustrates the tendency of the arcs to be located along the coastline. The theoretical explanation of the coastal effect has been given by Ponomarev (1964).

Samsonov and Zaretsky (1963) have found a non-monotonic change in P when moving towards the equator from the peak isochasm. Comparison with magnetic field maps shows that the regions of maximum concentration of the arcs coincide with the central regions of the East Siberian magnetic anomaly.

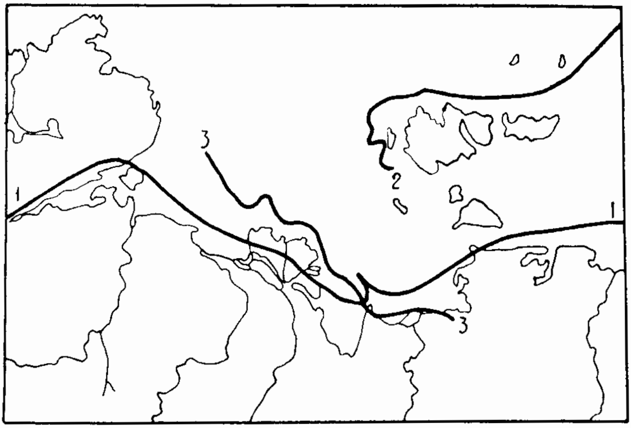


Fig. 16 Examples of the coastal effect in the location of auroral arcs in the region of Siberia (Nadoubovich 1967).
1, 11 March 1958, 1527 UT
2, 2 February 1959, 1341 UT
3, 21 January 1960, 1632 UT

6 Conclusion

There is no doubt that the atmospheric luminescence observed in the form of the normal types of aurora is due to energetic particle fluxes. The source of such particles may be the plasma of solar corpuscular streams transformed in the magnetosphere, particles accelerated within the magnetosphere at great distances from the earth, and particles accelerated by the electric fields within the ionosphere. Besides these, other acceleration mechanisms, such as the result of strong heating of the ionosphere by hydrodynamic waves (Krasovskii 1967), are possible.

If the IGY and the IQSY programmes have solved in the main the problem of the space–time distribution of the frequency of occurrence of ordinary aurorae, further investigations must be directed to elucidating the cause of the phenomenon. To achieve this it is necessary, in our opinion, to carry out complex observations of atmosphere luminescence using both ground stations and the rockets and satellites which have already been started (Evans 1965, Johnson *et al.* 1967).

Satellite measurements make it possible to obtain prompt and detailed latitudinal cross sections of the luminescence intensity, to observe simultaneously the luminescence and the particles that produced it, to observe the energy spectrum of such particles and the direction of their movement, to observe the luminescence in the ultraviolet (<2700 Å) including also day aurorae. Satellite measurements of such transient events as aurorae are severely limited: the satellite crosses the active forms of aurorae for fractions of a second, gives information on the course of an event only at a single point, and excludes the possibility of tracing the development of the process with time. Therefore the combination of satellite and ground measurements enabling the aurorae to be synoptically studied is important.

Observations using all-sky cameras should be prolonged to obtain the planetary distribution of the luminescence intensity, and monochromatic determination should be added to the network.

Both photography and photoelectric photometry from the ground network and from satellites should be carried out using absolute photometric standardization in order to compare the energy balances of the aurorae and the intruding corpuscular streams.

Particular attention should be paid to the study of the luminescence in the polar cap using satellites in polar orbits and expanding and strengthening the high-latitude observatory network, in particular in the Antarctic.

It is necessary to carry out photoelectric measurements both from ground stations and from satellites up to an intensity of 0.1 rayleigh in order to detect and study the subvisual luminescence (red aurorae). It is very desirable to carry out such observations at middle and high latitudes during intense magnetic storms.

The study of weak luminescences in the near-polar region and at low latitudes should be combined with vertical ionospheric soundings and rocket launchings.

In parallel with the planetary observations from the network of cameras, photography with exposures of fractions of a second, giving a high resolution, should be carried out at individual points simultaneously with the launching of sounding rockets to resolve the development of the process with altitude.

The luminescence at conjugate points should be investigated more thoroughly.

Realization of this observation programme would make it possible to solve many urgent problems of aurorae; in particular, the problem of the role of various factors in the formation of aurorae and the problem of the use of aurorae as an indicator of the geophysical activity index and as an original spectrometer of charged particles.

References

AITKEN, W. M., 1965, Some aurora australis lower border heights, 1961, *J. Atmos. Terr. Phys.*, **27**, 745–749.

AKASOFU, S.-I., 1961, Thickness of the active auroral curtain, *J. Atmos. Terr. Phys.*, **21**, 287–288.

—— 1963a, The dynamical morphology of the aurora polaris, *Ann. IGY* (Pergamon Press, Oxford), **20**, Part III, 311–364.

—— 1963b, The dynamical morphology of the aurora polaris, *J. Geophys. Res.*, **68**, 1667–1673.

—— 1963c, Deformation of magnetic shells during magnetic storms, *J. Geophys. Res.*, **68**, 4437–4445.

—— 1964a, The latitudinal shift of the auroral belt, *J. Atmos. Terr. Phys.*, **26**, 1167–1174.

AKASOFU, S.-I., 1964b, The development of the auroral sub-storm, *Planet. Space Sci.*, **12**, 273–282.

—— 1965, Dynamic morphology of auroras, *Space Sci. Rev.*, **4**, 498–540.

—— 1966a, The auroral oval, the auroral sub-storm and their relation with the internal structure of the magnetosphere, *Planet. Space Sci.*, **14**, 587–595.

—— 1966b, Electrodynamics of the magnetosphere: geomagnetic storms, *Space Sci. Rev.*, **6**, 21–143.

AKASOFU, S.-I., and S. CHAPMAN, 1962, Large-scale auroral motions and polar magnetic disturbances, *J. Atmos. Terr. Phys.*, **24**, 785–796.

—— 1963, The lower limit of latitude (US sector) of northern quiet auroral arcs and its relation to $D_{st}(H)$, *J. Atmos. Terr. Phys.*, **25**, 9–12.

AKASOFU, S.-I., and D. S. KIMBALL, 1964, The dynamics of the aurora — I. Instabilities of the aurora, *J. Atmos. Terr. Phys.*, **26**, 205–211.

—— 1965, Auroral morphology as shown by all-sky photographs (Arctic and Antarctic), *Ann. IGY* (Pergamon Press, Oxford), **38**, 1–299.

AKASOFU, S.-I., D. S. KIMBALL, and C. I. MENG, 1966, Dynamics of the aurora — VII. Equatorwards motions and the multiplicity of auroral arcs, *J. Atmos. Terr. Phys.*, **28**, 627–636.

ALFVÉN, H., 1955, On the electric field of magnetic storms, and aurorae, *Tellus*, **7**, 50–62.

ANDRIENKO, D. A., 1965a, Results of determination of the aurora altitudes on the observations in Tixie Bay in 1964, *Geomagn. i Aeronomiya*, **5**, 878–884.

—— 1965b, Determination of the altitudes of the homogeneous quiet arcs and bands of aurorae in Tixie Bay, *Geofiz. i Astr. No. 8* (Izd. Nauka, Moscow), pp. 35–39.

—— 1966, The dependence of the auroral heights on the increase of intensities, *Proc. Kiev State Univ.*, No. 7, 63–65.

Annals of the IGY, 1962, IGY Ascaplots (Pergamon Press, Oxford), **20**, Parts I, II, 1–307.

—— 1964, IGY auroral visoplots, **29**, 1–506.

Antarctic Atlas, 1966, Ed. B. G. Bakaiev (Ministry of Geology, USSR, Moscow, Leningrad), **1**.

AXFORD, W. I., H. E. PETSCHEK, and G. L. SISCOE, 1965, Tail of the magnetosphere, *J. Geophys. Res.*, **70**, 1231–1236.

BAGARIATSKY, B. A., and Y. I. FELDSTEIN, 1965, Peculiarities of auroral radar reflections, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 12* (Izd. Nauka, Moscow), pp. 5–59.

BARBIER, D., 1958, L'activité aurorale aux basses latitudes, *Annls Géophys.*, **14**, 334–355.

BATES, D. R., 1960, General character of auroras, *Physics of the Upper Atmosphere*, Ed. J. A. Ratcliffe (Pergamon Press, Oxford), pp. 269–294.

BATES, H. F., 1965, Some effects of dense Es clouds on high-altitude HF backscatter observations, *J. Geophys. Res.*, **70**, 5895–5906.

—— 1966, Latitude of the dayside auroras, *J. Geophys. Res.*, **71**, 3629–3634.

BATES, H. F., A. F. BELON, G. J. ROMICK, and W. J. STRINGER, 1966, On the correlation of optical and radio auroras, *J. Atmos. Terr. Phys.*, **28**, 439–446.

BELLEW, W., and S. M. SILVERMAN, 1965, The dependence of occurrence of midlatitude aurora on the sunspot cycle, *J. Geophys. Res.*, **70**, 4985–4986.

BELON, A. E., G. J. ROMICK, and M. H. REES, 1966, The energy spectrum of primary auroral electrons determined from auroral luminescity profiles, *Planet. Space Sci.*, **14**, 597–615.

BELOUSOV, B. G., L. V. LUKINA, and Y. I. FELDSTEIN, 1968a, Azimuth of auroral arcs at Vostok station during the IQSY, *Inf. Bull. Sov. Antarkt. Eksped.*, **69**, 46–49.

—— 1968b, Magnetic activity and aurora at Vostok station during the IQSY, *Inf. Bull. Sov. Antarkt. Eksped., No. 66*, pp. 36–41.

BELOUSOV, B. G., and B. S. MOISSEEV, 1960, Preliminary results of visual observations of auroras on the drifting stations SP-6 and SP-7 during 1958–1959, *Issled. Pol. Siyan.* (*Investigation of Aurorae*), *No. 4* (Izd. Akad. Nauk SSSR, Moscow), pp. 25–28.

BIRKELAND, K., 1908, On the cause of magnetic storms and the origin of terrestrial magnetism, *The Norwegian Aurora Polaris Expedition, 1902–1903* (Jacob Dybwad, Christiania), p. 1.

BLESS, R. C., C. W. GARTLEIN, D. S. KIMBALL, and G. SPRAGUE, 1959, Auroras, magnetic bays and protons, *J. Geophys. Res.*, **64**, 949–953.

Blundell, G., 1967, Analysis of auroral observations, Halley Bay, 1961 and 1962, *British Antarctic Survey Science Report, No. 48*, 1–59.

Bond, F. R., 1960, Motion of the aurora and magnetic bays, *Aust. J. Phys.*, **13**, 477–483.

Bond, F. R., and F. Jacka, 1962, Distribution of auroras in the southern hemisphere. II. Nightly probability of overhead aurora, *Aust. J. Phys.*, **2**, 261–272.

—— 1963, Distribution of auroras in the southern hemisphere. III. Comparison with northern hemisphere, *Aust. J. Phys.*, **16**, 514–519.

Booker, H. G., 1960, Radar studies of aurora, *Physics of the Upper Atmosphere*, Ed. J. A. Ratcliffe (Pergamon Press, Oxford), pp. 355–374.

Brunnelli, B. E., and S. M. Sandulenko, 1961, Radiolocational observations of aurorae at the USSR Antarctic stations in 1959, *Geomagn. i Aeronomiya*, **1**, 679–686.

Bullough, K., 1963, The radio aurora in high latitudes, *Proc. Int. Conf. on the Ionosphere, London 1962* (Institute of Physics and Physical Society, London), pp. 151–154.

Burdo, O. A., 1960, On the relation of both regular and irregular variations of geomagnetic field in high latitudes, *Trudy̆ Arkt. Antarkt. Nauchno. Issled. Inst.* (*Proc. Arctic Antarct. Inst.*), *Leningrad*, **260**, 21–45.

Chamberlain, J. W., 1958, Theories of the aurora, *Adv. Geophys.*, **4**, 109–215.

—— 1961, *Physics of the Aurora and Airglow* (Academic Press, New York and London).

Chapman, S., 1957, The aurora in middle and low latitudes, *Ann. IGY*, **4**, 25–40.

Chapman, S., and S.-I. Akasofu, 1964, The aurora, *Research in Geophysics*, Ed. H. Odishaw (The M.I.T. Press, Cambridge, Mass.), **1**, 367–400.

Cole, K. D., 1963, Motions of the aurora and radio-aurora and their relationships to ionospheric currents, *Planet. Space Sci.*, **10**, 129–164.

—— 1965, Stable auroral red arcs, sinks for energy of D_{st} main phase, *J. Geophys. Res.*, **70**, 1689–1706.

—— 1966, Magnetic storms and associated phenomena, *Space Sci. Rev.*, **5**, 699–770.

Cummings, W. D., R. E. LaQuey, B. J. O'Brien, and M. Walt, 1966, Rocket-borne measurements of particle fluxes and auroral light, *J. Geophys. Res.*, **71**, 1399–1408.

Currie, B. W., and C. K. Jones, 1941, Directional and diurnal characteristics of auroras at some places in Canada, *Terr. Magn. Atmos. Elect.*, **46**, 269–278.

Currie, B. W., and J. T. Weaver, 1955, Vertical extent of auroral arcs and bands, *Can. J. Phys.*, **33**, 611–617.

Dalgarno, A., 1965, Interaction of energetic charged particles with the atmosphere, *Auroral Phenomena*, Ed. M. Walt (Stanford University Press, Stanford, Calif.), pp. 39–45.

Davis, F. T., 1950, Visual observations in Canada in 1943–1947, *Bull. Int. Ass. Terr. Magn. Elect., No. 13*, 255–273.

Davis, L. R., O. E. Berg, and L. H. Meredith, 1960, Direct measurements of particle fluxes in and near auroras, *Space Research*, Ed. H. Kallmann Bijl (North-Holland Publ. Co., Amsterdam), pp. 721–735.

Davis, T. N., 1960, The morphology of the polar aurora, *J. Geophys. Res.*, **65**, 3497–3502.

—— 1962a, The morphology of the auroral displays of 1957–1958, 1. Statistical analyses of Alaska data, *J. Geophys. Res.*, **67**, 59–74.

—— 1962b, The morphology of the auroral displays of 1957–1958, 2. Detail analyses of Alaska data and analyses of high-latitude data, *J. Geophys. Res.*, **67**, 75–110.

—— 1963, Negative correlation between polar-cap visual aurora and magnetic activity, *J. Geophys. Res.*, **68**, 4447–4453.

—— 1966, The application of image orthicon techniques to auroral observation, *Space Sci. Rev.*, **6**, 222–247.

Davis, T. N., and R. N. Dewitt, 1963, Twenty-four-hour observations of aurora at the southern auroral zone, *J. Geophys. Res.*, **68**, 6237–6242.

Davis, T. N., and G. T. Hicks, 1964, Cinema photography of variations in auroral forms with an image orthicon television system, *J. Geophys. Res.*, **69**, 1931–1933.

Denholm, J. V., 1961, Some auroral observations inside the southern auroral zone *J. Geophys. Res.*, **66**, 2105–2112.

DENHOLM, J. V., and F. R. BOND, 1961, Orientation of polar aurora, *Aust. J. Phys.*, **14**, 193–195.

DESSLER, A. J., and R. D. JUDAY, 1965, Configuration of auroral radiation in space, *Planet. Space Sci.*, **13**, 63–72.

DUNGEY, J. W., 1968, The reconnection model of the geomagnetic tail, *Earth's Particles and Fields*, Ed. B. M. McCormac (Reinhold, New York), pp. 385–392.

DZYUBENKO, N. I., 1963a, On the daily drift of auroras with the latitude, *Geomagn. i Aeronomiya*, **3**, 140–146.

—— 1963b, Visual observation of aurorae on Muostakh during the IGY, *Geofiz. i Astr., No. 5* (Izd. Akad. Nauk Ukr. SSR, Kiev), pp. 317–322.

—— 1964a, Some results of visual observations of aurorae in Tixie Bay, *Geomagn. i Aeronomiya*, **4**, 190–192.

—— 1964b, East–west drifts of aurorae and azimuths of quiet arcs by observations in the region of Tixie Bay, *Geomagn. i Aeronomiya*, **4**, 659–667.

—— 1964c, The variation of auroral forms depending on the variation of solar activity, *Geomagn. i Aeronomiya*, **4**, 948.

—— 1965, About a strati-structure of fibrous arcs and bands of aurorae, *Geomagn. i Aeronomiya*, **5**, 360–363.

EATHER, R. H., and F. JACKA, 1966, Auroral absorption of cosmic radio noise, *Aust. J. Phys.*, **19**, 215–239.

EATHER, R. H., and B. P. SANDFORD, 1966, The zone of hydrogen emission in the night sky, *Aust. J. Phys.*, **19**, 25–33.

EGELAND, A., 1962, Studies of auroral reflections in the VHF band, *Ark. Geofys.*, **4**, 103–169.

EGELAND, A., and A. OMHOLT, 1966, Carl Störmer's height measurements of aurora, *Geofys. Publr*, **26**, 1–30.

ELVEY, C. T., 1957, Aurora borealis, *Adv. Electronics Electron Phys.*, **9**, 1–42.

—— 1964, Auroral morphology, *Planet. Space Sci.*, **12**, 783–798.

EVANS, J. E., 1965, Coordinated measurements on auroras, *Auroral Phenomena*, Ed. M. Walt (Stanford University Press, Stanford, Calif.), pp. 130–149.

EVANS, S., and G. M. THOMAS, 1959, The southern auroral zone in geomagnetic longitude sector 20°E, *J. Geophys. Res.*, **64**, 1381–1388.

EVLASHIN, L. S., 1961, Red colour auroras of A-type in high latitudes, *Geomagn. i Aeronomiya*, **1**, 531–533.

—— 1963, Some regularities of the behaviour of hydrogen emission in aurorae, *Geomagn. i Aeronomiya*, **3**, 496–501.

—— 1964, Hydrogen emission morphology in aurorae, *Studies of Aurorae, Geomagnetic Disturbances and Ionosphere in High Latitudes* (Izd. Nauka, Moscow), pp. 11–16 (in Russian).

—— 1969, Aurora monochromatic morphology in Murmansk on the data obtained by patrol spectrograph C-180-S, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 19* (Izd. Nauka, Moscow), in press.

EVLASHIN, L. S., and N. S. MALTSEVA, 1965, About the microvariation connection of the earth's magnetic field with different types of aurora, *Geomagn. i Aeronomiya*, **5**, 299–302.

FAIRFIELD, D. H., 1964, Trapped particles in a distorted dipole field, *J. Geophys. Res.*, **69**, 3919–3926.

FELDSTEIN, Y. I., 1960, Geographical distribution of aurora and azimuth of auroral arcs, *Issled. Pol. Siyan.* (*Investigations of the Aurorae*), *No. 4* (Izd. Akad. Nauk SSSR, Moscow), pp. 61–78.

—— 1961, Magneto-ionospheric disturbances and aurorae in the region near the pole, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 7* (Izd. Akad. Nauk SSSR, Moscow), pp. 43–50.

—— 1962a, Changes in the aurora zone location in connection with the solar activity cycle, *Geomagn. i Aeronomiya*, **2**, 571–572.

—— 1962b, Aurorae and magnetic activity near the polar region, *Geomagn. i Aeronomiya*, **2**, 851–854.

—— 1963a, The morphology of aurora and geomagnetism, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 10* (Izd. Akad. Nauk SSSR, Moscow), pp. 121–125.

—— 1963b, On morphology of aurora and magnetic disturbances in high latitudes, *Geomagn. i Aeronomiya*, **3**, 227–239.

—— 1964, Auroral morphology, *Tellus*, **16**, 252–267.

—— 1966a, The auroral oval-shaped zone location on the night side of the earth on magnetically quiet days, *Geomagn. i Aeronomiya*, **6**, 894–900.

—— 1966b, Peculiarities in the auroral distribution and magnetic disturbance distribution in high latitudes caused by the asymmetrical form of the magnetosphere, *Planet. Space Sci.*, **14**, 121–130.

Feldstein, Y. I., and N. F. Shevnina, 1963, Some results of visual observations of aurorae in the northern hemisphere during the IGY–IGC period, *Geomagn. i Aeronomiya*, **3**, 679–692.

Feldstein, Y. I., N. F. Shevnina, and L. V. Lukina, 1966, Aurora during magneto-disturbed and magneto-quiet periods, *Geomagn. i Aeronomiya*, **6**, 312–321.

—— 1967, Aurora in the period of the minimum of the solar activity cycle, *Geomagn. i Aeronomiya*, 7, 177–179.

Feldstein, Y. I., and E. K. Solomatina, 1961a, Some problems of the geographic distribution of aurorae in the northern hemisphere, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 7* (Izd. Akad. Nauk SSSR, Moscow), pp. 51–60.

—— 1961b, Auroras in the southern hemisphere, *Geomagn. i Aeronomiya*, **1**, 534–539.

Feldstein, Y. I., and G. V. Starkov, 1967, Dynamics of auroral belt and polar geomagnetic disturbances, *Planet. Space Sci.*, **15**, 209–229.

Frank, L. A., J. A. Van Allen, and J. D. Craven, 1964, Large diurnal variations of geomagnetically trapped and of precipitated electrons observed at low altitudes, *J. Geophys. Res.*, **69**, 3155–3167.

Fritz, H., 1881, *Das Polarlicht* (Kais. Akad. Wissenschaften, Leipzig).

Gadsden, M., 1959, Studies of the upper atmosphere from Invercargill, New Zealand, Part III: Radar echoes and magnetic activity, *Annls Géophys.*, **15**, 395–402.

Galperin, Yu. I., 1959, Hydrogen emission and two types of auroral spectra, *Planet. Space Sci.*, **1**, 57–62.

Galperin, Yu. I., I. A. Poluectov, and I. I. Sobelman, 1966, On the flux and energy spectrum of protons, responsible for hydrogen luminescence in aurora (Review), *Geomagn. i Aeronomiya*, **6**, 633–649.

Gartlein, C. W., 1958, Visual observation of the aurora: Geophysics and the IGY, *Geophys. Monogr. No. 2* (American Geophysical Union, National Research Council, Washington, D.C.), pp. 92–96.

—— 1966, Northern hemisphere synoptic auroral charts on polar projection, *Ann. IGY* (Pergamon Press, Oxford), **39**, Part II, 1–77.

Gartlein, C. W., H. E. Gartlein, and G. Sprague, 1960, The aurora and the local magnetic field, *IGY Gen. Rep. No. 12* (IGY WDC A, US National Academy of Sciences, Washington, D.C.), pp. 57–67.

Gartlein, C. W., P. M. Millman, and G. Sprague, 1965, *North American Aurora Visoplots* (WDC A, Ithaca, New York), pp. 1–190.

Gartlein, C. W., and G. Sprague, 1960, Auroral occurrence, *IGY Gen. Rep. No. 12* (IGY WDC A, US National Academy of Sciences, Washington, D.C.), pp. 68–73.

Gustafsson, G., 1964, Morphology of the visible aurora, its relation to magnetic variations and cosmic noise absorption, *Kiruna Sci. Rep. No. 4*, *Contr. NAF*, *61(052)*, pp. 1–23.

—— 1967, On the orientation of auroral arcs, *Planet. Space Sci.*, **15**, 277–294.

Harang, L., 1944, A study of auroral arcs and draperies, *Geofys. Publr*, **13**, 1–15.

—— 1945, A study of auroral arcs and draperies, *Terr. Magn. Atmos. Elect.*, **50**, 297–306.

—— 1951, *The Aurorae*, Eds. M. A. Ellison and A. C. B. Lovell (Chapman and Hall, London).

Hartz, T. R., and N. M. Brice, 1967, The general pattern of auroral particle precipitation, *Planet. Space Sci.*, **15**, 301–329.

Hatherton, T., and G. G. Midwinter, 1959, Diurnal variation of aurora and geomagnetic disturbance at New Zealand antarctic stations, *Nature, Lond.*, **184**, 889–890.

—— 1960, Observations of the aurora australis at New Zealand antarctic stations during IGY, *J. Geophys. Res.*, **65**, 1401–1411.

Heppner, J., 1954, A study of the relationships between the aurora borealis and the geomagnetic disturbances caused by electric currents in the ionosphere, *Thesis* (California Institute of Technology, Pasadena, Calif.), pp. 1–36.

Heppner, J. P., E. C. Byrne, and A. E. Belon, 1952, The association of absorption and Es ionization with aurora at high latitudes, *J. Geophys. Res.*, **57**, 121–134.

Hill, J. E., 1965, Auroral heights over Churchill, Manitoba, during International Quiet Solar Year, *Can. J. Phys.*, **43**, 1917–1919.

Hones, E. W., 1963, Motions of charged particles trapped in the earth's magnetosphere, *J. Geophys. Res.*, **68**, 1209–1219.

Hultqvist, B., 1958, The geomagnetic field lines in higher approximation, *Ark. Geofys.*, **3**, 63–77.

—— 1961, Circular symmetry in the geomagnetic plane for auroral phenomena, *Planet. Space Sci.*, **8**, 142–150.

—— 1962, On the orientation of auroral arcs, *J. Atmos. Terr. Phys.*, **24**, 17–30.

—— 1964, Aurora, *Goddard Space Flight Center Rep. No. X-611-64-97* (Goddard Space Flight Center, Greenbelt, Md.), pp. 1–125.

Hultqvist, B., and A. Egeland, 1964, Radio aurora, *Space Sci. Rev.*, **3**, 27–78.

Hunten, D. M., 1955, Some photometric observations of auroral spectra, *J. Atmos. Terr. Phys.*, 7, 141–151.

International Auroral Atlas, 1963 (Edinburgh University Press, Edinburgh).

Isaev, S. I., 1958, News about the nature of the aurorae, *Problemȳ Severa* (*The Problems of the North*), *No. 1* (Izd. Akad. Nauk SSSR, Moscow), pp. 133–148.

—— 1962, On the existence of increased auroral activity region in the middle latitudes, *Geomagn. i Aeronomiya*, **2**, 861–864.

Jacka, F., and J. Paton, 1963, Aurora, *IQSY Instruction Manual No. 3* (IQSY Secretariat, London). Reprinted as Chapter 10 of *Ann. IQSY*, Vol. 1.

Johnson, R. G., R. E. Meyerott, and J. E. Evans, 1967, Coordinated satellite, ground-based and aircraft-based measurement of auroras, *Aurora and Airglow*, Ed. B. M. McCormac (Reinhold, New York), pp. 169–190.

Jorjio, N. V., 1959, Electrophotometrical measurements in the auroral zone, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 1* (Izd. Akad. Nauk SSSR, Moscow), pp. 30–40.

Khorosheva, O. V., 1960, Brightness of the night sky according to the data of the northern stations, *Issled. Pol. Siyan.* (*Investigation of the Aurorae*), *No. 4* (Izd. Akad. Nauk SSSR, Moscow), pp. 52–55.

—— 1961a, On the space–time distribution of aurorae in the arctic during the winter 1957–1958, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 7* (Izd. Akad. Nauk SSSR, Moscow), pp. 14–21.

—— 1961b, About the connection of high-latitudinal geomagnetic disturbances with auroras, *Geomagn. i Aeronomiya*, **1**, 695–701.

—— 1962, Diurnal drift of the auroral closed ring, *Geomagn. i Aeronomiya*, **2**, 839–850.

—— 1963a, On the isochasms of aurorae, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 10* (Izd. Akad. Nauk SSSR, Moscow), pp. 126–132.

—— 1963b, Auroral arcs' extent and their space orientation, *Geomagn. i Aeronomiya*, **3**, 363–366.

—— 1967, Spatial–temporal propagation of aurorae, *Aurorae and Airglow*, *No. 16* (Izd. Nauka, Moscow), pp. 3–84.

Khvostikov, I. A., 1963, Physics of the ozonosphere and ionosphere, *Ionosf. Issled.* (*Ionospheric Research*), *No. 11* (Izd. Akad. Nauk SSSR, Moscow), pp. 5–667.

Kim, J. S., and B. W. Currie, 1958, Horizontal movements of aurora, *Can. J. Phys.*, **36**, 160–170.

—— 1960, Further observations of the horizontal movements of aurora, *Can. J. Phys.*, **38**, 1366–1379.

Kim, J. S., and R. A. Volkman, 1963, Thickness of zenithal auroral arc over Fort Churchill, Canada, *J. Geophys. Res.*, **68**, 3187–3190.

—— 1965, Thickness of zenithal auroral arc over Alaska, *J. Atmos. Terr. Phys.*, **27**, 321–328.

Kinsey, J. H., 1965, Auroral parallactic measurements at Byrd Station, Antarctica, during 1963, *J. Geophys. Res.*, **70**, 579–589.

KOROTIN, A. B., 1965, Precipitation zone of corpuscular stream and time spiral distribution of maximum disturbance, *Studies of Aurorae, Geomagnetic Disturbances and Ionosphere in High Latitudes* (Izd. Nauka, Moscow), pp. 35–40 (in Russian).

KRASOVSKII, V. I., 1961, Some results of investigations of aurora and night airglow during the IGY and IGC, *Planet. Space Sci.*, **8**, 125–141.

—— 1967, Aurorae, *Kosm. Issled.* (*Investigation of Space*), *No. 5*, pp. 71–80.

KRASOVSKII, V. I., I. S. SHKLOVSKY, YU. I. GALPERIN, E. M. SVETLINSKY, YU. M. KUSHNIR, and G. A. BORDOVSKY, 1961, Discovery of electrons with energy above 10 keV in the upper atmosphere, *Isskust. Sputniki Zemli* (*Artificial Earth Satellites*), *No. 6* (Izd. Akad. Nauk SSSR, Moscow), pp. 113–126.

LANGE-HESSE, G., 1964a, Südlichste Ausdehnung von Nordlichtern nach deutschen Land- und See-beobachtungen 1960 bis 1963 im Anschuss an das Internationale Geophysikalische Jahre, *Naturwissenschaften*, **51**, 376–378.

—— 1964b, Polarilichtbeobachtungen auf den Weltmeeren 1960–1963 im Anschluss an des IGY und der besonderer Berücksichtigung der deutschen Beitrage, *Seewart*, **25**, 89–106.

LASSEN, K., 1959, Existence of an inner auroral zone, *Nature, Lond.*, **184**, 1375–1377.

—— 1961a, Diurnal variation of high-latitude auroral frequency of magnetically quiet and disturbed days, *Nature, Lond.*, **192**, 345.

—— 1961b, Day-time aurorae observed at Godhavn 1954–1956, *Publner Danske Met. Inst.*, No. 15, pp. 5–70.

—— 1963, Geographical distribution and temporal variations of polar aurorae, *Publner Danske Met. Inst.*, No. 16, pp. 5–79.

LASSEN, K., O. R. LAURSEN, and J. OLSEN, 1964, Danish visual aurora observations, 1957–1960, *Publner Danske Met. Inst.*, No. 18, pp. 5–41.

LEADABRAND, R. L., 1965, Electromagnetic measurements of auroras, *Auroral Phenomena* Ed. M. Walt (Stanford University Press, Stanford, Calif.), pp. 99–129.

LEBEDINSKY, A. I., 1952, Rayed and arc forms of aurorae, *Dokl. Akad. Nauk SSSR* (*C. R. Acad. Sci., URSS*), **86**, 913–915.

—— 1956, Electrical discharges and the interpretation of auroral types, *The Airglow and Aurora* (Pergamon Press, Oxford), pp. 222–224.

LEONARD, R. S., 1962, Distribution of radar auroras over Alaska, *J. Geophys. Res.*, **67**, 939–952.

MCEWAN, D. J., and R. MONTALBETTI, 1958, Parallactic measurements of aurorae over Churchill, Canada, *Can. J. Phys.*, **36**, 1593–1600.

MCILWAIN, C. E., 1960, Direct measurement of particles producing visible auroras, *J. Geophys. Res.*, **65**, 2727–2747.

—— 1961, Coordinates for mapping the distribution of magnetically trapped particles, *J. Geophys. Res.*, **66**, 3681–3691.

MAEHLUM, B., and B. J. O'BRIEN, 1963, Study of energetic electrons and their relationship to auroral absorption of radio waves, *J. Geophys. Res.*, **68**, 997–1010.

MALKO, L. N., 1965, Some peculiarities of latitudinal drift in aurora, *Studies of Aurorae, Geomagnetic Disturbances and Ionosphere in High Latitudes* (Izd. Nauka, Moscow), pp. 17–21 (in Russian).

—— 1966, About the auroral zone, *Geomagn. i Aeronomiya*, **6**, 307–311.

—— 1967, Frequency of auroral appearance in Murmansk in the years of the solar activity maximum and minimum, *Geomagn. i Aeronomiya*, **7**, 78–82.

MALKO, L. N., and G. V. STARKOV, 1965, Some peculiarities of auroral distribution with height, *Geomagn. i Aeronomiya*, **5**, 188–190.

MALVILLE, J. M., 1959, Antarctic auroral observations, Ellsworth Station, *J. Geophys. Res.*, **64**, 1389–1393.

—— 1960, The effect of the initial phase of a magnetic storm upon the outer Van Allen belt, *J. Geophys. Res.*, **65**, 3008–3010.

—— 1964, Diurnal variation of high-latitude auroras, *J. Geophys. Res.*, **69**, 1285–1292.

MAWSON, D., 1925, Records of the aurora polaris, *Scient. Rep. Australas. Antarct. Exped.*, **2**, 1.

MAYAUD, P. N., 1960, Un nouveau système de coordonnées magnétiques pour l'étude de la haute atmosphère: les coordonnées de l'anneau equatorial, *Annls Géophys.*, **16**, 278–288.

MEEK, J. H., 1953, Correlation of magnetic, auroral and ionospheric variations at Saskatoon, *J. Geophys. Res.*, **58**, 445–456.

MEGILL, L. B., and N. P. CARLETON, 1964, Excitation by local electric fields in the aurora and airglow, *J. Geophys. Res.*, **69**, 101–122.

MEINEL, A. B., B. J. NAGARD, and J. CHAMBERLAIN, 1954, A statistical analysis of low-latitude aurorae, *J. Geophys. Res.*, **59**, 407–413.

MEINEL, A. B., and D. H. SCHULTE, 1953, A note on auroral motion, *Astrophys. J.*, **117**, 454–455.

MONTALBETTI, R., and D. J. MCEWAN, 1962, Hydrogen emissions and sporadic E layer behaviour, *J. Phys. Soc. Japan*, **17**, A-1, 212–215.

MONTBRIAND, L. E., and A. VALLANCE JONES, 1962, Studies of auroral hydrogen emissions in west-central Canada, *Can. J. Phys.*, **40**, 1401–1410.

MOORCROFT, D. R., 1961, Models of auroral ionization, *Can. J. Phys.*, **39**, 695–715.

MOROZUMI, H. M., 1963, Semidiurnal auroral peak and VLF emission observed at the South Pole, 1960, *Trans. Amer. Geophys. Un.*, **44**, 798–805. (Preprinted in *IG Bulletin*, No. 73, pp. 16–23.)

—— 1966, Different geomagnetic variations associated with corpuscular precipitations on day and night side of the auroral zone, *Planet. Space Sci.*, **14**, 87–89.

MURCRAY, W. B., 1966, An observation of the height–luminosity distribution of auroral Hβ emission, *Planet. Space Sci.*, **14**, 812–814.

NADOUBOVICH, YU. A., 1967, Coastal effect in aurora, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 14* (Izd. Nauka, Moscow), pp. 5–77.

NADOUBOVICH, YU. A., and G. V. STARKOV, 1961, The fibrous structure of faint auroral homogeneous arcs, *Geomagn. i Aeronomiya*, **1**, 57–61.

NIKOLSKY, A. P., 1956, On the second zone of increased intensity of magnetic disturbances in the near polar region, *Trudy̆ Arkt. Antarkt. Nauchno-Issled. Inst.* (*Proc. Arctic Antarct. Inst.*), *Leningrad*, **83**, 5–83.

O'BRIEN, B. J., and G. D. LAUGHLIN, 1962, An extremely intense electron flux at 1000 kilometer altitude in the auroral zone, *J. Geophys. Res.*, **67**, 2667–2681.

O'BRIEN, B. J., and H. TAYLOR, 1964, High-latitude geophysical studies with satellite Injun 3, 4. Auroras and their excitation, *J. Geophys. Res.*, **69**, 45–63.

OGUTI, T., 1963, Inter-relations among the upper atmosphere disturbance phenomena in the auroral zone, *JARE, Sci. Rep., Ser. A, No. 1*, pp. 1–82.

OHL, A. I., 1960, On the 11-year cycles of aurora number variations, *Problemy̆ Arkt. Antarkt.* (*Problems of the Arctic and Antarctic*), *No. 2*, 77–82.

OMHOLT, A., 1962, Velocities of very active auroral rays, *Planet. Space Sci.*, **9**, 285–286.

—— 1963, Observations and experiments pertinent to auroral theories, *Planet. Space Sci.*, **10**, 247–262.

OMHOLT, A., W. STOFFREGEN, and H. DERBLOM, 1962, Hydrogen lines in auroral glow, *J. Atmos. Terr. Phys.*, **24**, 203–209.

PATON, J., 1965, Auroral activity during 1964, *Observatory*, **85**, 271–272.

PATON, J., and S. EVANS, 1964, Aurorae, *Antarctic Research*, Ed. R. Priestley (Butterworth and Co. (Publishers), London), pp. 318–332.

PIDDINGTON, J. H., 1965, The morphology of auroral precipitation, *Planet. Space Sci.*, **13**, 565–577.

—— 1967, A theory of auroras and the ring current, *J. Atmos. Terr. Phys.*, **29**, 87–105.

PLETNEV, V. D., G. A. SKURIDIN, V. P. SHALIMOV, and I. N. SHVACHUNOV, 1965, Processes of the intrusion into the earth's magnetosphere of solar stream particles, their capture and acceleration, and their role in the dynamics of geomagnetic trapping, *Issled. Kosm. Prostr.* (*Space Exploration*), (Izd. Nauka, Moscow), pp. 285–314.

POGORELOV, V. I., 1962, Fluctuations of electron density in ionization zone of aurorae, *Geomagn. i Aeronomiya*, **2**, 68–70.

PONOMAREV, E. A., 1964, The sea current influence on the dynamics of aurora, *Geo-Geliofiz. Effekti Kosm. Luch. Pol. Siyan.* (*Geo- and Helio-physical Effect of Cosmic Rays and Aurorae*), (Izd. Nauka, Moscow), pp. 107–112.

—— 1966, About the nature of the electron streams generating aurorae in their zone maximum in auroral quiet time, *Izv. SibIZMIRAN*, **1**, 3–23.

REES, M. H., 1963, Auroral ionization and excitation by incident energetic electrons, *Planet. Space Sci.*, **11**, 1209–1218.

REES, M. H., and G. C. REID, 1959, The aurora, the radiation belt and the solar wind: a unifying hypothesis, *Nature, Lond.*, **184**, 539–540.

ROACH, F. E., and M. H. REES, 1960, The absolute zenith intensity of OI 5577 Å at College, Alaska, *J. Geophys. Res.*, **65**, 1489–1493.

ROACH, F. E., and J. R. ROACH, 1963, Stable 6300 Å auroral arcs in mid-latitudes, *Planet. Space Sci.*, **11**, 523–545.

ROMICK, G. I., and C. T. ELVEY, 1959, Variations in the intensity of the hydrogen emission line Hβ during auroral activity, *J. Atmos. Terr. Phys.*, **12**, 283–289.

SAMSONOV, V. P., and N. S. ZARETSKY, 1963, Azimuthal and geographical auroral ray distribution on Yakutsk station data, *Geomagn. i Aeronomiya*, **3**, 246–251.

SANDFORD, B. P., 1964, Aurora and airglow intensity variations with time and magnetic activity at southern high latitudes, *J. Atmos. Terr. Phys.*, **26**, 749–769.

—— 1967a, High latitude night-sky emissions, *Aurora and Airglow*, Ed. B. M. McCormac (Reinhold, New York), pp. 443–452.

—— 1967b, Polar-glow aurora, *Space Research VII*, Ed. R. L. Smith-Rose (North-Holland Publ. Co., Amsterdam), pp. 836–848.

SCHNEIDER, O., 1964, L'investigation actuelle de l'aurore australe, *Contrnes Inst. Antarct. Argent., No. 82*, pp. 1–54.

SCHRÖDER, W., 1965, Appearance of aurora in connection with the planetary geomagnetic coefficient *Kp*, *J. Geophys. Res.*, **70**, 2262.

SEATON, M. J., 1954, Excitation processes in the aurora and airglow, *J. Atmos. Terr. Phys.*, **4**, 285–294.

SHABANSKY, V. P., 1965, Motion of various energy particles in the rotating magnetosphere, *Kosm. Issled.* (*Investigation of Space*), *No. 3*, pp. 221–230.

—— 1968, Magnetospheric processes and related geophysical phenomena, *Space Sci. Rev.*, **8**, 366–454.

SHERET, M. A., and G. M. THOMAS, 1961, Auroral observations at Halley Bay, Antarctica, during 1959, *Nature, Lond.*, **189**, 826.

SLUTZ, R. J., and J. R. WINKELMAN, 1964, Shape of the magnetospheric boundary under solar wind pressure, *J. Geophys. Res.*, **69**, 4933–4948.

STARKOV, G. V., 1961, Azimuths and velocities of homogeneous arcs of aurorae, *Pol. Siyan. Svech. Noch. Neba* (*Aurorae and Airglow*), *No. 7* (Izd. Akad. Nauk SSSR, Moscow), pp. 22–26.

STARKOV, G. V., and Y. I. FELDSTEIN, 1967a, Orientation of extent of aurorae, *Geomagn. i Aeronomiya*, **7**, 72–77.

—— 1967b, A scheme of an elementary disturbance in aurorae on the day side of the earth, *Geomagn. i Aeronomiya*, **7**, 367–369.

—— 1967c, Aurora during the IQSY period, *Geomagn. i Aeronomiya*, **7**, 744–745.

—— 1969, The influence of the ring current on the location of auroral oval, *Geomagn. i Aeronomiya*, **9**, in press.

STOFFREGEN, W., 1961, The east–west drift of auroral forms determined from all-sky camera films, *J. Atmos. Terr. Phys.*, **21**, 257–260.

STOFFREGEN, W., and H. DERBLOM, 1962, Auroral hydrogen emission related to charge separation in the magnetosphere, *Planet. Space Sci.*, **9**, 711–716.

STÖRMER, C., 1930, *Photographic Atlas of Auroral Forms* (A. W. Bröggers Boktrykkeri A/S, Oslo).

—— 1955, *The Polar Aurora* (Clarendon Press, Oxford).

STRINGER, W. J., and A. E. BELON, 1967, The statistical auroral zone during IQSY and its relationship to magnetic activity, *J. Geophys. Res.*, **72**, 245–250.

STRINGER, W. J., A. E. BELON, and S.-I. AKASOFU, 1965, The latitude of auroral activity during periods of zero and very weak magnetic disturbance, *J. Atmos. Terr. Phys.*, **27**, 1039–1044.

TAYLOR, H. E., and E. W. HONES, 1965, Adiabatic motion of auroral particles in a model of the electric and magnetic fields surrounding the earth, *J. Geophys. Res.*, **70**, 3605–3629.

TVERSKOY, B. A., 1964, Dynamics of the radiation belts of the earth, I. The sources of rapid particles, *Geomagn. i Aeronomiya*, **4**, 224–232.

UNWIN, R. S., 1959, Movement of auroral echoes and the magnetic disturbance current system, *Nature, Lond.*, **183**, 1044–1045.

UNWIN, R. S., 1966, The morphology of the VHF radio aurora at sunspot maximum, I. Diurnal and seasonal variations, *J. Atmos. Terr. Phys.*, **28**, 1167–1182.

VALLANCE JONES, A., 1965, Optical measurements of auroras, *Auroral Phenomena*, Ed. M. Walt (Stanford University Press, Stanford, Calif.), pp. 20–38.

VEGARD, L., 1912, On the properties of the rays producing aurorae borealis, *Phil. Mag.*, **23**, 211–237.

VEGARD, L., and O. KROGNESS, 1920, The position in space of the aurora polaris from observations made at the Haldde Observatory 1913–1914, *Geofys. Publr*, **1**, 1–172.

VESTINE, E. H., 1944, The geographic incidence of aurora and magnetic disturbance, northern hemisphere, *Terr. Magn. Atmos. Elect.*, **49**, 77–102.

VESTINE, E. H., and W. L. SIBLEY, 1959, Remarks on auroral isochasms, *J. Geophys. Res.*, **64**, 1338–1339.

VESTINE, E. H., and E. J. SNYDER, 1945, The geographic incidence of aurora and magnetic disturbance, southern hemisphere, *Terr. Magn. Atmos. Elect.*, **50**, 105–124.

WEILL, G. W., 1958, Aspects de l'aurore observée à la base Dumont d'Urville en Terre Adélie, *C. R. Acad. Sci., Paris*, **246**, 2925–2927.

WEILL, G. W., M. FAFIOTTE, S. HUILLE, and J. DELANNOY, 1965, La structure de la zone aurorale arctique en periode de minimum d'activité solaire, *Annls Géophys.*, **21**, 469–474.

WHITE, F. G., and M. GEDDES, 1939, The Antarctic zone of maximum auroral frequency, *Terr. Magn. Atmos. Elect.*, **44**, 367–378.

WILLIAMS, D. J., and G. D. MEAD, 1965, Nightside magnetosphere configuration as obtained from trapped electrons at 1100 km, *J. Geophys. Res.*, **70**, 3017–3035.

YEVLASHIN, L. S., *see* EVLASHIN, L. S.

ZHIGALOV, L. N., 1966, Antarctic auroral distributions and their relation with magnetic disturbance, *Trudȳ Arkt. Antarkt. Nauchno-Issled. Inst.* (*Proc. Arctic Antarct. Inst.*), *Leningrad*, **280**, 48–56.