Auroral morphology, II. Auroral and geomagnetic disturbances

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ABSTRACT

Data from visual observations at middle latitudes give information on the southern boundary of aurora appearance in zenith. Comparison of the aurora zone location with the linear current in the ionosphere and with the magnetic disturbance is made. Current orientation in the ionosphere and the aurora arc direction are considered.

1. The southern boundary of aurora appearance in the zenith

GARTLEIN and others (1960) on the basis of the visual observation materials for the part of the IGY period defined the location of the southern boundary of aurora appearance in the zenith in the northern hemisphere with the planetary Kp index one and five. HULTQVIST (1961*a*) showed that the location of the southern boundary is in good agreement with his calculated projects of circles in the geomagnetic equatorial plane. In connection with the treatment of the data of aurora visual observations it appeared to be possible to make a more accurate comparison of the aurora zone location and the southern boundary of aurora appearance in the zenith. *Annals of IGY* (1962) give geomagnetic latitudes of the southern boundary of aurora appearance in the zenith for each six-hour interval of the universal time for eight longitudinal belts. Geomagnetic meridians with the intervals of 45° served as the belt boundaries. The location of the equatorial boundary of aurora appearance in the zenith was observed on the planetary scale only in the northern hemisphere. On longitudes 235–280° and 10–55° the data for the southern boundary location are very scarce.

The location of the aurora southern boundary greatly depends on the level of geomagnetic disturbance. Therefore, in making the statistic analysis it is feasible to consider separate days with different intensity of magnetic disturbance. For each day by the universal time we took a distance to the southern boundary from the geomagnetic pole $\theta°$ as a maximum value from the four values for the corresponding six-hour intervals. The same days were characterized by the maximum value of the planetary index of magnetic activity Kp from the eight values. We took the median value as a value $\theta°$, characterizing the location of the southern boundary for the corresponding index of magnetic activity (FELDSTEIN & SHEVNINA, 1963*a*).

As a rule it coincides with more frequently observed values of $\theta°$.

Fig. 1 gives the location of the southern boundary of the aurora appearance in the zenith with $Kp = 2(a)$, $Kp = 4(b)$, $Kp = 6(c)$ for the winter season of 1957–58. At the longitudes 10–55° the southern boundary is shown with approximation by dashed line. It is natural to compare the southern boundary of the aurora appearances in the zenith with the zone for night aurorae, because in the middle latitudes aurorae appear preferably at night hours and at those hours they are observed at the greatest distance from the pole. One should note a rather good correspondence between the form of the aurora southern boundary and the zone for night aurorae. The southern boundary of aurora appearance in the zenith is located farther from the pole than the aurora zone even in weak magnetic disturbances. It is natural, because aurorae cover at a given time a large interval of latitudes and the aurora zone might be identified with the centre of this latitudinal interval. Fig. 1 shows that with the increase of magnetic disturbance the southern border of aurora appearance in the zenith withdraws from the pole along all longitudes of the northern hemisphere.

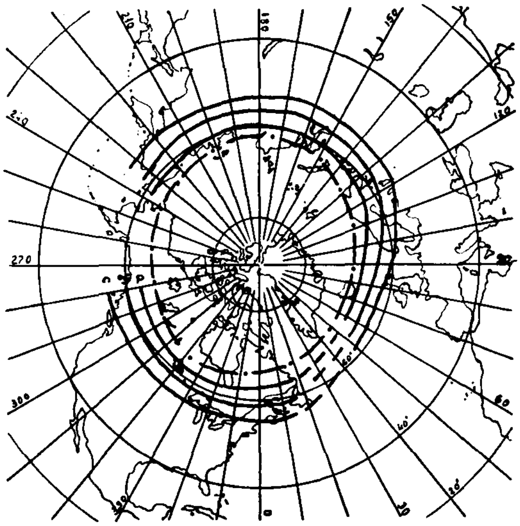

FIG. 1. The southern boundary of the aurora appearance in the zenith in the northern hemisphere in the winter 1957–58. The dashed-dotted line—the zone for night aurorae.

$a - K_p = 2$; $b - K_p = 4$; $c - K_p = 6$.

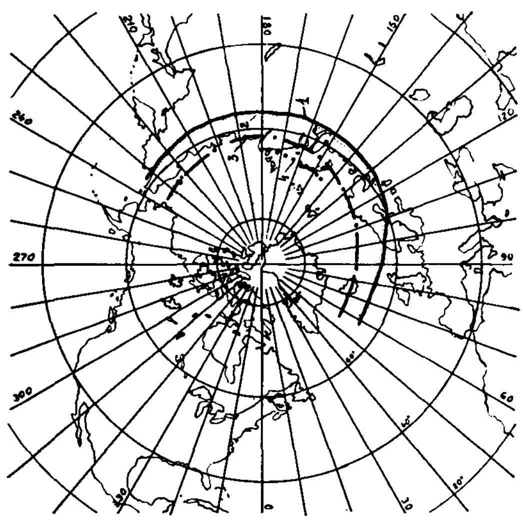

FIG. 2. The southern boundary of the aurora appearance in the zenith in the eastern hemisphere. The solid line—the winter of 1957–1958 (1), dots—the winter of 1959–60 (2). A dashed-dotted line (3)—the location of the zone of night aurorae for the winter of 1957–58, the dots at the longitudes 140°–180° (4)—the location of the aurora zone in the winter 1954–1955.

According to the results of the aurora visual observations on the territory of the U.S.S.R. (in the winter of 1957–58) a middle location of the southern border of the aurora appearance in the zenith was defined when observing all the days, that corresponds to index $Kp = 4$. The distance between the southern border thus found and the zone for night aurorae is of 6 degrees by the latitude. This result based on the statistic analysis allows to draw a conclusion that on the average the aurora simultaneously covers on the night side the region spreading 12° by the latitude. In each concrete case a latitude interval, covered by aurora, depends on magnetic disturbance intensity. With increased intensity of the planetary magnetic disturbance the aurorae on the night side, probably, cover simultaneously a larger interval of latitudes.

The study of changes of the southern border of aurora appearance in the zenith during a cycle of solar activity presents a great interest. The data, given in Fig. 2, show that the average location of the southern boundary in the eastern hemisphere practically did not change for the period from 1957 to 1959. With the same ntensity of the geomagnetic disturbance the southern border was situated in the winter of 1959–60 at the same latitudes as in the winter of 1957–58. Probably, the cyclic changes in the middle location of the southern border might be the consequence of rarer appearance of intensive magnetic disturbances in the years of the minimum of the cycle of solar activity. Fig. 2 gives also the location of aurora zone in the winter of 1957–58, typical for the maximum of solar activity cycle, and for a restricted region of the longitudes ($\Lambda = 140$–$180°$) in the winter of 1954–1955, according to the data of aurora visual observations of 50 stations (FELDSTEIN, 1962*a*). The displacement of the aurora zone to the pole in transition from the years of maximum of solar activity cycle to the years of minimum is small and on the average is 2.5–3° by the latitude. Such displacement of the aurora zone to the pole during the years of minimum of solar activity is equivalent to the shift of the 1.5 Earth's radius in the equatorial plane of the region, in which the charged particles responsible for the aurora appearance on the Earth's night side, move. Small changes in the location of the aurora zone in Antarctica, stipulated by cyclic variations of the solar activity level, are mentioned by SHERET & THOMAS (1961).

2. Auroral zone and magnetic disturbances

Aurora appearance on the Earth's night side is accompanied by strong magnetic disturbances. An intensive linear current flows at the latitudes of the zone for night aurorae. This current might be interpreted as the concentration of current lines of the surface ionospheric current system. The determination of coordinates of this current on the basis of the data on the magnetic field variations gives an independent method of determining the aurora zone location (VESTINE, 1944; BENKOVA, 1953). For the winter of 1957–58 we have calculated the value and direction of the disturbance vector in the horizontal and vertical planes for the observatories Tromsö, Dixon, Tixie, Welen, College in the deviations from the magnetic-quiet days. For these calculations the results of all-day observations were used. The geomagnetic field variations observed on the Earth's surface depend on the outer and inner sources. In calculating the field intensity, depending on the outer source, it was assumed that it was twice as intensive as the field from the inner source. By the formulas for linear current with the account of the Earth's sphericity the location of the outer source of magnetic disturbance at after-midnight hours was defined, when the value of the disturbed vector in the horizontal plane reaches maximum negative values. At these hours the replacement of the surface ionospheric current system by the linear current is most reliable. Fig. 3 presents the calculated location of the linear current. Comparing the results of analysis on the night aurora distribution one sees a good agreement between the linear current location and the night aurora zone. However, the linear current is situated at all the longitudes 1.5° to the south from the aurora zone. A more southern location of linear current may be explained by a greater statistical importance of intensive magnetic disturbances in calculating the value of the resulting vector of disturbance.

The aurora zone location depends on the magnetic disturbance level, moving to the equator with the increase of disturbance. The charged particle intrusions into the upper layer of the atmosphere, resulting in aurora appearance, are also responsible for intensive magnetic disturbances. The analysis of the latitudinal distribution of the mean-daily values of

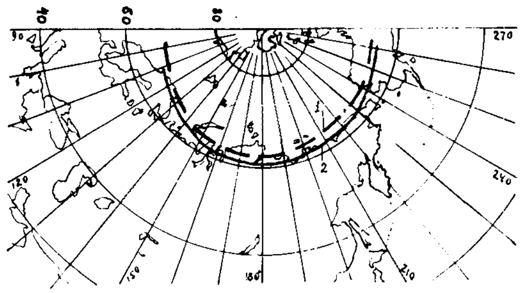

FIG. 3. The zone location for night aurorae (1) and the location of the linear current responsible for the variations of the magnetic field near the aurorae zone (2).

magnetic activity in the winter of 1957–58 showed that the magnetic activity, estimated by the index Q value, has the largest value in the zone for night aurorae (FELDSTEIN, 1961*c*, 1963*b*). At midday and midnight meridians maximum values of Q index are observed at different latitudes. At the geomagnetic midnight the Q index reaches its maximum value at the observatory of Dixon ($\varphi' \sim 68°$), at midday in the Tihaja Bay ($\varphi' \sim 73°$). Thus, the region of the maximum magnetic activity notably shifts along the latitude, approaching the pole at day hours and withdrawing from the pole at night hours (FELDSTEIN, 1963*c*).

NIKOLSKY (1956) and BURDO (1960) showed that the maximum values of magnetic disturbances are characterized by spiral distributions. Fig. 4 gives spiral distributions of aurora appearance frequency in the zenith and maximum values of the Q index of magnetic activity for the winter season of 1957–58 in the northern and southern hemispheres. The comparison of the spiral distributions in aurorae and the magnetic activity shows that the magnetic disturbances at night hours coincide with the aurorae in the zone for night aurorae in space and time. Within the zone the maximum of the daily variations of the frequency of aurora appearance in the zenith exceeds the night maximum of magnetic activity (observing all the days). On magnetic-disturbed days at night hours the magnetic activity spiral in the northern hemisphere well agrees with the corresponding spiral of aurorae. The morning aurorae at the latitudes of the aurora oval zone ($\varphi' \sim 68–78°$) are only a little ahead of the corresponding magnetic disturbances. Thus, one

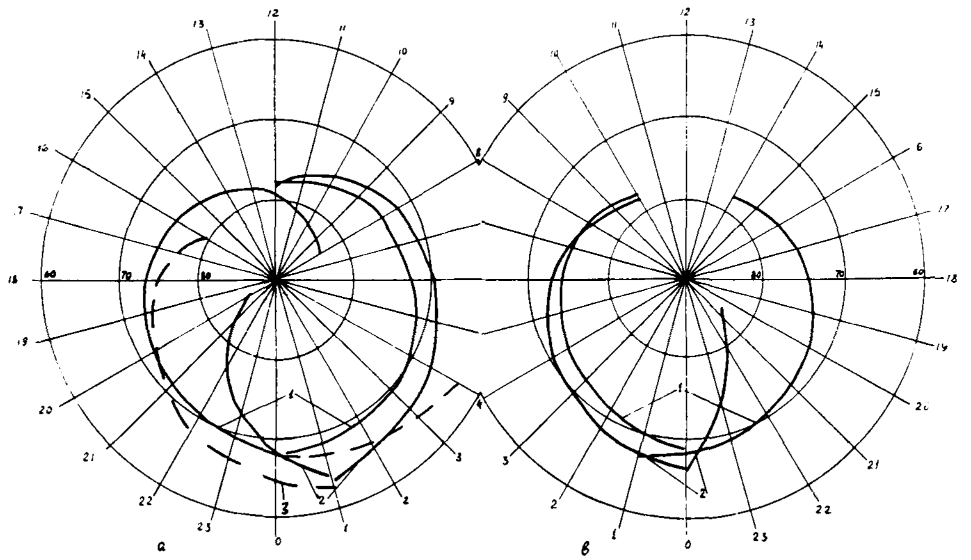

FIG. 4. The cuts of the spirals, characterizing the period of the largest frequency of aurora appearance in the zenith (1) and the maximum values of Q index of magnetic disturbance (2) by the observation through all the days (solid lines): *a*—the northern, *b*—the southern hemisphere. The dashed line shows a cut of the spiral at the evening hours for magnetic activity on magneto-disturbed days in the northern hemisphere. The coordinate system—the corrected geomagnetic latitude and the geomagnetic time.

can probably believe that in the region of the aurora oval zone the intrusion of corpuscular streams occurs near the spiral cuts, obtained according to the geomagnetic disturbance observations.

3. Orientation of auroral arcs and ionospheric-current system of geomagnetic disturbances

The treatment of aurora photos of high-latitudinal stations showed the presence of very noticeable daily variations in the aurora arc orientation. HULTQVIST (1962) gives a summary of the main-obtained results. The decrease of azimuth arcs from the evening to morning hours near the aurora zone in the northern hemisphere is considered from the point of view of ALFVEN's theory (1950). This theory quantitatively explains the character of daily variations; however, by applying this theory it is difficult to explain large values of daily variation amplitudes in arc azimuths and the increase of daily variation amplitudes with the latitude increase. FELDSTEIN (1960) and KHOROSHEVA (1962) explain daily variations in orientation of auroral arcs by the fact that aurorae are situated along the oval zone. The Earth rotating under the oval, the azimuths of the aurora stretched forms, observed at the zenith of the station at different moments of the local time, change. The azimuth variations are explained by the fact that the night cut of the spiral has larger azimuths than the morning one (Fig. 4). The stations, situated at the latitudes $\phi' < 68°$, approach the aurora oval zone at the nearest distance at near-midnight hours. Within the interval of the latitudes $68° \leqslant \phi' \leqslant 78°$ the station twice crosses the aurora oval zone. The *latitude is greater, the difference in time between* the station passing under the morning and night cuts of spirals is greater. Monotonous changes of azimuths along the cuts of spirals bring to the increase of daily variations amplitude with the increase of latitude. In the near-polar region ($\phi' \geqslant 79°$) the aurora oval zone approaches the station at the nearest distance at the near-midday hours. Proceeding from the mutual location of the observation point and the aurora oval zone it is natural to compare arc azimuths observed in reality with the azimuths of the aurora oval zone: at midnight hours at $\phi' < 68$, at morning and evening hours at $68 \leqslant \phi' \leqslant 78°$ and at near-midday hours at $\phi' > 79°$. Table 1 gives the azimuths of the

TABLE 1. *Azimuths of aurora arcs.*

No.	Stations	The azimuths of the aurora oval zone		Observed azimuths with the account of correction for a nondipole field	
		Morning hours	Night hours	Morning hours	Night hours
1.	Wiese	75	102	65	112
2.	Pyramida	72	104	65	108
3.	Baker-Lake	—	104	—	113
4.	Churchill	78	100	70	106
5.	Barrow	82	98	76	96
6.	Dixon		90		93
7.	Shmidt		90		89
8.	Fort Yukon		90		88
9.	College		90		89
10.	Tromsö		90		84
11.	Kiruna		90		95
12.	Farewell		90		96

aurora oval zone as well as the azimuths observed in reality with consideration of the correction for the non-dipole part of the geomagnetic field by HULTQVIST (1962). It follows from the table that to the south and at the latitudes of the aurora oval zone a good correspondence between the direction of aurora arcs and the azimuths of the aurora oval zone is observed. Consequently, the orientation of the aurora arcs and orientation variations during 24 hours at the latitudes up to $\phi' \sim 78°$ are well explained by the aurora location along the aurora oval zone. At the morning hours in passing from the morning cut of the spiral to the night one (Fig. 4) one should observe a jump in the arc azimuths. Such a jump was actually observed in Kiruna at 8 o'clock of the geomagnetic time (HULTQVIST, EGELAND & GUSTAFSSON, 1961*b*). The arc azimuths for the stations under the numbers 3–5, 8, 9, 12 are taken from DAVIS (1961), for the stations 1, 2, 6, 7 from FELDSTEIN (1960) and STARKOV & FELDSTEIN (1960), for the station 11 from HULTQVIST (1962) and for the station 10 from HARANG (1945). In the near-polar region daily variations in the orientation of aurora arcs differ from the daily variations observed at the oval zone latitudes. The IGY materials confirmed the rotation of aurora arcs in the nearpolar region at 360°, found for the first time by WEILL (1958). HULTQVIST (1962) noted a discrepancy of data by various authors dealing with this phenomenon. In the papers by WEILL (1958) and DENHOLM & BOND (1961) the azimuths were measured from the direction to the geographic pole, and in the paper by DAVIS (1960, 1961)—to the geomagnetic pole. However, the character of azimuth dependence on the local time remained the same in spite of the fact that the geographic and geomagnetic azimuths in high latitudes greatly differ. This discrepancy in fact is only seeming. Fig. 5 gives

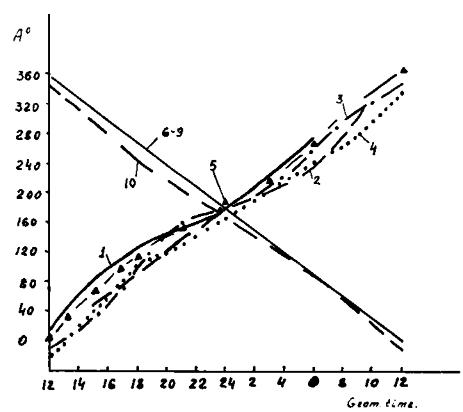

FIG. 5. The variations of arc azimuths and aurora bands at the stations of Resolute-Bay (1), Thule (2), Alert (3), by Davis (1961), SP-7 the season of 1957–58 (4), SP-7 the season of 1958–59 (5), Vostok (10) by Feldstein (1960), Wilkes, Dumon-D'Urville, Scott, Hallet (6–9) by Denholm and Bond (1961). The azimuths were measured to the east from the direction to the geomagnetic pole in the northern hemisphere. The time is geomagnetic.

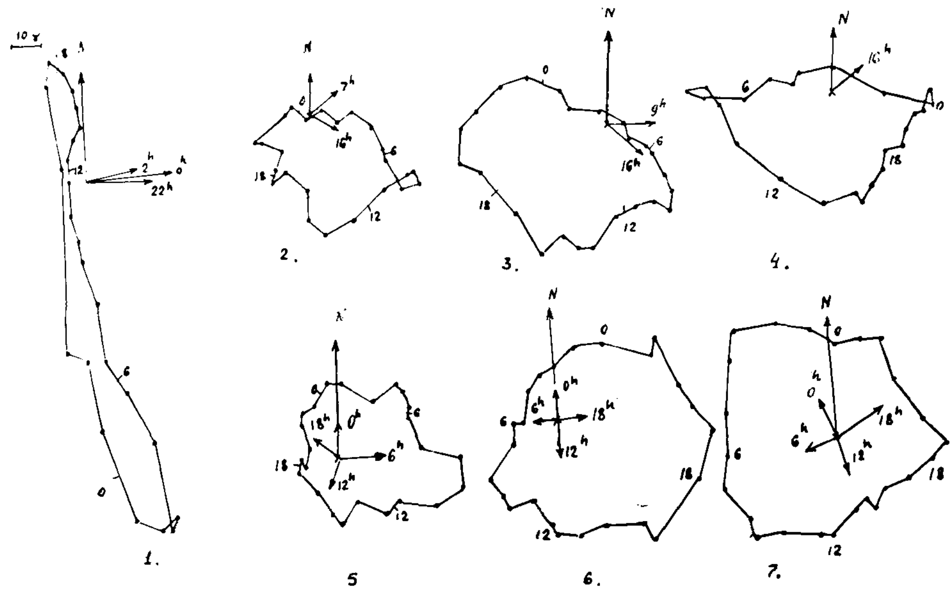

FIG. 6. The diagrams of daily variations of the direction and value of the disturbance vector in the horizontal plane. Daily variations at all the stations were calculated as a difference between all the days and the quiet ones. The arrow with the letter N shows the direction to the geomagnetic pole in the northern hemisphere, the arrows with the numeral at the ends show the azimuths of aurora arcs at the corresponding moments of the geomagnetic time. The figures in the diagrams—the hours of the geomagnetic time 1—College (I, II, XI XII—1957), 2—Baker-Lake (I, II, XI, XII—1958), 3—Murchison-Bay (XI, XII—1957, I, II—1958), 4—Mirny (V–VIII—1958), 5—Resolute-Bay (I, II, XI, XII—1958), 6—Scott (V–VII—1958), 7— Vostok (V–VIII—1958).

the graph of the variations of arc azimuths and aurora bands in the northern and southern hemispheres depending on the geomagnetic time. Both the measuring of the azimuths from the direction of the geomagnetic meridian and the usage of the geomagnetic time excludes discrepancy noticed by Hultqvist in the results of various authors. Fig. 5 shows that at the geomagnetic midnight and midday the aurora arcs and bands are orientated in the direction of the geomagnetic meridians. At the same time at midday hours the aurora oval zone crosses the midday meridian at an almost right angle. One can suppose that the mechanism, defining the arc orientation in the region of the aurora oval zone and within the zone, is probably different.

COLE (1960), DAVIS (1960, 1961) and FELDSTEIN (1960) made a supposition that the arc rotation at 360° in the near-polar region might be naturally connected with the character of the geomagnetic field variations in the near-polar region. In the near-polar region the projection of the vector of the magnetic field disturbance on the horizontal plane rotates along the circle with daily variations. This rotation is in the same direction as the rotation of the aurora arcs. Cole and Davis believe that the aurora location above the polar cap is the same as the location of ionospheric current system responsible for geomagnetic disturbances. Cole believes that the stretched forms of aurorae are visible current lines of the ionospheric current system of the geomagnetic disturbances. This opinion is confirmed by the fact that in the region of the zone for night aurorae the direction of the disturbance vector in the horizontal plane coincides with the perpendicular to the direction of the stretched forms of aurorae (DAVIS, 1961; SOBOUTI, 1961). However, in the near-polar region the angle between the arc direction and the vector of the geomagnetic field disturbance is only 30°–50° (the arc exceeds the vector of disturbance) and not 90°, as it should be in the case if Cole's hypothesis is correct (FELDSTEIN, 1960). These results are based on the comparison of aurora arc orientation at the drifting station SP-7 in the winter 1957–58 and the character of magnetic field variations in the near-polar region according to data obtained by CHAPMAN & BARTELS (1940).

This paper gives a more detailed comparison of arc and band orientation and the direction of the disturbed vector of the magnetic field for one and the same period of time.

Fig. 6 gives the vector diagrams of daily variations of direction and the value of the disturbance vector in the horizontal plane. The comparison of orientation of the disturbance vector and aurora arcs results in the following:

(*a*) In the region of the zone for night aurorae (Dixon, Tromsö, College, Halley Bay, Sodankyla) the direction of the disturbance vector makes the angle of about 90° with the directions of aurora arcs. The azimuth decreases a little during the night hours for the stations of the northern hemisphere (station College Fig. 6: *1*).

(*b*) In the near-polar region (Resolute-Bay, Thule, Scott, Dumont-D'Urville, Vostok) the field vector rotates clockwise in the northern hemisphere and counter-clockwise in the southern. This rotation in sign is analogous to the above-mentioned for the arcs and band of aurorae in the near-polar region. The field vector is not 90° with the direction of aurora arcs, but lags only somewhat behind the direction of aurora arcs in the northern and southern hemispheres (the stations of Resolute Bay, Scott, Vostok Fig. 6: *5*, *6*, *7*). The angle between the direction of the disturbance vector and the direction of the aurora arc changes at different hours of the day from 0° to 55° remaining for the near-polar stations mainly within 10°–30° and never makes an angle of 90°.

(*c*) At the latitudes where the aurora oval zone is situated at near-midday hours the character of variation of aurora arc orientation at night hours qualitatively differs from the character of variation of disturbance vector orientation. The disturbance vector rotates clockwise in the northern hemisphere, and counter-clockwise in the southern (the stations of Baker-Lake, Murchison-Bay, Mirny Fig. 6: *2*, *3*, *4*). At the same time the arc azimuths in this region decrease from the evening hours to the morning hours in the northern hemisphere and increase in the southern. Consequently, the variations of the arc azimuths and the disturbed vector of the geomagnetic field at night hours develop in the counterphase. At the evening and morning hours, when the aurora oval zone is situated above the station, the direction of the disturbed vector goes approximately perpendicular to the direction of the aurora arcs. In comparison to the direction of the disturbance vector with the direction of the aurora arcs at the station of Murchison-Bay the observations for the aurorae at the station Pyramida were used. At the observatory Mirny due to the coming of light time there is no observations for orientation of aurora arcs at before-midday hours, therefore Fig. 6 gives the preferable aurora location only at the evening hours when the oval zone is situated above Mirny.

A space coincidence of the current orientation in the ionosphere and of the stretched forms of aurorae in the region of the aurora oval zone and the absence of such a coincidence in the near-polar region may be explained by the fact that the magnetic disturbances in the near-polar region in the local winter season are mainly stipulated by electromagnetic processes in the aurora oval zone. The corpuscular intrusion in the upper layers of the atmosphere along the aurora oval zone causes aurora appearance at these latitudes and increases ionization. With the presence of winds or local electrical fields this brings about the ionospheric current system of geomagnetic disturbances, enveloping all the polar cap. The fact, that the processes at the latitudes of the aurora oval zone to a great extent stipulate the magnetic disturbances in winter in the near-polar region, results in the absence of a close connection between the aurora appearance in the zenith in this region and the local magnetic disturbance, defined by the indexes Q and K (FELDSTEIN, 1961*d*, 1962*b*; LASSEN, 1961).

The identity at the latitudes of the aurora oval zone and the difference in the near-polar region in the orientation of the current lines of the ionospheric current system and of the aurora stretched forms are noted on the planetary scale. Fig. 7*a* gives the mean orientation of auroral arcs for various local times. Smoothed orientations of auroral arcs are given by the dashed curves. Fig. 7*b* gives the direction and the value of the disturbance vector. The length of arrow presents in scale the absolute value of the disturbance vector in the horizontal plane, stipulated by the outer sources. The dashed

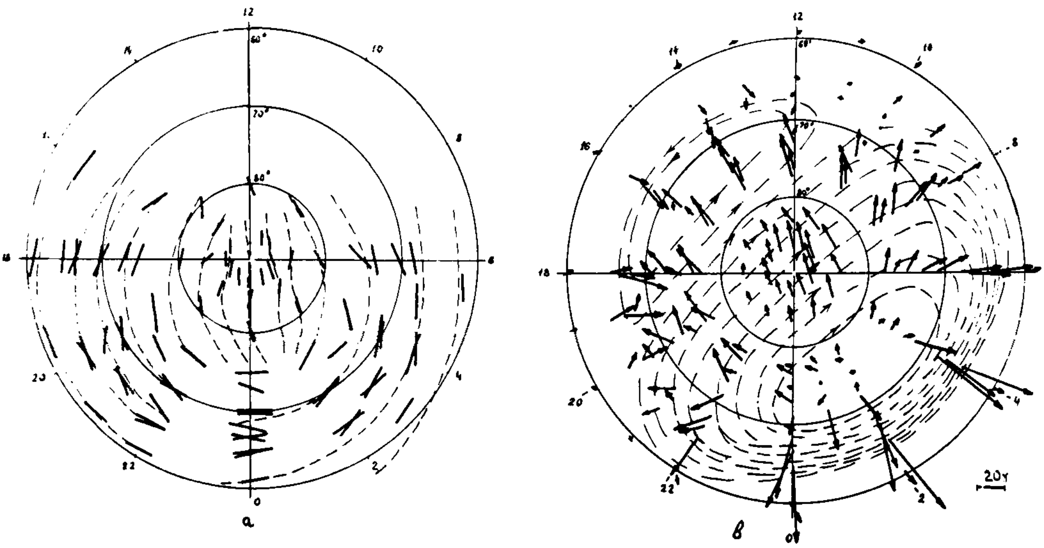

FIG. 7. (*a*) The mean location of aurorae in the northern hemisphere in the winter of 1957–58. There were used the observation results of the stations Thule, Resolute-Bay, Baker-Lake, Churchill, Barrow, Fort-Yukon, College, Farewell (by Davis, 1961), SP-7, Wiese, Dixon, Shmidt (by Feldstein, 1960), Tromsö (by Harang, 1945). (*b*) The direction and the value of the disturbance vector on all the days as difference from the quiet field in the horizontal plane for the winter season of the IGY. There were used the observation results of the stations Thule, Resolute-Bay, Godhavn, Murchison-Bay, Baker-Lake, Heiss, Chelyskin, Dixon, Tromsö, College, Lerwik. The coordinate system—the corrected geomagnetic latitude and the geomagnetic time by Hultqvist.

lines show current lines directed perpendicularly to the disturbance vector. Between the neighbouring current lines the current of 20,000 A flows. Comparison of Fig. 7*a* and 7*b* indicates that near the aurora zone the directions of current and aurora arcs are identical, in the near-polar region the angle being approximately 50°. Thus, the idea of the coincidence of the geometrical picture of aurora distribution and the current system in the near-polar region is in all probability untrue. In the near-polar region the mean direction of currents makes a large angle with the mean orientation of aurora arcs.

The aurora oval zone allows to explain a number of geophysical phenomena in high latitudes from a new point of view and namely to explain the distribution of the disturbance vector on the Earth's surface. The current system, given in Fig. 7*b*, consists of two current curls, which well agree in form and in location with the idealized current system by CHAPMAN (1935). For separate magnetic storms the current systems at definite moments of time were compiled by BENKOVA (1953), VESTINE (1940), FUKUSHIMA (1953), etc. They well agree with Chapman's system along the general lines. The distribution of the disturbance vector in the polar cap, given in Fig. 7*b*, may be interpreted by the current flowing in the western direction along the auroral oval zone. At the geomagnetic midnight the maximum of the current intensity is located at $\phi' \sim 65°$, at midday $\phi' \sim 76°$, at 18 o'clock $\phi' \sim 73°$, at 6 o'clock $\phi' \sim 66°$. The current flowing in the western direction brings to the decrease of the northern component of the geomagnetic field vector along the aurora oval zone. At midday hours at $\phi' \sim 76°$ the value of the disturbance vector is smaller than at midnight hours at $\phi' \sim 65°$. The current along the aurora oval zone is stipulated by the intrusion of corpuscular streams along the zone. The evening current curl, causing the increase of a horizontal component, is the consequence of the closing of part of the current flowing along the aurora oval zone in lower latitudes on the evening side. The currents in the near-polar region are also the consequence of the closing of part of current arising along the auroral oval zone from the evening to the morning side of the Earth through the near-polar region.

Conclusion

1. The southern boundary of aurora appearance in the zenith in the northern hemisphere corresponds in form to the zone for night aurorae. With the increase of the magnetic disturbance intensity the southern boundary of the aurora appearance in the zenith withdraws from the pole. During the solar activity cycle the location of the southern boundary changes a little.

2. The location of linear current responsible for the value and direction of the disturbed vector at night hours agrees well with the distribution of night aurorae. Daily values of Q index of magnetic activity reach the largest values at the latitudes of the night aurora zone. In the region of the oval zone of aurorae the intrusion of corpuscular streams into the upper layers of the atmosphere occurs near the spiral cuts, which were discovered from observations of the geomagnetic disturbances.

3. The variations of auroral arc azimuths from the evening to morning hours at the latitudes up to $\phi' \sim 78°$ are explained by the aurora location along the auroral oval zone. With the increase of the latitude the amplitude of daily variations also increases. The comparison of current orientation in the ionosphere, responsible for geomagnetic disturbances, and auroral arcs, showed that the orientation of currents and the stretched forms of aurorae in the region of the auroral oval zone is identical. In the near-polar region one does not observe this correspondence.

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