Polar Auroras, Polar Substorms, and Their Relationships with the Dynamics of the Magnetosphere[1]

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Abstract. Comparison is made between the position of the auroral oval during both night and day and that of the boundaries of trapped radiation according to observations from the satellite Alouette 2. We show that visual auroras are located on the poleward side of the boundary of smoothly closed field lines. From the data on auroral dynamics, information is obtained on some parameters of the geomagnetic field, i.e., field intensity in the magnetospheric tail, cross-sectional dimensions of the tail at various geocentric distances, and the length of the tail. The density of low-energy plasma at geocentric distances of 5 to 9 R_E is estimated for various periods of the solar activity cycle. The influence of the magnetospheric ring current on the position of the auroral oval is considered. On the basis of polar auroral observations, estimates are made of variations in ring current parameters at times of ring current enhancement. *DP* and *DPC* magnetic field variations at high latitudes, linked with the structure of the geomagnetic field in the magnetosphere, are also discussed.

DP variations are characterized by current electrojets, a western one within the auroral oval and an eastern one in the evening hours at $\Phi \sim 65°$, where Φ is the invariant latitude. The *DPC* variations of greatest intensity are noted on the daytime side of the earth. The field variations are due to a counterclockwise current. We show that the current system of Chapman's *SD* variations is a superposition of two different types of variations, *DP* and *DPC*.

INTRODUCTION

Statistical analysis of photographic observations of polar auroras during the IGY has shown that discrete forms of visual aurora appear most frequently along an oval longitudinal distribution, which is situated at $\Phi \sim 67°$–$68°$ near midnight and at $\Phi \sim 67°$–$77°$ in midday [*Feldstein,* 1960, 1963*b*]. This oval auroral zone is not just a result of statistical processing of observations. In many specific cases the extended shapes of auroras on magnetoquiet days are located along the oval that extends from high latitudes during the day to Fritz auroral zone latitudes at night [*Khorosheva,* 1963; *Akasofu,* 1964]. At present the asymmetrical boundary of the zone of visual auroras, relative to the geomagnetic pole, is accepted by many researchers. See the reviews by *Krassovsky* [1967], *Davis* [1967], *Feldstein et al.* [1968*a*], *Akasofu* [1968*a*], *Hultqvist* [1967], *Lassen* [1967], and *Jacka and Bond* [1968]. The oval shape of the most

[1] Invited review paper read by I. A. Zhulin at the International Symposium on the Physics of the Magnetosphere, Washington, D. C., September 3–13, 1968.

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frequent appearance of auroras at zenith was verified for the period of IQSY by *Stringer and Belon* [1967], *Lassen* [1967], and *Wiens* [1968].

The oval zone concept allowed us to generalize our understanding of the auroral zone and also to explain the known displacement of auroral glows during a 24-hour period [*Alfvén*, 1960; *Störmer*, 1955]. It was found that the *Fritz* [1881]-*Vestine* [1944] zone reflects the distribution on the earth's surface of nighttime auroral glows, whereas the inner *Nikolsky* [1956]-*Alfvén* [1955] zone reflects the distribution of daytime auroras.

Alfvén [1967] noted that the daily variations in the distribution of auroras were observed by Gillensheld who investigated the variations of a parameter n, the ratio of the number of observations with auroras over the northern half of the sky to the total number of observations. However, this parameter permits only an ambiguous treatment of the observational results and does not quantitatively define the magnitude of the daily shift of the oval zone. In particular, the concept of two zones of polar auroras surrounding the geomagnetic pole at all times at $\Phi \sim 67°$ and $\Phi \sim 80°$ (a concept to which *Alfvén* [1955] adhered) could have resulted in the variations of Gillensheld's parameter n.

Piddington [1965*a*, 1957], *Akasofu* [1966*a*], and *Feldstein* [1966*a*] related the asymmetric location of the auroral oval relative to the geomagnetic pole to the large-scale structure of the geomagnetic field within the bounds of the magnetosphere. It was found that the auroral oval is located near the outer boundary of the region of trapped electrons with $E > 40$ kev [*Frank et al.*, 1964; *McDiarmid and Burrows*, 1964; see also *O'Brien*, 1963]. This component of trapped radiation defines the boundary of lines of force for which trapped particle adiabatic invariants are conserved and separates the regions of closed field lines and open field lines (those undergoing a sharp break in the neutral sheet of the magnetospheric tail).

For brevity, in the following, we shall speak of closed and open lines of force of the geomagnetic field, bearing in mind that we also understand by open lines those that close in the magnetospheric tail but undergo a sharp break in the region of the neutral sheet.

The day and night portions of the auroral oval differ in a number of characteristics [*Feldstein*, 1968]. They are apparently due to electrons of different origin, i.e., from the magnetospheric tail neutral sheet at night and from the region between the magnetopause and the shock front in the daytime. However, these auroras of different origin are connected in the oval zone by the magnetic field geometry in the magnetosphere.

Figure 1 shows a meridional cutaway of a simplified configuration of the geomagnetic field agreeing with the observations of *Ness* [1965] and *Speiser and Ness* [1967]. A probable position of the auroral oval is indicated as being at the boundary of closed field lines. The night boundary of high-energy trapped radiation serves as an indication of the neutral sheet's extension toward the earth. The conclusion that the auroral oval is located on the poleward side of the boundary of trapped radiation was based initially on a comparison of these two parameters obtained statistically for various periods of differing magnetic activity. For this reason, it remained unclear whether the auroral oval was

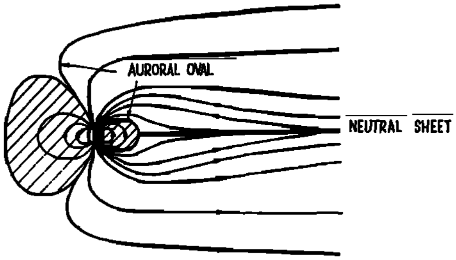

Fig. 1. Configuration of the earth's magnetic field in a meridional plane containing the dipole axis and the solar direction. The shaded region contains the region of closed field lines at whose boundary the auroral oval is located.

located within or without the closed geomagnetic field lines [*Hultqvist,* 1968]. Such an investigation became possible only after *Feldstein and Starkov* [1967] and *Feldstein et al.* [1968*c*] determined the dynamics of the oval as a function of the intensity of polar magnetic substorms (DP) and of the magnetospheric ring current (DR), and after *McDiarmid and Burrows* [1968] had identified the various types of boundaries of trapped electrons with $E > 35$ kev.

Atmospheric luminescence in the form of discrete shapes along the auroral oval is caused by fluxes of electrons with energies $E < 10$ kev [*Sharp et al.,* 1965]. Besides optical effects, the injection, along the oval, of fluxes of energetic particles into the upper layers of the atmosphere increases the ionization and causes the following disruptions of the structure of the lower ionosphere: (*a*) anisotropic electron inhomogeneities in the *E* and *F* layers, causing the appearance around the geomagnetic pole of a belt of auroral radio reflections in the shortwave band, coinciding with the auroral oval [*Bates,* 1966; *Bates et al.,* 1966; *Unwin,* 1968]; (*b*) local inhomogeneities at oval latitudes in the ionization maximum of the *F* region of the ionosphere, with sharp ionization density fluctuations [*Lund et al.,* 1967]; and (*c*) both the integral electron density of ionization in a column of unit cross section [*Lund et al.,* 1967] and the electron and ion densities increase at altitudes of ~1000 km [*Zmuda et al.,* 1968].

In addition to geophysical phenomena characterized by oval symmetry, certain manifestations of anomalous processes in the upper atmosphere at high latitudes have a circular symmetry; they attain maximum intensity in the annular region at $\Phi \sim 67°–70°$ [*Hartz and Brice,* 1967]. On the daytime side of the annular region, electrons with energies > 25 kev are responsible for the geophysical phenomena [*Johnson et al.,* 1966], and during near-midnight hours the annular and the oval zones coincide. As a rule, the particle intrusions on the dayside of the annular zone are not accompanied by discrete forms of auroral and magnetic disturbances; rather, they cause smooth variations of as much as several decibels in the absorption of cosmic noise when the magnetic field is quiet [*Driatzky,* 1968]. Considered below in detail are only some of the geophysical phenomena in the oval zone.

Substantial magnetic field variations are observed at an altitude of ~1100 km on the poleward side of the oval boundary in the form of transverse fluctuations with amplitudes to several hundred gammas [*Zmuda et al.,* 1966, 1967]. On the ground, negative bays are interpreted by *Feldstein* [1963*a*, 1968], *Feldstein and Zaitzev* [1965*a*, *b*], *Akasofu et al.* [1965], and *Akasofu* [1966*b*] as the indications of a western electrojet within the bounds of the auroral oval. This western electrojet, being a composite part of the DP current system, and the particular DPC type of magnetic field variations in the near-polar region are related to the inner structure of the magnetosphere [*Feldstein and Zaitzev,* 1968*a*; *Akasofu and Kawasaki,* 1968]. The DP and DPC current systems, providing a generalized representation of the variations of the magnetic field on the ground, are apparently linked in a specific fashion with convective large-scale plasma motions in the magnetosphere [*Obayashi,* 1967]. Determining the basic characteristics of the current systems for various types of magnetic variations, which sometimes differ quite substantially, judging by the data of various authors [*Cole,* 1966; *Akasofu,* 1966*b*; *Obayashi and Nishida,* 1968; *Nagata and Fukushima,* 1968; *Feldstein and Zaitzev,* 1968*a*], is a matter of considerable interest in the physics of the magnetosphere.

AURORAL OVAL AND BOUNDARY OF THE REGION OF CLOSED FIELD LINES

McDiarmid and Burrows [1968] have determined the invariant latitudes Φ of various types of trapped electron high-latitude boundaries for energy $E >$ 35 kev during the flight of the satellite Alouette 2 launched in November 1965. Φ_b is the latitude at which the counting rate of electrons first reaches background, i.e., trapped electrons with $E > 35$ kev are absent on $\Phi > \Phi_b$; Φ_s is the boundary of stable trapping, within which are found electrons capable of drifting around the earth, and Φ_e is the latitude of the beginning of a sharp intensity decrease of trapped electrons during the night hours (an order of magnitude in an interval of less than 0.5°). The mutual location of the auroral oval and the boundaries Φ_s and Φ_b is shown in Figure 2. The specific values of Φ_b and Φ_s for the period from December 1965 to February 1966, according to data from satellite Alouette 2 (kindly contributed to us by I. B. McDiarmid), were averaged for the corresponding values of the index Q of magnetic activity on the night side of the earth obtained from the data of magnetic observatories located at $\Phi \sim 65°$. The position of the auroral oval was taken according to *Feldstein and Starkov* [1967, 1968]. During magnetoquiet periods in the near-midnight hours, Φ_b and Φ_s differ by no more than 1°–2°, and the auroral region is located on the near-polar side of the boundary of the outer radiation zone. During magnetic disturbances, the boundary of the auroral oval coincides with the value of Φ_s within the limits of a few tenths of a degree, which is evidence that the auroral oval is located,

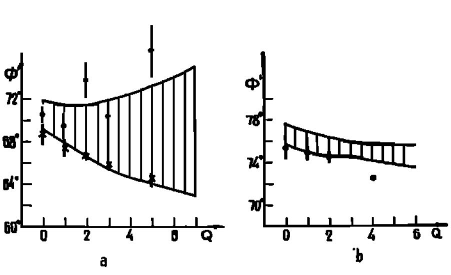

Fig. 2. Variation with increasingly intense magnetic disturbance of the position of the region of auroral appearance at zenith (shaded) and of the boundary of trapped $E > 35$-kev electrons according to Alouette 2 data. The stable trapping boundary Φ_s is shown by crosses and the boundary of closed field lines Φ_b, by circles. The vertical lines show the root-mean-square deflections (*a*) near-midnight and (*b*) near-midday.

independent of magnetic disturbance intensity, beyond the boundary of the outer radiation belt (within which the magnetic lines of force differ little from dipole lines). As the magnetic disturbance increases, the boundary of the oval, as well as Φ_s, shifts to lower latitudes. Thus in the near-midnight hours, the southern boundary of the auroral oval coincides with the outer boundary of the magnetospheric region, in which stably trapped energetic electrons are capable of drifting around the earth.

During intense disturbances, Φ_b corresponds to the near-polar boundary of the oval zone and indicates the latitude limit of the region where fluxes of directly accelerated radiation are projected from the geomagnetic tail. Possibly Φ_b represents the latitude of extreme field lines, closing in the magnetospheric tail but stretched in the antisolar direction and differing essentially in shape from the dipole field. As Q increases, so does the latitude interval between Φ_s and Φ_b, which corresponds to the expansion in the antisolar direction of the region of the tail in which plasma acceleration takes place. The small difference between Φ_s and Φ_b in magnetoquiet periods is evidence of partial acceleration to energies greater than 35 kev in a very narrow region of space. Therefore, Φ_b–Φ_s is the region of the tail transformed to a latitude interval in which are generated fluxes of electrons observed on satellites as sharp intensity increases of both trapped and precipitated electrons.

Observations from the satellite Injun 3 on magnetoquiet days [*Maehlum*, 1968*a*] also indicate a close connection between the positions of the boundary of trapped $E > 40$-kev electrons and the luminescence region. In the near-midnight hours, a sharp near-polar boundary for streams of precipitated and trapped electrons is always observed, precipitation occurring in a narrow region near this boundary. Luminescence of intensity more than 500 R is observed on the poleward side of the latitude of a sharp increase of electron precipitation into the atmosphere. The auroral maximum is located poleward of the trapping boundary.

During the near-midday hours and independent of magnetic activity the auroral oval is located on the poleward side of the boundary of the region where trapped electrons, capable of moving along closed field lines, are detected. Since on the daytime side the region of smooth closed field lines reaches the magnetopause, the southern boundary of the oval defines the latitude at which the last closed field line intersects the earth's surface. Consequently, the southern boundary of the auroral oval on the day- and nightsides of the earth corresponds to the highest latitude on the earth's surface of smooth closed magnetic force lines of a dipole type.

When processing the results of observations, it was found that for the near-midday hours Φ_b depends essentially on time; this is apparently due to the daily rotation of the geomagnetic dipole axis. The values, shown in Figure 2, were computed for the 0200–1000UT interval, since the data on the polar auroral oval in daytime were obtained from observations at eastern hemisphere stations intersecting the near-midday meridian at 0200–1000UT. The variation with UT of the near-polar boundary of soft electrons is described by *Maehlum* [1968*b*], according to observations from Aurora 1.

The connection between polar aurora and fluxes of electrons observed by the satellites Electron 1 and 2, beyond the boundary of the outer radiation belt at night, was noted by *Vernov* [1965].

Figure 3 compares the limit positions of closed field lines Φ_b and of the sharp nighttime intensity decrease of trapped electrons Φ_e for the period December 1965–June 1966 after *McDiarmid and Burrows* [1968], with the position of the auroral oval zone in the IQSY period after *Stringer and Belon* [1967]. The isolines of the relative number of auroral shapes (forms) equal to 20% were taken for the boundaries of the oval zone, within 1° limits of geomagnetic latitude for a 15-min interval. The oval zone is located near the poleward boundary of the limit of closed lines. If for the night hours we assume the boundary of the trapped radiation to be the latitude of sharp decrease in its intensity, the oval will be located precisely on the poleward side of the boundary of trapped radiation with $E > 35$ kev; this also constitutes the boundary of closed lines of force of the geomagnetic field for all hours of the day. On the poleward side of this boundary, Aurora 1 revealed large fluxes of soft electrons [*Burch,* 1968]. According to *O'Brien* [1967], the auroral oval is located along the high-latitude boundary of the region of trapped electrons. This conclusion is based upon *O'Brien*'s [1964] and *O'Brien and Taylor*'s [1964] data on simultaneous observations of auroras and particle fluxes on the satellite Injun 3; therefore, the southern boundary of the auroral oval corresponds to the latitude of smooth closed geomagnetic field lines and coincides with the outer boundary of the radiation belt. The variation of its position with the rise of DP intensity reflects the dynamics of the large-scale structure of the magnetic field inside the magnetosphere.

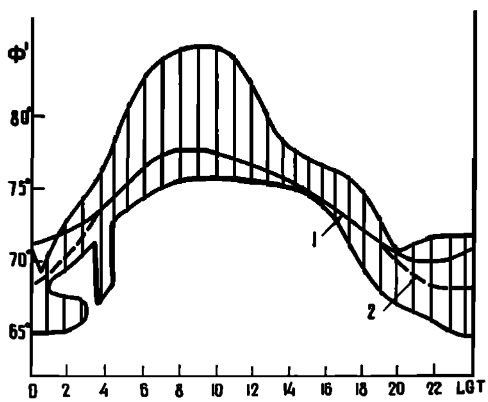

Fig. 3. Comparison of the location of the oval zone of polar aurora (shaded) in 1964–1965, with the boundaries of trapped $E > 35$-kev electrons according to Alouette 2 data: (1) limits of closed field lines, Φ_b; (2) sharp decrease in the intensity of electrons in night hours, Φ_e.

POLAR AURORAL OVAL AND CERTAIN PARAMETERS OF THE MAGNETIC FIELD IN THE MAGNETOSPHERE

The position of the region of closed geomagnetic field lines and the geomagnetic latitude of this region's boundary on the earth's surface may be obtained by considering the magnetic field within the magnetosphere. This field consists of the field B_{DCF} due to magnetospheric surface currents, the geomagnetic dipole field B_M, the field B_{DT} due to the magnetospheric tail currents, and the ring current field B_{DR}.

The B_{DCF} field has been computed by *Mead* [1964] and is determined by the geocentric distance of the magnetospheric boundary at the subpolar point. *Hones* [1963] and *Shabanskiy* [1968] have shown that the field due to currents on the magnetospheric surface can be duplicated by a specially chosen dipole. Although this substitution is rather rough, it is useful for studying the dynamics of the magnetospheric shape with varying solar-wind parameters.

The current field in the neutral sheet of the magnetospheric tail may be represented as the field of a plate, along which a surface current I_N flows from the morning toward the eveningside. This surface I_N is linked with the magnetic field of the tail by the relation $B_{DT}{}^T = 2\pi I_N$. The relations describing the field B_{DT} inside the region of closed field lines are given by *Shabanskiy* [1968].

The field B_{DR} due to the drift of trapped radiation in the geomagnetic field (mainly protons with energies of several tens of kev) was computed by *Akasofu and Chapman* [1961] and *Akasofu and Cain* [1962] for various parameters characterizing the distribution of particles by equatorial radius and pitch angles.

Postulating that within the bounds of closed field lines in the equatorial region in the longitude section $\delta\lambda$ the magnitude flux

$$F_1 = \int^{\delta\lambda} \int_1^{L(\lambda)} B_z L \, dL \, d\lambda \qquad (1)$$

is equal to the magnetic flux in the same longitude sector through the earth's surface in one hemisphere,

$$F_2 = \int^{\delta\lambda} \int_0^{\phi(\lambda)} B_r \cos\phi \, d\phi \, d\lambda \qquad (2)$$

Akasofu [1966*a*], *Williams and Mead* [1965], *Williams and Ness* [1966], and *Shabanskiy* [1968] determined the geomagnetic latitude of the intersection of closed lines of force with the earth's surface. In equations 1 and 2, B_r is the radial component of the magnetic field on the earth's surface, B_z is the field component on the equator in the direction of dipole axis, and $L(\lambda)$ is the equatorial boundary of closed field lines.

On the earth's surface the magnetic field was assumed to be a dipole field, but in the equatorial plane the field is composed of $B_M + B_{DCF} + B_{DT} + B_{DR}$. The equality $F_1 = F_2$ is rigorously fulfilled only in the near-midday or near-midnight hours, when the lines of force are not azimuthally distorted; thus, only these time intervals are considered below.

Quantitative calculations carried out by *Shabanskiy* [1968] in the two-dipole approximation have shown that in the absence of the ring current the boundary of closed field lines on the dayside is determined by the expression

$$\cos^2 \phi_d = (3 - 2f)/2L_1 \tag{3}$$

where L_1 is the geocentric distance of the subsolar point and $f \approx 1$ characterizes the shape of magnetosphere surface. The field due to currents in the tail's neutral sheet also influences the position of the daytime closed field line boundary. Taking the neutral sheet into account leads to the relation

$$\delta\phi_d = -\frac{4° \ \delta B_{DT}{}^{T}}{\sin \phi \ \cos \phi B_0} L_1{}^2 \tag{4}$$

Equations 3 and 4 yield $\Phi_d = 76°$ for $L_1 = 9$, and $\Phi_d = 77°$ for $L_1 = 10$ with $B_{DT}{}^T \sim 20\gamma$; therefore, the closed lines of force intersect the earth's surface at polar auroral oval latitudes on the dayside of the earth on magnetoquiet days.

The observed variations in the position of the southern boundary of the oval with enhancement of *DP* allow us to estimate the limit of L_1 variations. From equation 3 it follows that

$$\delta\phi_d = \frac{90°}{\pi L_1 \cos \phi \sin \phi} (\delta L_1 \cos^2 \phi + \delta f) \tag{5}$$

For magnetospheric contractions from $L_1 \sim 10$ with preservation of the shape,

$$\delta\phi_d = 0{\cdot}6\delta L_1 \tag{6}$$

As the index Q increases from 0 to 6, the southern boundary of the oval shifts toward the equator by 2.3° (Figure 2*b*). This means that the daytime boundary of the magnetosphere approaches the earth from 10 R_E to 6 R_E. With the increase of Q the field in the tail $B_{DT}{}^T$ also increases and causes shift in Φ_d of $\sim$1° to the south according to equation 4. Consequently, the data on the position of the oval's daytime boundary indicate that on the dayside the magnetopause does not get closer to the earth than 7 R_E. The location of the boundary at $L_1 < 7$ is possible during the development of a ring current in the magnetosphere and has been observed by *Freeman and Maguire* [1968].

The latitude at which the boundary of closed field lines touch the ground on the nightside of the earth as a function of $B_{DT}{}^T$ was computed by *Williams and Ness* [1966], taking into account the field of currents B_{DCF} and B_{DT}. Postulating that this boundary coincides with the southern boundary of the auroral oval, *Starkov et al.* [1968] estimated the value of the field in the tail at $\sim$10 R_E for different *DP* intensities.

The dependence of $B_{DT}{}^T$ on the equivalent amplitude of index Q on the nightside of the earth is plotted in Figure 4. As the magnetic disturbance increases, $B_{DT}{}^T$ rises from $\sim$13γ at magnetoquiet times to $\sim$47γ during intense disturbances. These values of the tail field, like the increase of $B_{DT}{}^T$ with the rise of *DP*, agree well with satellite observations [*Ness,* 1965; *Williams and Ness,* 1966; *Ness and Williams,* 1966; *Behannon and Ness,* 1966; *Behannon,* 1968; *Mihalov et al.,* 1968; *Yeroshenko* 1968].

If the geomagnetic tail is assumed to be formed by lines of force from the near-polar regions located inside the auroral ovals in each hemisphere,

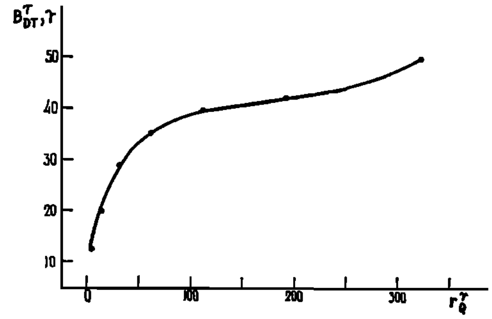

Fig. 4. Intensity of the field in the magnetospheric tail plotted against the intensity of *DP*.

the magnitude of the magnetic flux in the tail and its variations during magnetic disturbances can be estimated. Determination of the magnetic flux is very important for theories relating the acceleration of particles in the tail and the development of auroras to convective motion of matter and of the frozen-in magnetic field in the magnetosphere [*Piddington,* 1967; *Unti and Atkinson,* 1968].

Inside the ovals in both hemispheres, the flux is computed from the relation

$$F_3 = (4\pi M/R_E) \cos \Theta_M \sin^2 \Theta \tag{7}$$

where M is the earth's magnetic moment, θ_M is the displacement of the auroral oval from the geomagnetic pole, and θ is the polar distance of the oval boundaries from its center. The magnetic flux variation, computed by equation 7, is plotted in Figure 5, where θ_M and θ are taken from the data shown in Figure 2.

When $DP \sim 300\gamma$ on the ground, $F_3 = 2.3 \cdot 10^{17}$ gauss/cm² and increases with the growth of DP by 10^{17} gauss/cm². As DP develops, the transition from a quiet field to bay maximum takes place in ~1 hour, so that the rate of variation of the magnetic flux, carried by the solar wind into the magnetospheric tail is about 3×10^{13} gauss cm²/sec.

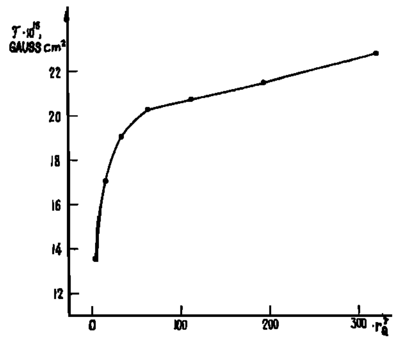

Fig. 5. Magnetic flux from the polar caps into the magnetospheric tail plotted against variation in the *DP* intensity.

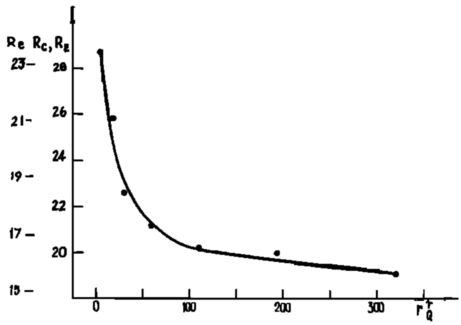

Fig. 6. Radius in earth radii of the magnetospheric tail cross section with the change of *DP*. R_e is the cross section in the shape of an ellipse, and R_c is the cross section in the shape of a circle.

Observations of auroras allow us to determine independently two parameters characterizing the magnetic field of the tail: (1) the intensity $B_{DT}{}^{T}$ and (2) the magnetic flux F_3 in the tail. These are linked by the relation

$$F_3 = B_{DT}{}^{T} S \quad (8)$$

where S is the area of the tail's cross section. Assuming a circular cross sectional shape with radius R_{ϕ} [*Gosling et al.*, 1967] or an elliptical shape with an equatorial diameter of $2R_E$ having a polar-to-equatorial axis ratio of 3:2 [*Behannon*, 1968], one may determine the radius of the magnetospheric tail as a function of *DP* intensity on the basis of data on the auroral oval position. In its cross section the tail's field was assumed to be constant in accord with the experimental data [*Behannon*, 1968; *Mihalov et al.*, 1968]. The results of the calculations are shown in Figure 6. According to satellite observations the radius of the tail is ~16–20 R_E at R ~10 R_E [*Heppner et al.*, 1967; *Behannon*, 1968], which is in agreement with the estimates based on the position of the auroral oval.

Satellite measurements of the field in the tail do not allow us to separate the temporal variations due to magnetospheric compression by the solar wind from those resulting from an increase of magnetic flux in the tail, both of which occur simultaneously [*Yeroshenko*, 1968]. Observations of auroras permit such a separation [*Starkov et al.*, 1968].

Using satellite data on magnetic field intensity in the tail at various geocentric distances and data on the magnitude of the magnetic flux in the tail determined from ground observations of the auroral oval position, *Shevnin and Feldstein* [1968] were able to compute the dimensions of the tail's cross section at geocentric distances up to 31.7 R_E for different *DP* intensities. Those authors used the IMP 1 onboard magnetograms [*Behannon and Ness*, 1966] over a period including five magnetic storms in 1964, for time intervals when the field direction in the tail was nearly solar or antisolar.

The magnetic flux in the magnetospheric tail was computed for corresponding hourly intervals with the aid of equation 7, using values of Q indices and the *DR* field.

The results of computing the equatorial radius R_e of the tail's elliptical cross section in the absence of field line reconnection (conservation of magnetic flux), are shown in Figures 7*a* and 7*b* for four pairs of Q indices. The values of R_e, given in Figure 6, are characteristic for $R < 12\ R_E$ and are plotted in Figure 7*a* as circles at 10 R_E. This is due to the fact that during a magneto-quiet period the line of force of the oval boundary intersects the equatorial plane on the nightside at $R \sim 10\ R_E$. Besides, according to the model used for the calculation of R_e shown in Figure 6, $R > 8\ R_E$ [*Williams and Ness*, 1966].

The smooth curves of Figure 7*a* reflect the variation of R_e of the magnetospheric tail on the nightside of the earth at the corresponding *DP* intensity. R_e increases with the distance from the earth (the tail expands). For a fixed R the radius of the tail decreases with the increase of magnetic disturbance.

The dependence of R_e on R is plotted in Figure 7*b*; crosses indicate the R_e of the tail obtained from observations of the magnetosphere boundary position

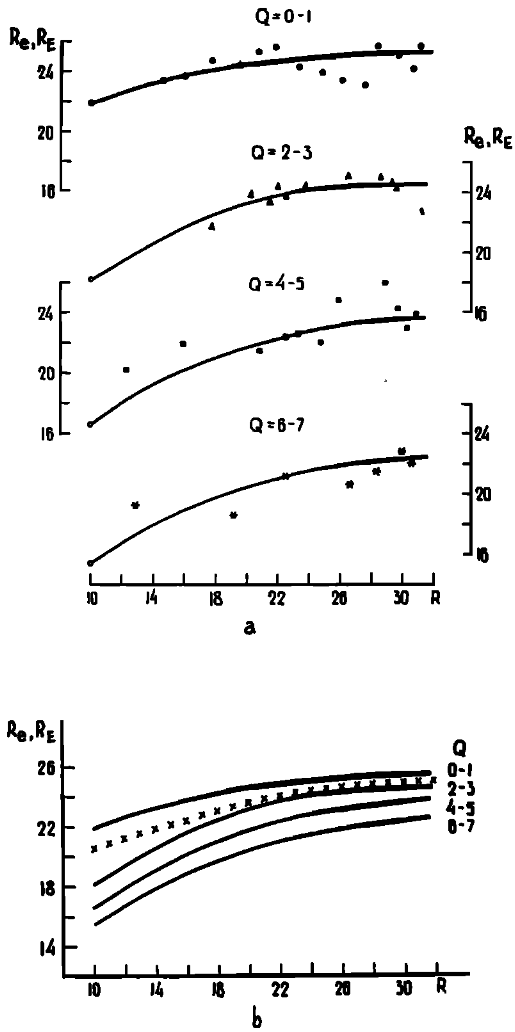

Fig. 7. (*a*) Equatorial radius of the magnetospheric tail (R_e) for various distances (R) from the earth in the plane of the night meridian with variation of magnetic disturbance on the earth's surface. (*b*) Solid lines are identical with those in Figure 7*a*. Crosses represent the R_e according to observations from Explorer 33 [*Behannon,* 1968]. Distances are in earth radii.

by the satellite Explorer 33 [*Behannon,* 1968]. The computed values of R_e up to $R = 31.7\ R_E$ and those observed on Explorer 33 are in good agreement, provided we assume that the position of the magnetopause from the satellite measurements reflects relatively magnetoquiet conditions.

Within the tail a nonzero vertical component of the magnetic field [*Speiser and Ness,* 1967; *Mihalov et al.,* 1968; *Behannon,* 1968] leads to a decrease of magnetic flux with the increase of R. If the vertical field component $B_{DT}{}^N$ at $R >$ 10 R_E decreases according to the relation $B_{DT}{}^N = 30/R$ (which does not contradict the experimental data), we must expect that R_e will decrease at the expense of reconnection by only ~3% at R = 30 R_E and by 2% at R = 20 R_E as compared to their values computed without considering the reconnection.

Shabanskiy [1968] obtained a relation linking the nightside boundary and median line of the auroral oval with the dimensions of the region from which plasma is injected in the earthward direction. The configuration of the magnetic field between closed and open magnetic lines of force in the near-midnight hours and the dimensions of the injection region constituting (3/2) Δ are shown in Figure 8*a*. The projection of the injection region on the earth's surface along distorted field lines corresponds to the auroral oval.

When the magnetic field is quiet, the dimensions of the injection region are rather small; its center is located on $L_{N0} \sim 10$. As *DP* increases, the field B_{DT} grows. The relation determining the dimensions of the injection region at the transition from quiet to disturbed conditions as a function of tail field intensity has the form

$$\frac{B_0}{L_{N0}{}^3} - \frac{B_{DT}{}^{\tau}}{\pi} \ln \frac{2R_T}{\Delta} = 0 \tag{9}$$

Here B_0 is the magnetic field on the equator, and 2 R_T is the diameter of the tail.

For the projection of the boundaries of the injection region when the field is distorted, equations 1 and 2 lead to

$$\cos^2 \phi = (3/2)\,(1/L) \tag{10}$$

Equations 9 and 10 define the geomagnetic latitude of the boundaries and of the point A of the projection of the injection region on the earth's surface. They are plotted as dashed lines in Figure 8*b*. The dotted curves correspond to the first stage of auroral oval displacement toward the equator with a small increase of disturbance. Solid lines show the boundaries and the oval's median

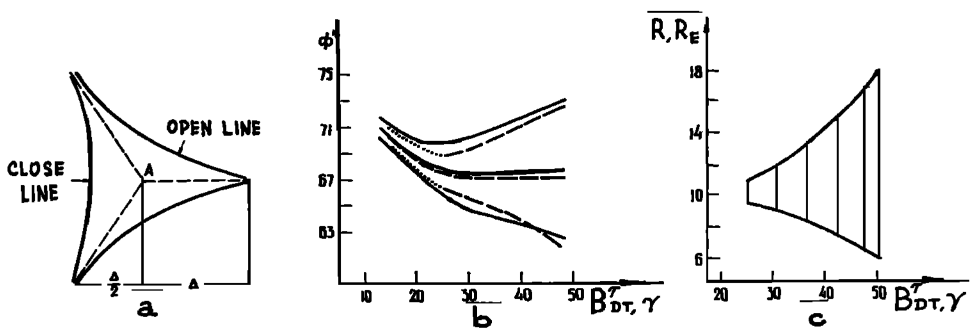

Fig. 8. (*a*) Schematic representation of the region on the nightside, from which the plasma leading to the appearance of polar aurora is injected. (*b*) Dependence of ϕ' boundaries and the auroral oval median line near midnight on the field intensity in the magnetospheric tail. The theoretical dashed curve is from *Shabanaskiy* [1968], and the solid one corresponds to the auroral oval in the IGY period. (*c*) Dimensions of the magnetospheric region in the antisolar direction (shaded) from which plasma is injected in the earthward direction.

TABLE 1. Length of the Geomagnetic Tail Expressed in Earth Radii (R_E)

	Lower Limit	Upper Limit
$Q = 0$	129 ± 6	155 ± 9
$Q = 1$	144 ± 8	173 ± 10

line obtained from the observational data taken during the IGY period [*Feldstein and Starkov,* 1967] in the near-midnight hours; here Q indices are replaced by the corresponding values of $B_{DT}{}^{T}$ according to the data of Figure 4. Considering the qualitative character of Shabanskiy's theory, one should underscore the good agreement of the conclusions stemming from it with observations.

The geocentric distances of the injection region's boundaries are shown in Figure 8*c*. As $B_{DT}{}^{T}$ increases, the region in which plasma is observed expands; its nearer boundary approaches the earth while the remote one recedes from it. The approach to earth, as *DP* increases, of the region in which plasma fluxes from the magnetospheric tail are observed agrees with the observations from the ATS 1 satellite [*Freeman and Maguire,* 1967]. From observations of the motion of the oval's poleward boundary it follows that on different occasions the remote boundary of the injection region may recede to distances substantially greater than 18 R_E, since polar auroras of the zonal type appear in separate rare cases up to the geomagnetic pole [*Geophysical Institute Annual Report,* 1967].

The length of the magnetospheric tail in *Dungey*'s [1961, 1965] open-model magnetosphere may be determined on the basis of direct measurements of interplanetary plasma velocity and of the rate of magnetic field line movement through the polar cap, which is assumed to be equal to the velocity of visible formations in polar auroras. Using the solar plasma velocity of *Snyder et al.* [1963], the motion velocities in near-polar auroras in the direction of the midday-midnight meridian in magnetoquiet periods of *Feldstein et al.* [1968*b*], and the oval's diameter after *Feldstein and Starkov* [1967], we have obtained for the length of the magnetospheric tail the values given in Table 1.

If we extrapolate to greater distances the dependence of the field intensity of the tail in magnetoquiet periods obtained by *Behannon* [1968] for $R < 80$ R_E, we find at $125\ R_E < R < 175\ R_E$ a tail field 4γ (i.e., equal to or smaller than the interplanetary field). The energy density of the magnetic field then becomes equal to the hydrostatic pressure of solar plasma. At these distances the tail will not be clearly defined; its dimensions, obtained on the basis of data on the auroral oval, apparently do not contradict experimental data. Its length, $\sim$150 R_E, also agrees with theoretical estimates by *Dessler* [1964, 1968], according to which the minimum possible tail length would be $\sim$100 R_E.

AURORAL OVAL AND DENSITY OF LOW-ENERGY PLASMA IN THE MAGNETOSPHERE

From the data on the position of the oval's southern boundary near midnight and during $Pi2$-pulsation periods, it was possible to estimate the density of the cold low-energy plasma in the magnetosphere at geocentric distances from 5 to 9 earth radii [*Troitskaya et al.*, 1968]. On the basis of morphological regularities of P_i2, *Raspopov* [1968] and *Rostoker* [1968] concluded that a possible mechanism of P_i2 formation is the resonance of Alfvén waves in the tube of force extending from the night portion of the oval zone to the equatorial region directly adjacent to the beginning of the neutral sheet.

In such a case, the oscillation period is determined from the equation

$$T = \int_{-\Phi_0}^{\Phi_0} \frac{2\,dS}{V_a} \tag{11}$$

where dS is an element of arc of the field line, Φ_0 is the geomagnetic latitude at which the boundary of closed field lines reaches the earth's surface, and V_a is the Alfvén velocity. When the first adiabatic invariant is conserved, the concentration of plasma along the magnetic line of force is, according to *Parker* [1957],

$$n_s = n_e\left[\frac{H_e}{H_S}\right]^{(\alpha-1)/2} \tag{12}$$

where n_s is the density of plasma at the point S of the line of force with field intensity H_S, n_e is the density on the equator and α is the parameter characterizing the particle pitch-angle distribution. For a dipole magnetic field

$$T = A\,\frac{(n_e)^{1/2}}{\cos^8 \Phi_0}\,J(\alpha, \Phi_0) \tag{13}$$

where

$$A = \frac{8(\pi m_H)^{1/2}}{H_0} \qquad R_E = 3.68(10)^{-2}$$

$$J(\alpha, \Phi_0) = \int_0^{\Phi_0} \left(\frac{\cos^{3/2}\Phi}{(1 + 3\sin^2\Phi)^{1/8}}\right)^{\alpha-1} \cos^7\Phi\, d\Phi$$

In this way the period of oscillations is determined by the plasma density in the equatorial dipole plane, the geomagnetic latitude of the point where the field line intersects the surface, and the parameter α. The values of J (α, Φ_0), computed by *Ohl* [1963], are constant for $\Phi_0 > 45°$ and are 0.24 at $\alpha = 10$ and 0.53 at $\alpha = 0$. The plasma density rises with the approach to the earth's surface and consequently $\alpha < 1$. The latitude of the point where the oscillating tube of force adjacent to the neutral sheet touches the ground may be determined by the data on the position of the southern boundary of the auroral oval in the near-midnight hours and in the period of P_i2-pulsation appearance. Then, equation 13 yields n_e as a function of Φ_0 or of geocentric distance $R = 1/\cos^2 \Phi_0$. The periods of P_i2, observed at 2202 LT in the winter of 1957 and 1961 at the Borok and Alushta observatories, are shown in Figure 9 as a function of the intensity of magnetic disturbance at Kiruna observatory (Q index).

As the disturbance increases, the oscillation periods decrease. If P_i 2 originates at the boundary of closed field lines, the decrease of T with the rise of Q is determined by the onset of oscillations on still shorter field lines. *Maehlum and O'Brien* [1963] and *Williams* [1967] have shown that the boundary of the region of trapped radiation in nighttime does indeed approach the earth in periods of magnetic disturbances.

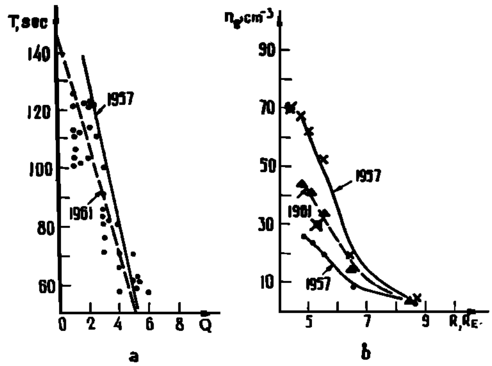

Fig. 9. (*a*) Period of type P_i2 pulsations in winter as a function of *DP* intensity. Dots represent the individual values of 1961, dashes and solid line are linear approximations for 1961 and 1957, respectively, using the method of least squares. (*b*) Plasma intensity in the equatorial plane at various geocentric distances. Crosses indicate 1957 ($\alpha = 0$); dots, 1957 ($\alpha = -2$); triangles, 1961 ($\alpha = 0$); dots with crosses are measurements by IMP 1 on November 27, 1963.

We assume that the latitude Φ_0 of the closed field line boundary for the corresponding Q is equal to the latitude of the southern boundary of the auroral oval in the near-midnight hours of the IGY period. The dependence of n_e on R in 1957 and 1961, computed by equation 13, is plotted in Figure 9*b*. For 1967 the calculation was performed for $\alpha = 0$ and $\alpha = -2$. These are possible boundary values of α. Even for $\alpha = -2$ the plasma density according to equation 12 decreases along the field line by more than 3 orders; this exceeds significantly the plasma density decrease estimated theoretically [*Eviator et al.*, 1964]. In addition, n_e decreases by a factor of 1.5 with the decrease in solar activity. This decrease continued toward the year 1964. The computed values of n_e do not differ from the IMP 1 measurements [*Serbu and Maier*, 1966], which are presented in Figure 9b for the winter day of November 27, 1963. Taking into account that, as indicated by the data on pulsations, n_e continued to decrease from 1961 to 1964, one should expect that n_e is in better agreement with the experimental data for $\alpha = 0$ than for $\alpha = -2$. An accurate accounting of the propagation path of the oscillations, in particular of the field line deviation from the dipole, should allow us to derive a more specific conclusion on the value of the parameter α, which constitutes an important characteristic of the low-energy plasma filling the magnetosphere.

AURORAL OVAL AND THE RING CURRENT IN THE MAGNETOSPHERE

A characteristic of magnetic storms is the ring current enhancement within the closed field line region. A direct demonstration was obtained by *Frank* [1967] of the connection between *DR* and the appearance in the magnetosphere of a large flux of charged particles. The main contribution to this enhanced radiation belt energy was made by protons with $3 \leq E \leq 50$ kev. Inside the magnetosphere the ring current distorts the field lines and consequently changes the position of the auroral oval. *Akasofu and Chapman* [1963] have determined the minimum geomagnetic latitude of quiet uniform arcs observed over USA territory in night hours as a function of the magnitude of D_{st} variation (a measure of ring current intensity). Their results are presented in Figure 10*a*. As D_{st} increases, arcs are located at lower and lower latitudes. *Feldstein and Starkov* [1968] and *Feldstein et al.* [1968*c*] determined the position of the northern and southern boundaries of the oval in near-midnight and near-midday hours as a function of D_{st} for fixed values of the *Q* index. The D_{st} values were obtained from *Sugiura* [1965]. The corresponding positions of the oval are shown in Figure 10*b*. The *DR* amplification (negative D_{st}) leads to the shift of both oval boundaries to lower latitudes and slight oval expansion. Analogous results are obtained also for other hours of the day. The asymmetric development of *DR* in the main phase of the storm also affects the position of the southern boundary of the oval.

The oval's shift toward the equator with D_{st} enhancement results in a change in the magnetic flux forming the magnetosphere tail. The corresponding values of ΔF are shown in Figure 11 for indices $Q = 3$ and $Q = 5$. The calculations were performed by using equation 7.

Variations in the magnetosphere's inner structure during the development of *DR* have been considered by *Akasofu* [1966*a*], *Shabanskiy* [1968], *Shevnin et al.* [1968], and *Hoffman and Bracken* [1967].

During the generation of the ring current, equations 1 and 2 lead to the following relation for the latitude of the southern boundary of the auroral oval without (Φ_0) and with (Φ) the presence of the ring current, $\sin^2 \Phi = \sin^2 \Phi_0$

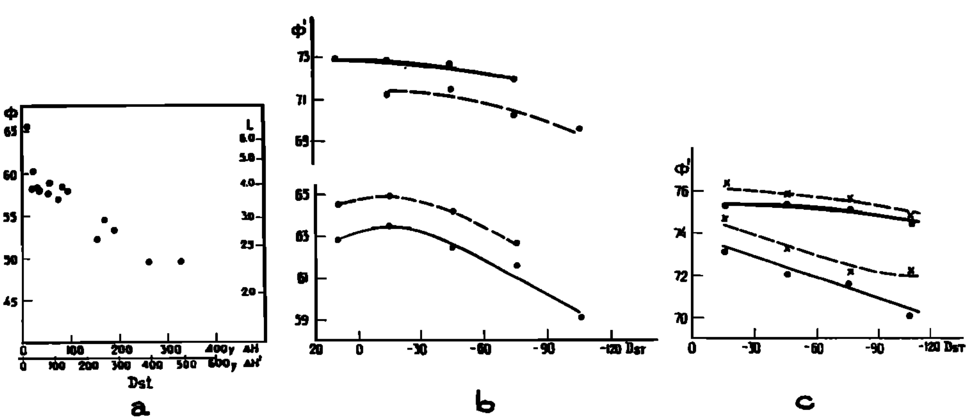

Fig. 10. (*a*) Position of quiet arcs in night hours in USA territory during the IGY period as a function of D_{st}. (*b*) Position of the northern and southern boundaries of the oval zone of auroras at $Q = 3$ and $Q = 5$ in near-midnight in the IGY period as a function of D_{st}. (*c*) This figure is the same as Figure 10 *b* but represents near-midday hours.

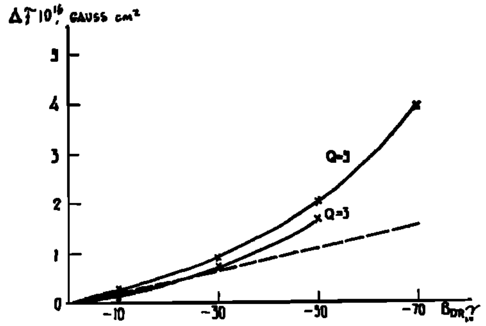

Fig. 11. Variation ΔF in the magnetic flux forming the tail of the magnetosphere with enhancement of the ring current. The dashed curve corresponds to the theoretically expected ΔF value.

$+ I_r$, where

$$I_r = \frac{R_E^3}{M} \int_{R_E}^{r} (B_{DR} + B_{DR}')r\, dr$$

Here B'_{DR} is the field due to currents induced in the earth. With the increase of I_r the boundary Φ of closed field lines and, consequently, the southern boundary of the oval shift to lower latitudes. This explains the appearance of auroras at $\Phi \sim 50°$–$55°$ in night hours in periods of intense storms. I_r depends on the variation of field intensity B_{DR} of the ring current with the equatorial radius. Comparison of the position of oval boundaries at different B_{DR} intensity on the earth's surface with the theoretical model ring current according to *Akasofu and Cain* [1962] allows us to draw certain conclusions regarding the variation of the model's parameters. Plotted in Figure 11 are the values of ΔF for a model characterized by parameters $r_{eo} = 3.2\ R_E$; $g1 = 2.146$, $g2 = 0.759$, and $\alpha = 2$. It follows from the comparison with experimental data that it is impossible to duplicate the results of observations with model representations merely by a simple increase of particle density in the radiation belt without changing its geometric characteristics. *Shevnin et al.* [1968] concluded that the results of model calculations agree with the observations, provided that the density maximum of ring current protons shifts during *DR* intensification by ~3–3.5 R_E and that the proton belt thickness increases by virtue of the receding of its outer boundary.

POLAR AURORAS ALONG THE OVAL IN DAY AND NIGHT HOURS

The atmospheric luminescences arising along the auroral oval in the day and nighttime regions differ in a number of characteristics:

(1) Rayed forms of aurora prevail in the daytime in quiet periods, while uniform arcs dominate the night hours [*Feldstein,* 1966*a*]; their activation proceeds in different fashions as the auroral substorm develops [*Feldstein and Starkov,* 1967].

(2) During daytime hours, glows are located at great heights [*Starkov,* 1968]. Indeed, an anomalously high ionization density is observed in winter on the dayside of the ionospheric *F* region at $\Phi \sim 76°$–$80°$ [*Yudovich,* 1963; *Besprozvannaya and Gorbushina,* 1965; *Oguti and Murubashi,* 1966].

(3) Auroral activity begins at different times in the night and day sectors [*Khorosheva,* 1962, 1967; *Akasofu,* 1964; *Starkov and Feldstein,* 1967].

(4) In magnetoquiet periods the auroral oval disintegrates into two parts. There are periods when auroras are observed only in the day and night sectors [*Lassen,* 1963; *Feldstein and Starkov,* 1967], being altogether absent either in the morning or the evening.

Stringer and Belon [1967] and *Akasofu* [1968*b*] also pointed out the necessity of isolating the daytime glows at $\Phi \sim 78°$ as a separate type by morphological features.

Apparently, auroras on the day- and nightsides of the auroral oval are due to electrons of different origins penetrating the upper atmospheric layers. The nighttime glow is due to plasma injection from the magnetospheric tail [*Axford et al.,* 1965; *Piddington,* 1967; *Shabanskiy,* 1968; *Ivanov,* 1967]. In daytime the glow originates from the region between the magnetopause and the shock front [*Pletnev et al.,* 1965]. The injection of charged particles into the magnetosphere on the dayside takes place through high-latitude neutral lines, formed by the solar-wind interaction with the geomagnetic field [*Piddington,* 1965*a*].

The frequency of daytime auroral appearance is ~100%, indicating that the aurora in this region constitutes a permanent terrestrial characteristic existing continuously as does the solar wind. In exceptionally magnetoquiet periods, the oval is located at $\Phi \sim 78°$–$80°$. Near midnight there is also observed a continuous luminescence, even in periods with $K_p = 0$ [*Stringer et al.,* 1965; *Feldstein,* 1966*b*]. Radio observations of the position of a radio-wave scattering region, which coincides with the glow region, corroborated the constant existence of scattering regions at $\Phi \sim 70°$ in the night hours [*Bates et al.,* 1966]. Hence it follows that in the total absence of planetary magnetic disturbances the asymmetry of the auroral oval and, consequently, of the region of closed geomagnetic field lines is preserved.

It will be shown below that magnetic disturbances also differ essentially on the day- and nightsides of the earth. There is located within the bounds of the auroral oval a westward electrojet, stronger at night than during the day. On the dayside, the arc generates a special type of disturbance that appears constantly as do the polar auroras but reaches notable intensity only during the summer. These two types of disturbances are basically different in nature, as are daytime and nighttime auroras.

As was shown by *Freeman and Maguire* [1967, 1968], nighttime polar auroras and magnetic disturbances are caused by plasma fluxes from the magnetosphere tail. The absence of plasma at $R \sim 6.6\ R_E$ on magnetoquiet days and the appearance of abnormally high fluxes only around midnight (the disturbance being feeble) with gradual increase of the time interval as the magnetic activity increases, all agree well with the variations in the position of aurora oval.

The oval of polar auroras is located on the boundary of smooth closed field lines. In the near-midnight hours this boundary is the outer limit of the region of stable trapping and is situated at $\Phi \sim 67°$; in the near-midday hours the stable trapping boundary is at $\Phi \sim 70°$–$71°$. Observed along it are a series of geophysical phenomena due to intrusion of geomagnetically trapped particles.

The presence of electrons with $E > 25$ kev results in anomalous absorption of cosmic noise in the morning and evening hours, whereas protons are responsible for the appearance of positive bays in the evening hours [*Pudovkin et al.*, 1968]. Along the auroral oval, whose boundary is located in the daytime on $\Phi \sim 76°$–$78°$, electrons with $E < 10$ kev are being injected. Electrons with $10 < E < 40$ kev are possibly injected in the latitude interval between the auroral oval's equatorial boundary and the region of stable trapping. On the poleward side of the boundary of closed field lines, electrons with $E < 10$ kev are injected, having energy of the order of a kilovolt on the nightside and of hundreds of electron volts on the dayside. The position of this region depends essentially on the level of magnetic activity; during intense disturbances its poleward boundary may be located at $\Phi \sim 75°$ on both the day- and nightsides of the earth.

Thus, at high latitudes, energetic particles are injected in a wide region. However, depending upon their energy, the zones of injection may have different symmetries [*Piddington*, 1965*b*], and the geometry of the magnetic field in the magnetosphere substantially influences the character of these symmetries.

THE DP CURRENT SYSTEM AND THE AURORAL OVAL

The current system providing a generalized representation of the distribution on the ground of a perturbed geomagnetic field vector may be located solely in the ionosphere [*Chapman*, 1935] or encompass both the ionosphere and magnetosphere [*Birkeland*, 1908; *Boström*, 1968; *Atkinson*, 1967]. *Fukushima* [1968] has shown the equivalence of the field of these current systems on the ground.

Shown schematically in Figures 12*a*, 12*b*, and 12*c* are the systems of polar magnetic *DP* disturbances currently discussed in the literature: the two-vortex classical system from the data of *Nagata and Fukushima* [1952] and *Fukushima* [1953]; the single-vortex system with a westward electrojet along the auroral oval and closing currents through the near-polar and middle latitudes [*Feldstein,*

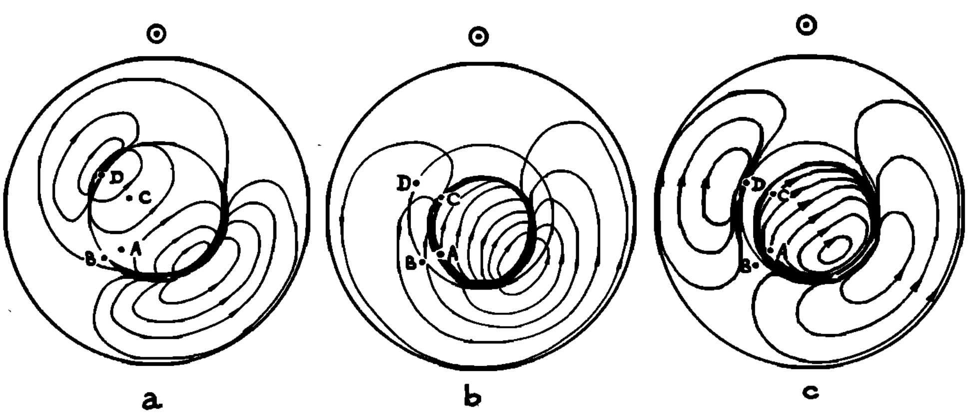

Fig. 12. Schematic representation of the current system of polar magnetic *DP* disturbance in the Northern Hemisphere: (*a*) classical current system; (*b*) single-vortex system with westward electrojet along the auroral oval; (*c*) double-vortex with westward electrojet along auroral oval. The solar direction is upward.

1963*a*; *Akasofu et al.*, 1965]; and a two-vortex system with a westward electrojet within the bounds of the auroral oval and an eastward electrojet in the evening hours on $\Phi \sim 65°$ [*Feldstein and Zaitzev*, 1965*b*; *Afonina and Feldstein*, 1968].

The main difference between the current systems of Figures 12*a*, 12*b*, and 12*c* consists in the presence of a westward electrojet along the auroral oval, located at $\Phi \sim 67°$ at night, at $\Phi \sim 70°$ at 2100 LT and at $\Phi \sim 75°$ at 1800 LT. The electrojet intensity decreases from night to day. We use the term 'electrojet' in high-latitude regions where the lines of the ionospheric current system thicken as a consequence of increased ionosphere conductivity due to injection of particles of any sign. The occurrence of current systems of the types shown in Figures 12*a*, 12*b*, and 12*c* will result in a different direction of the perturbed vector at $\Phi \sim 70°$ for 2100–2200 LT (points A, B), and at $\Phi \sim 75°$ for 0900–1000 LT, and also will result in different magnitudes at $\Phi \sim 75°$ and 67° at 1800 LT (points D, C). The field variations during the evening hours from pairs of observatories located

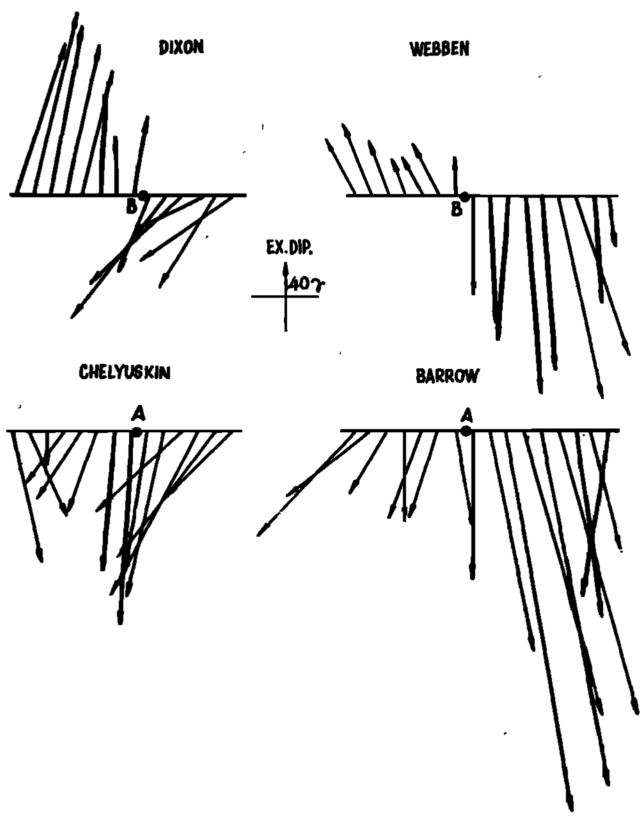

Fig. 13. Direction and magnitude of magnetic field's perturbation vectors of generalized magnetic bay at Dixon-Chelyuskin and Wellen-Barrow observations for the period November 1957–February 1958. The position of the points A and B is shown in Figure 12.

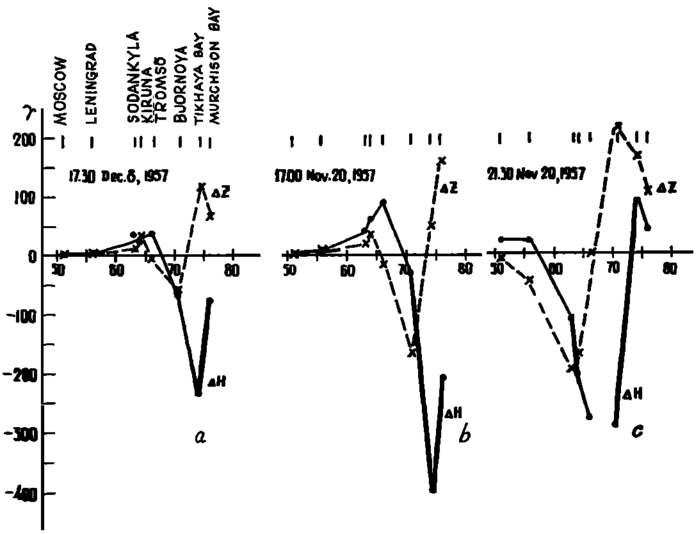

Fig. 14. Variation of the horizontal component ΔH and of the vertical component Δ_z of the bay-like perturbation field at the geomagnetic longitude ~120° in evening (*a, b*) and night (*c*) hours.

along approximately the same meridian are shown in Figure 13. One pair of stations (Chelyuskin and Barrow) is on $\Phi \sim 70°$; the second (Dixon and Wellen) is on $\Phi \sim 65°$ (where the sign of the perturbed vector changes from positive to negative at 2000–2100 LT). At the time of the perturbed vector transition through zero at Dixon and Wellen, the perturbation vector in Chelyuskin and Barrow is directed toward the equator. The preferred direction of the perturbation vector toward the equator at $\Phi \sim 70°$ at the time of the bay sign change from positive to negative on $\Phi \sim 65°$ was obtained earlier by *Akasofu et al.* [1965] and *Akasofu* [1966*b*]. This is evidence of the extension of the westward electrojet from the midnight to the evening sector, which follows also from the current systems of Figure 12*b* and 12*c*. The examination of *DP* field variations at Churchill and Baker Lake at 0900–1000 LT also shows the preferred direction of the field to be toward the equator on $\Phi \sim 75°$, which corresponds to the current systems of Figures 12*b* and 12*c*.

The values of the *DP* field at 1730 and 1700 UT (~1800 hours local time) from a network of European stations are plotted in Figures 14*a* and 14*b*. The magnetograms from the Bzornoya and Tromsö observatories for separate periods were kindly presented to us by O. Harang. The existence of two electrojets may be noticed: (1) a weak eastward one on $\Phi \sim 66°$ (point D of Figure 12*c*) and (2) an intense westward one on $\Phi \sim 74°$ (point C of Figure 12*c*). The intense narrow westward current on $\Phi \sim 74°$ cannot be explained by the closing through the polar regions of the weak eastward current on $\Phi \sim 66°$. Near midnight LT (2130 UT, Figure 14*c*), there exists a single wide electrojet on $\Phi \sim 68°$.

Intense negative *DP* in the evening hours is accompanied by injection into the ionosphere, on $\Phi \sim 74°$, of intense particle fluxes. Two cases of negative *DP* in the evening hours on Heis Island are shown in Figure 15. Such bays are always

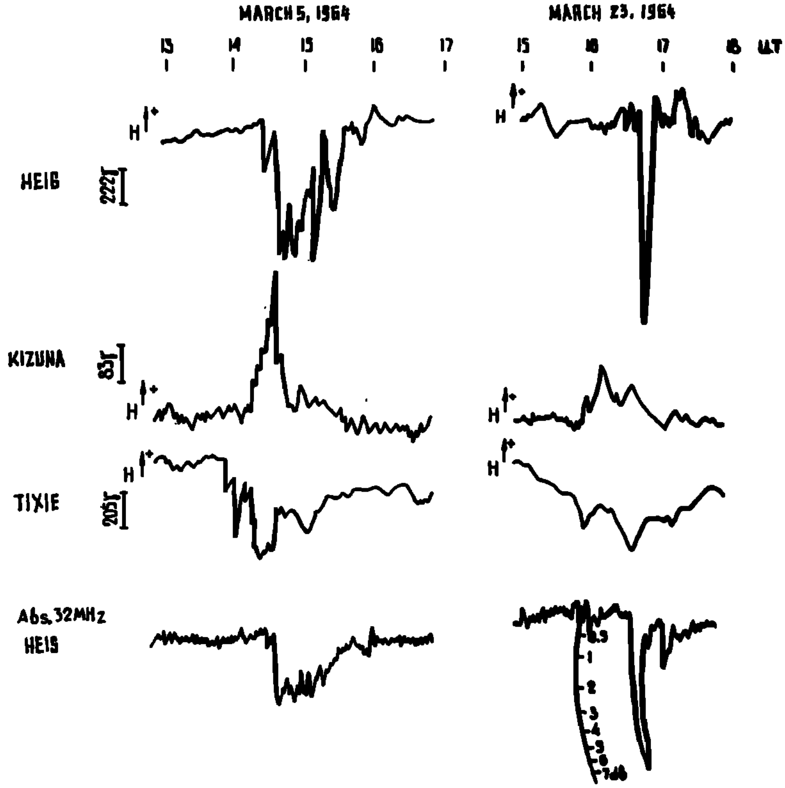

Fig. 15. Bay-like disturbances and absorption of cosmic noise at a frequency of 32 MHz on March 5, 1964, and March 23, 1964, on Heis Island ($\Phi = 74.3°$, $\Lambda = 144.1°$), in Kiruna ($\Phi = 64.3°$, $\Lambda = 104.8°$), and in Tixie ($\Phi = 65.6°$, $\Lambda = 194.9°$).

attended by a sharp increase in cosmic noise absorption, evidence of an increase in the ionization of the upper atmosphere as a consequence of the injection of electrons. (Riometer data were kindly made available by V. M. Driatsky.) The overlapping of the zone of localization of negative bays with particle injection in the evening hours, along with the character of the spatial distribution of the *DP* field, provides the basis for the assumption that negative bays on $\Phi \sim 74°$ in the evening sector are due to the westward electrojet.

Apparently the westward electrojet is not limited to $\Phi \sim 67°$ only in the night sector and spreads in the evening hours to higher latitudes. This fact supports the existence of the currents systems shown in Figure 12 (*b*, *c*).

During nighttime the westward electrojet is located on the poleward side of the boundary of trapped electrons [*Craven*, 1967]. The position of the equivalent linear current in a period of negative *DP* and the boundary of the trapping region of electrons with $E \geqq 280$ kev (from data of the satellite 1963 38C) are plotted in Figure 16 for the time interval 2300–0100 LT. The satellite data were kindly made available by *D. J. Williams* [1967]. The position of the linear current was

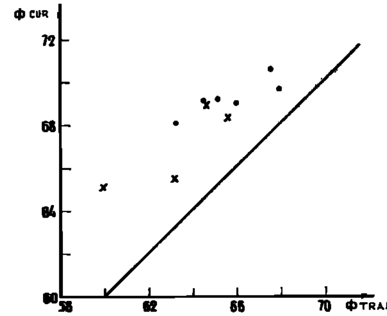

Fig. 16. Latitude of the equivalent linear current Φ_{cur} at ionospheric heights at the time the satellite 1963 38C determined the trapping region boundary for electrons with $E > 280$ kev. Φ_{cur} is given according to data from the pair of observatories at Barrow-College; the *x* values are according to data from Tixie.

computed by the magnetograms of observatories situated no further than 15° from the meridian of the trapping boundary as determined by the satellite. It follows from the data of Figure 16 that the shift toward the pole of the linear current and of the boundary of trapped electrons is synchronous and that the current is always located on the poleward side of the trapping region.

There is an essential difference between the current systems represented in Figures 12*b* and 12*c*, concerning the currents in the evening sector on $\Phi \sim 66°$. According to Figure 12*b* the positive bays in the evening hours are due to a return current from the westward electrojet, and according to Figure 12*c*, the positive bays are due to a return current from a separate eastward electrojet.

The fact that positive bay-like disturbances in the evening hours are not a return current from the westward electrojet is substantiated by: (1) the presence of negative bays in middle and low latitudes during the evening hours, whose amplitude does not increase toward the equator; (2) the appearance at separate times of large positive perturbed field vectors during the abrupt attenuation of the westward electrojet; (3) the nonsynchronism in the growth and decay of the eastward and westward electrojets; (4) the development of positive bays independent of the negative ones; and (5) the measurements on OGO 2 in the storm period of March 13–14, 1966, [*Langel and Cain*, 1967].

The eastward current on $\Phi \sim 65°$ in evening hours is considered an electrojet, since (1) thickening (crowding) of current lines in the ionosphere current system is noted; and (2) positive bays are attended by an ionization increase in the ionosphere.

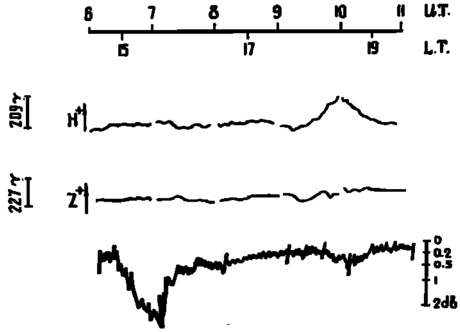

Fig. 17. Variations of the *H*- and *Z*-components of the magnetic field and absorption of 32 MHz cosmic noise at Tixie during the evening hours of January 29, 1964.

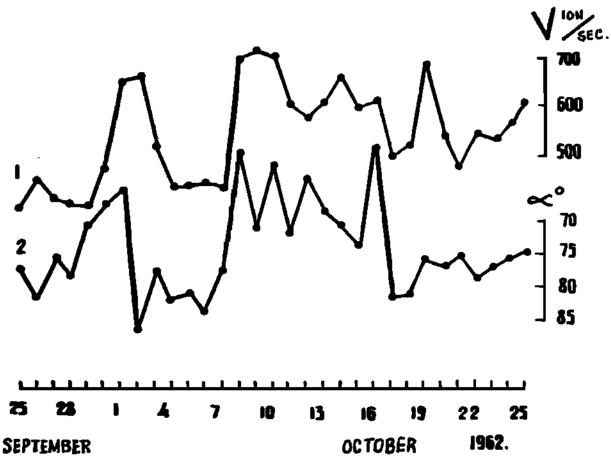

Fig. 18. Average daily values of (1) solar wind velocity and of (2) the angle α at the station Alert.

The evening variations of the magnetic field on $\Phi \sim 65°$ are plotted in Figure 17. The positive bay of ~200γ at 1800–1900 LT is accompanied by an increase of ~0.5 db in absorption at 32 MHz. According to *Driatskiy* [1968], whose riometer data are shown in Figure 17, positive bays in winter are always accompanied by absorption increases of 0.2–0.5 db. The low value of absorption is due to the fact that the ionization during positive bays is caused by injection of protons [*Pudovkin and Yevlashin,* 1962; *Baird,* 1968].

Mansurov and Mansurova [1968] compared the direction of the ionospheric current in the near-polar region with the mean daily values of solar-wind velocity from the data of *Snyder et al.* [1963]. Certain periods were noted, such as that shown in Figure 18, when similar behavior was observed between the solar-wind velocity V and the angle between the current direction and the midday meridian plane. Apparently a definite connection exists between the current direction in the near-polar region and the solar-wind velocity, which determines the direction of the interplanetary magnetic field. The cyclical variation of the angle α allowed an estimate of the solar-wind velocity ratio from maximum to minimum as equal to 1.7. It was found that the value of the angle α, read from the magnetosphere's axis of symmetry and theoretically determined by *Walters* [1964] for the Mariner 2 flight period, coincides with the direction of the interplanetary magnetic field.

VARIATIONS OF THE MAGNETIC FIELD IN THE NEAR-POLAR REGION

There exist in the near-polar region, even on exceptionally magnetoquiet summer days, magnetic field variations of irregular character in time [*Bobrov,* 1961; *Fukushima,* 1962]. During these disturbances at latitudes $65° \leq \Phi \leq 68°$ in nighttime, the magnetic field is quiet. Such disturbances, taking place mostly in daytime with maxima during the summer solstice, were called 'permanent' by

Mayaud [1955]. Permanent disturbances are characterized by a high level of short-period field fluctuations.

Nagata and Kokubun [1962] reported an additional variation at high latitude, denoted by S_q^p. Its summer current system in the northern hemisphere is illustrated in Figure 19. According to *Akasofu* [1966*b*], *Feldstein and Zaitzev* [1967], and *Mansurov and Mansurova* [1967], it is not free from the influence of *DP* disturbance electrojets.

Nishida [1968] obtained a current system for high latitudes analogous to the one shown in Figure 19. It was obtained during a period of $K_p = 3+$ and encompassed the entire terrestrial globe. It is also probably not free from the influence of *DP* and from the asymmetrical part of *DR,* which contributes to 0.5- to 1.5-hour field variations at lower latitudes.

The space-time distribution of magnetic field vector variations during universally magnetoquiet summer days during the IGY was computed as departures from values in the near-midnight hours of exceptionally quiet periods [*Feldstein and Zaitzev,* 1967; 1968*b*]. *Kawasaki and Akasofu* [1967] determined the vector field variations from the exceptionally quiet day of May 8, 1964, as departures from average daily values. The respective field vector distributions are shown in Figure 20. Despite the difference in methods of separating out vector variations, the following similar results were obtained: (1) the field variations encompass mainly the daytime side of the polar cap; (2) from $70° \leq \Phi \leq 80°$ at 1200 to 1800 UT, field vectors are mostly directed toward the pole, and for $\Phi > 80°$ they are directed toward the sun; (3) the distribution of field vectors differs essentially from *DP*. The current system describing the field distribution of the complementary variation in exceptionally magnetoquiet periods is illustrated in Figure 21. For internationally magnetically quiet days, it was obtained by*Feldstein and Zaitzev* [1967, 1968*b*] and consists of a single vortex, situated on the daytime side of the earth, with a counterclockwise current.

These current systems are in good agreement with the distribution of the disturbance field in isolated periods of very quiet summer days [*Fairfield,* 1963],

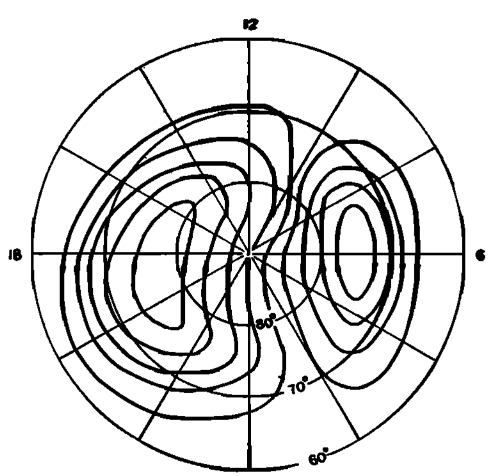

Fig. 19. Equivalent current system during international magnetoquiet days for the summer solstice of the IGY period after *Nagata and Kokubun* [1962]. There are 2×10^4 amperes between current lines.

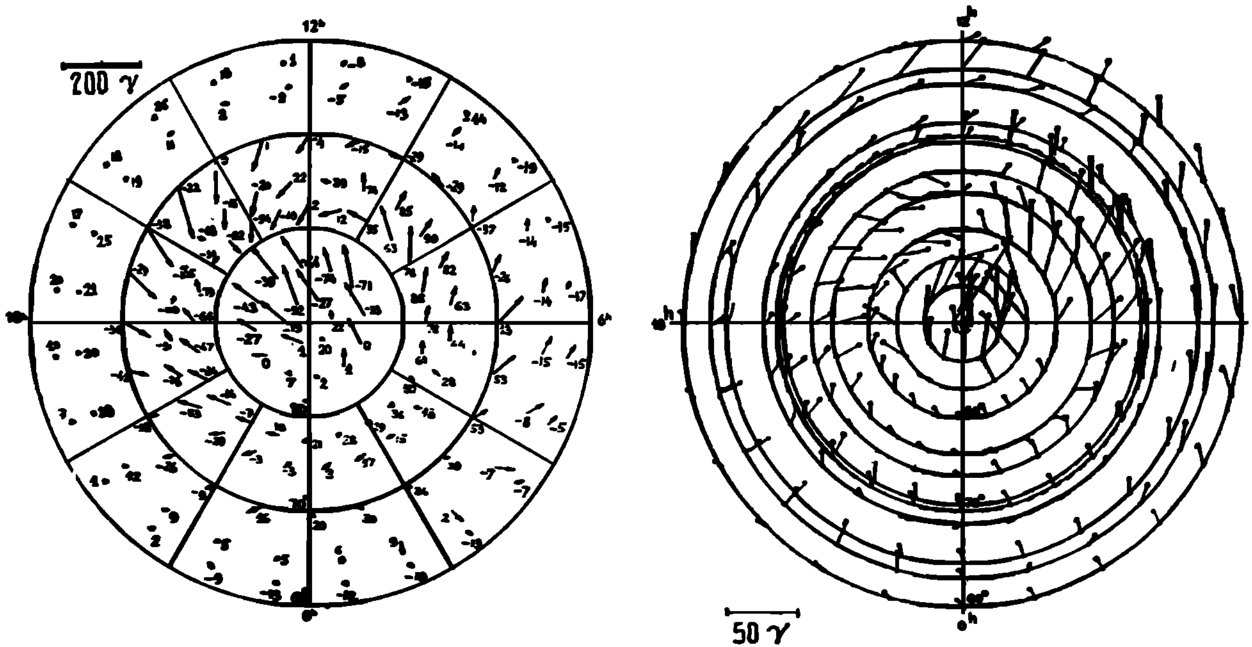

Fig. 20. Distribution of variation vectors in the horizontal (arrow) and vertical (numeral) planes during (*a*) quiet days of the IGY summer after *Feldstein and Zaitzev* [1967], and (*b*) on May 8, 1964, after *Kawasaki and Akasofu* [1967].

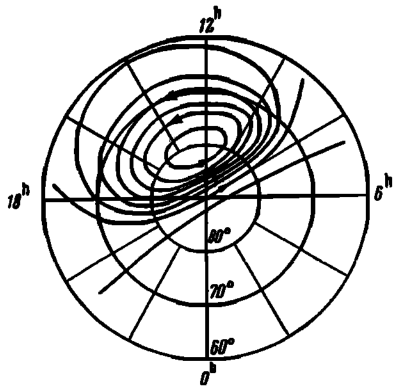

Fig. 21. Equivalent current system of *DPC* in magnetoquiet periods of international quiet days for the summer solstice of the IGY period. There are 10^4 amperes between current lines.

as well as with the complementary field variations of April 1, 1964, at 1100–1200 UT [*Ivanov and Mikerina*, 1967]. The current systems so obtained characterize the smooth additional variations of the field in the near-polar region, called by us *DPC* (polar cap disturbances).

At high latitudes the *DPC* variation is observed not only on magnetoquiet days but also during magnetic disturbances. Its intensity in the summer season increases with the rise of K_p [*Nagata*, 1968; *Feldstein and Zaitzev* 1968*a*]. The existence of *DPC* in magneto-disturbed days explain the different distribution of horizontal and vertical components of the perturbed vector on international magneto-disturbed days in winter and summer.

The smooth *DPC* field variations do not disappear even in exceptionally magnetically quiet periods ($K_p = 0_o$).

Plotted in Figure 22 are magnetograms from a series of northern high-latitude observatories from May 12, 1964, from 1500 to 1800 UT with $K_p = 0$. During this period the Resolute Bay and Mould Bay observatories entered the region of the *DPC* current eddy, and distinct field variations from ~50γ to 80γ are observed for a quiet field in the auroral zone at night. *Kawasaki and Akasofu* [1967] noted the presence of *DPC* variations on May 8, 1964, with $K_p = 0_o$. Therefore, observations during the IQSY confirmed the permanent existence of *DPC* variations in the near-polar region for $K_p = 0_o$.

The location of the *DPC* current system on the dayside with its center at the latitude of the oval zone is evidence of the fact that the existence of *DPC* is due to continuous plasma injection through the neutral line toward the daytime side of the near-polar region even in exceptionally magnetically quiet days.

The solar-wind parameters may vary in short time periods, and these variations are naturally reflected in the intensity of the *DPC* variation. The *DPC* variation is seen as sharp field increases in near-polar observatories with a quiet field on the nightside of the auroral zone. The variations of 0.5- to 1.5-hour duration are super-imposed on the smooth variations described by the *DPC*-type current system of Figure 21. When computing the field vectors characterizing such disturbances, it is easy to eliminate the uncertainty connected with the choice of a threshold level.

The distribution of field vectors for two concrete cases of disturbances at $K = 1$ and $1+$ is plotted in Figure 23. The magnitude and direction of the vectors agree well with the *DPC* current system obtained during the statistical analysis of the field of magnetic disturbances in the near-polar region during magnetoquiet periods. The similarity of the current system is evidence that (1) isolated, well-defined disturbances in the near-polar region in magnetoquiet periods are the consequence of sharp, sporadic enhancements of the *DPC* current system, and that (2) the form of the *DPC* current system is independent of the choice of the threshold level of the perturbation vector and is characterized by an intense current eddy on the dayside of the earth, shifted to the evening hours.

Mansurov and Mansurova [1965] obtained for an isolated disturbance on the magnetoquiet day of December 12, 1958, the distribution shown in Figure 23 of field vectors in the southern polar region after a solar chromospheric flare. In the same paper there is a note that during the summer on magnetically quiet days an additional mechanism exists which generates a zonal current system within the circumpolar region having a direction from the morning toward the evening hours. This zonal system is not connected with the current system S_q and therefore is basically different from the above-suggested *DPC* system, which mainly contributes to field variations in the circumpolar region on quiet days.

Comparison of the magnitude of vectors at $K_p = 1$ and $K_p = 1+$ yields evidence of sharp enhancement of the *DPC* current eddy intensity with the increase of K_p and appearance in the postmidnight hours of bay-like disturbances in the latitudes of the oval zone. It is possible that these bays are caused by inflow of a part of the current from the daytime side of the near-polar region through a channel of higher conductance along the auroral oval, but it is not ruled out that

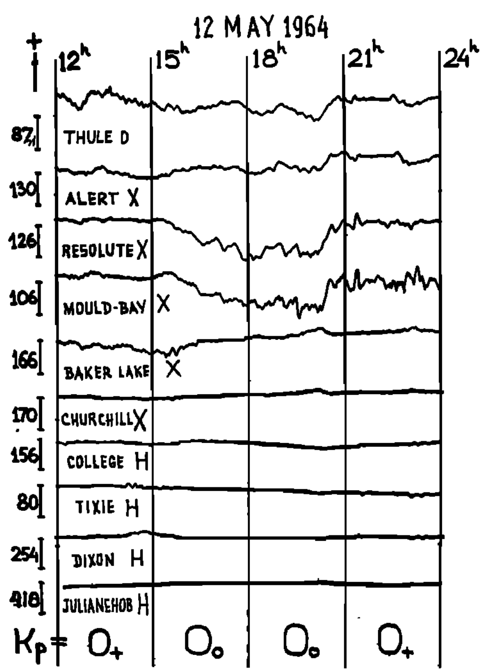

Fig. 22. Variations of the magnetic field at high-latitude observatories on May 12, 1964.

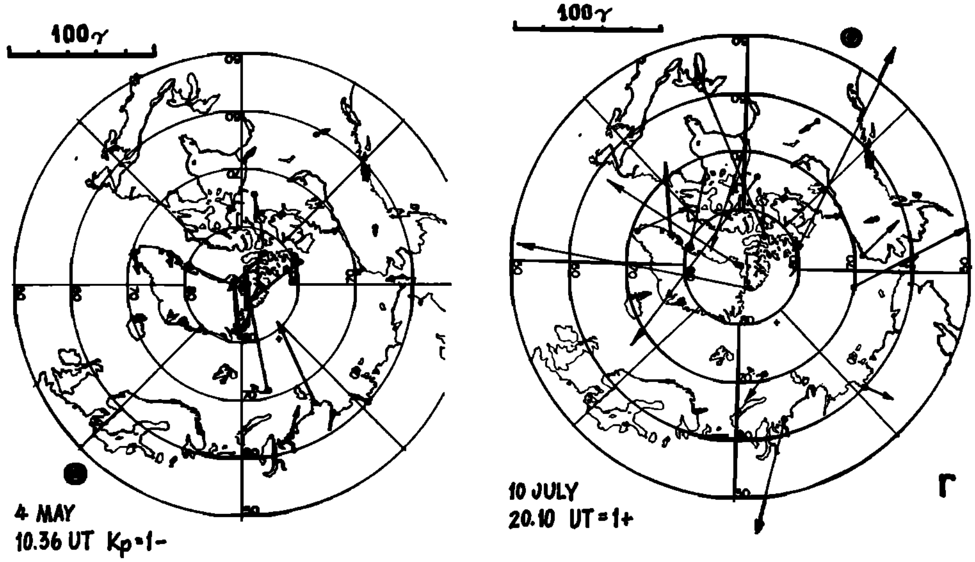

Fig. 23. Space-time distribution of the perturbed vector for (*a*) May 4, 1964, at 1036 UT with $K_p = 1$ and for (*b*) July 10, 1964, at 2010 UT with $K_p = 1+$. The coordinate net is geomagnetic. The solar direction is indicated by a circle at the edge of the map. The cross indicates the geographic pole.

on the nightside, as *DPC* are enhanced, bays appear as a consequence of particle injection from the magnetosphere tail.

Various mechanisms leading to variation of the magnetic field in the near-polar region are considered by *Wescott and Mather* [1965], *Akasofu and Kawasaki* [1968], and *Shabanskiy* [1968].

Starting from the fact that *DPC* and *DP* are different components of the perturbed field at high latitude, the *DS* variation (or its value S_D, averaged over disturbed days) should be assumed to be a complex phenomenon that, at high latitude, would be the sum of component parts, $DS = DP_W + DP_E + DPC$.

The ratio between the various *DS* components varies in the course of a storm and of the solar activity cycle. At the same time, isolated *DS* components are tightly linked with the structure of the magnetosphere: (1) the westward electrojet is located on the near-polar side of the boundary of closed geomagnetic field lines, branching into the near-polar and middle latitudes; and (2) there exist, on the dayside in the region of the neutral line, permanent disturbances arising as a consequence of solar wind interaction with the geomagnetic field.

Acknowledgments. The author expresses his deep gratitude to Dr. V. M. Driatsky for making available the riometer observations of the Heis and Tixie observatories, to Dr. O. Harang for the magnetograms from the Bjornoya and Tromsö observatories, to Dr. I. B. McDiarmid for his data on the satellite Alouette 2, to Dr. D. J. Williams for the data from the satellite 1963 38C, which were used in the present review. When writing the review, the author made wide use of investigations conducted with his colleagues Dr. A. D. Shevnin, R. G. Afonina, G. V. Starkov, A. N. Zaitzev, and N. F. Shevnina with whom numerous useful discussions were held. The author also acknowledges the cooperation of Z. A. Lobachevskaya in helping to put the present review paper in shape.

ADDENDUM

The opinion was expressed by *Mishin et al.* [1968] that the concept of an oval zone is a consequence of insufficient data or of incorrect data processing and that the concept of two quasi-circular zones of injection situated at $\Phi \sim 77°$ and $\Phi \sim 67°$ corresponds more correctly to contemporary data concerning geomagnetic activity in polar auroras.

Let us consider the fundamental data upon which this conclusion is based.

Space-time distribution of magnetic activity. The isolines of the hourly amplitude of the horizontal component r_H^γ [*Zhigalov,* 1967; *Loomer and Whitham,* 1963] and of the Q index [*Feldstein,* 1963*a*] are plotted in coordinates ϕ and t in Figures 24*a*, *b*, and *c*. The data shown correspond more closely to the oval zone, along which the intensity of a disturbance decreases from the nighttime to the daytime hours, than to two quasi-circular zones. These data were obtained from the averaging of observations from stations situated at different longitudes, as well as along a single meridian.

From the space-time distributions of r_H^γ, according to *Mishin et al.* [1966] and *Mishin and Troshichev* [1966], shown in Figure 25 for the winter season, the existence of two quasi-circular zones of magnetic disturbances is not clearly evident. One may speak either about one zone at $\Phi \sim 65°$ in Figures 25*a* and 25*b*, or of the circular zone at $\Phi \sim 67°$ plus an oval distribution in Figure 25*c*. Consequently, there are not two discrete zones on $\Phi \sim 77°$ and $\Phi \sim 67°$ in Figure 25 separated by a minimum in intermediate latitudes during the morning and evening hours.

A look at the observatory magnetograms for $\Phi \sim 65°$ (for example, Dixon and Kiruna) shows that at these observatories the magnetic field is, as a rule, quiet in midday. In magnetoquiet days there is hardly a zone of maximum activity on these latitudes.

In connection with the sharp enhancement of permanent magnetic disturbances on the daytime of the oval for the summer season, the magnetic activity has maxima on the day- and nightsides of the oval, which does not contradict the concept of oval zone.

Space-time distribution of polar auroras. The variation in the frequency of auroral appearance at various longitudes in the course of a day is shown in Figure 26 according to *Khorosheva* [1967]. It may be seen that when data are averaged in a large longitudinal interval, a scatter exists in the latitude distribution of polar auroras; nevertheless, maxima in the latitude distribution unambiguously point to the existence of the oval. This is precisely the conclusion obtained by *Feldstein* [1963*b*].

If, as considered by *Mishin et al.* [1968], there existed two quasi-circular zones at $\Phi \sim 77°$ and $\Phi \sim 67°$, the probability of appearance of auroras in morning and evening hours at $\Phi \sim 73°–75°$ would be much less than at 67° and 77°. However, polar auroras are nearly always observed at zenith in the morning and evening hours at Baker Lake ($\Phi = 75°$).

Radio-reflections from polar auroras. Plotted in Figure 27 is the position of the southern boundary of the scattering region according to *Bates* [1966], and

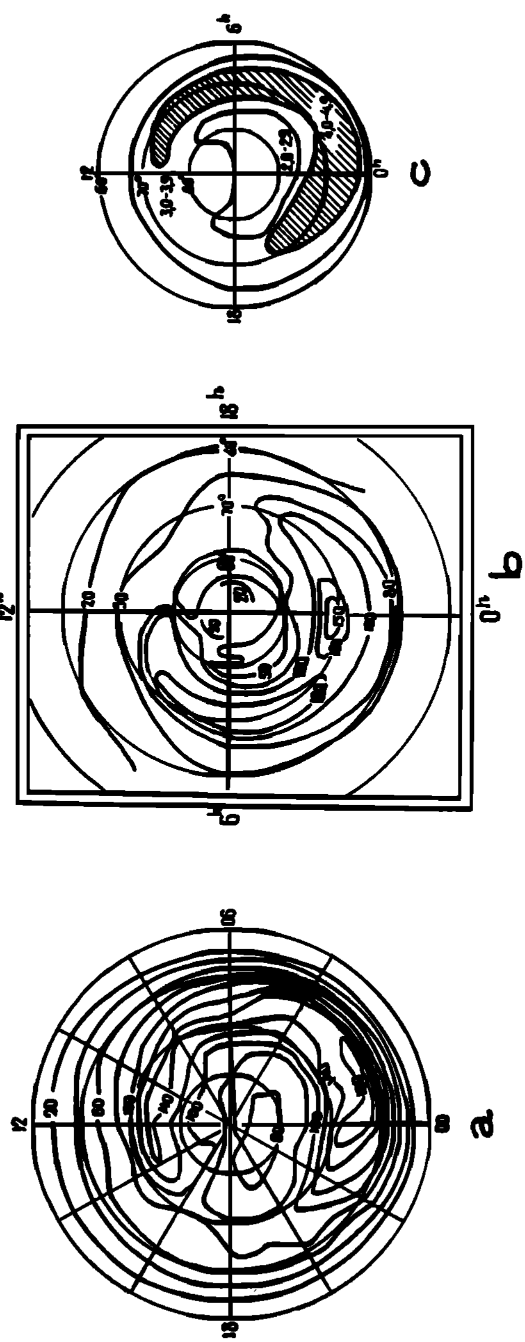

Fig. 24. Space-time distribution of magnetic activity: (*a*) r_H' according to *Loomer and Whitham* [1963], Northern Hemisphere 1960; (*b*) r_H'' according to *Zhigalov* [1967], Southern Hemisphere, winter 1958; (*c*) *Q*-index according to *Feldstein* [1963*a*], Northern Hemisphere, winter 1957–1958.

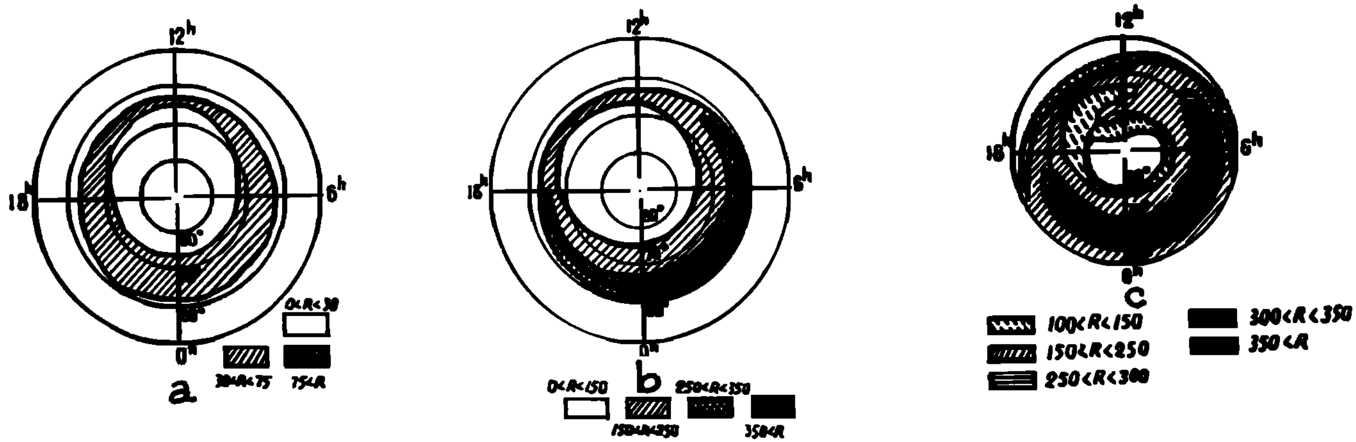

Fig. 25. Space-time distribution of magnetic activity in the Northern Hemisphere: (*a*) according to *Mishin et al.* [1966] for quiet days of the IGY winter period; (*b*) according to *Mishin et al.* [1966] for disturbed days of the IGY winter period; (*c*) according to *Mishin and Troshichev* [1966] for disturbed days of the IGY period.

it agrees well with the position of the auroral oval. The scattering region, as does the auroral oval, exists practically continuously day and night. Multiple-frequency sounding for the determination of the position of the radiowave scattering region at high latitudes [*Bates,* 1966] appears at present the most reliable radar method for determining the oval's position.

Other arguments, presented by *Mishin et al.* [1968], are not contradictory to the concept of an oval zone:

1. the presence of gaps between the day and night portions of the auroral oval,

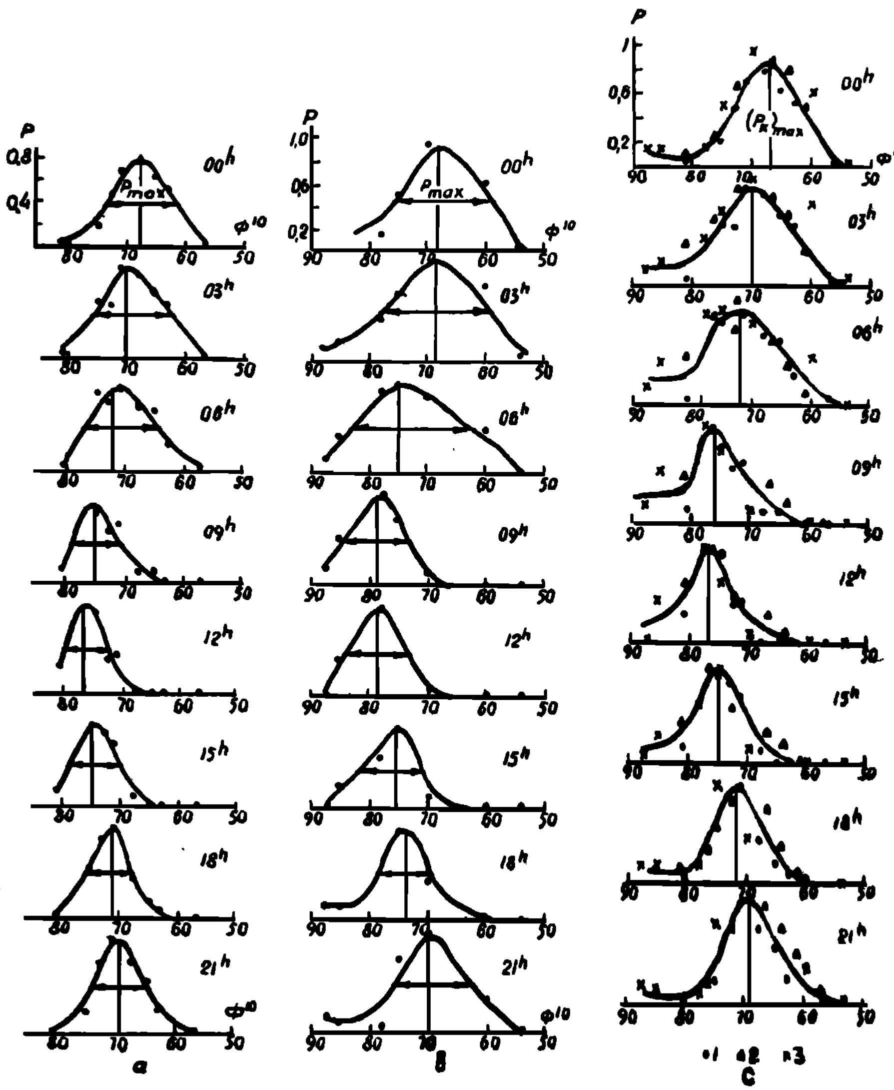

Fig. 26. Variation with latitude of the frequency of auroral appearance at various hours of local time: (*a*) Eastern Hemisphere λ = 120° E (USSR stations); (*b*) Western Hemisphere λ = 95° W; (*c*) average for USSR (1). Scandinavian (2), and American (3) stations.

2. the independence of day and night auroral shapes,
3. the circular shape of the boundary of stable trapping of electrons according to data of Alouette 2,
4. precipitation of electrons with energies in tens of kev at $\Phi \sim 67°–70°$,
5. the presence of an eastward electrojet, since a westward current is connected with the auroral oval,
6. the difference in regularities characteristic of the magnetic disturbance on the day- and nightsides of the earth, and
7. the difference in the energies of particles responsible for the activity in daytime at $\Phi \sim 77°$ and nighttime at $\Phi \sim 67°$.

It is surprising how the concept of *Mishin et al.* [1968] agrees mainly with the zones of injection discussed by *Hartz and Brice* [1967], *Oguti* [1966], and *Sanford* [1964], whereas the fact of an oval symmetry for a series of geophysical phenomena is asserted in the three indicated works.

Thus, it follows from the above that the concept of an oval zone is fruitful for explaining regularities in the course of numerous geophysical events at high latitudes, e.g., discrete forms of auroras, variations of the magnetic field, the region of auroral radiowave scattering, the zone of precipitation of electrons with $E < 10$ kev, and others.

There is also no doubt that in order to explain the space-time characteristics of a number of other geophysical phenomena, such as diffusive polar auroras, cosmic noise absorption, boundaries of stable trapping of electrons with $E > 40$ kev, and others, circular symmetry is indicated; consequently, the concept of a quasi-circular zone at $\Phi \sim 65°–70°$ is appropriate.

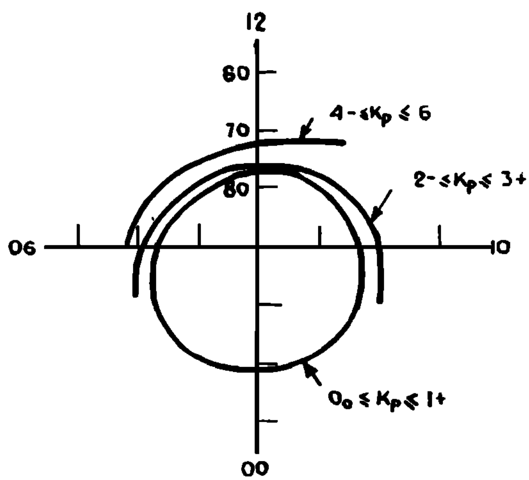

Fig. 27. Mean geomagnetic latitude of the southern boundary of the radio-wave scattering belt in 1965, as a function of the geomagnetic time for the indicated K_p intervals. The data for $\Phi < 68°$ are not available.

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