ionospheric level and what part is not by joining results of studies on relevant phenomena.

Martyn, D.F.: I think that the existence of the electrojets, equatorial and auroral, proves that at least a substantial part of the disturbance current-system flows in the ionosphere.

Smith, E.J.: In view of satellite data obtained by magnetometers on Vanguard III and Explorer VI, wouldn't you agree that there is one possible source of the primary storm field responsible for the main phase which can be eliminated from further consideration, *i.e.*, a current in or near the ionosphere?

Vestine, E. H.: In the auroral regions, electrojets flowing in the low ionosphere appear, and estimates made indicate that closure of current flow may occur in conducting layers more or less transverse to the geomagnetic field. The satellite measurements indicate ring-current sources as well. It seems therefore natural to regard these as often appearing together, but it is not clear than one should be regarded as primary and the other secondary.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part I

I-1-P3. On Auroral Isochasms and the Orientation of Auroral Arcs

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Published observational data concerning the configuration and location of the northern and southern aurorol zones are reviewed and are compared with circles projected from the geomagnetic equatorial plane, outside the earth, on to the earth's surface along the geomagnetic field lines (in an approximation which includes the five first terms of the spherical harmonic development). Other auroral distance parameters are also compared with these circle projections.

Very good agreement has been found for the northern hemisphere. More accurate data are still needed for those parts of the southern auroral zone which lie over the ocean at a great distance from the Antarctic continent. In the author's opinion it is highly probable that the northern and southern auroral zones are geomagnetically conjugated curves and that they correspond to projections of circles in the geomagnetic equatorial plane on to the earth's surface along the real geomagnetic field lines.

Regularities in the average direction of arcs and bands at a given time are discussed. The results of an investigation of the diurnal variation in the direction of quiet auroral arcs at Kiruna are presented, and the observational results are compared with Alfvén's theory.

It has been found that near the auroral zones the diurnal variation curve is similar to the theoretical curve of Alfvén. Of special interest is a "discontinuity" observed in the mornings at Kiruna.

§ 1. Introduction

There are good reasons for postulating circular symmetry, in the geomagnetic equatorial plane outside the earth's surface, of distance parameters representing statistical averages for corresponding variables of those processes, in and near the equatorial plane, which are associated with the occurrence of auroral phenomena in or near the two auroral zones. Only the dipole field affords a measurable contribution in the equatorial plane at a distance of several earth radii from the earth's surface, and the dipole field is circularly symmetric. Thus the configuration in the geomagnetic equatorial plane will not be influenced by the earth's rotation, provided minor effects of the different directions of the geomagnetic and the rotation axes are disregarded. The equatorial plane process will therefore be seen in the same distance range from all meridians on the earth. It follows that—if the processes in the equatorial plane and in the auroral zones are connected by the real magnetic field lines, as seems physically plausible — the only longitudinal dependence of *e.g.* the averages of a great many auroral locations observed at fixed points on the earth and equally distributed with regard to geomagnetic time, will be that introduced by the deviation of the earth's magnetic field from a dipole field. This deviation is appreciable at and near to the earth's surface.

According to this view the configuration in one hemisphere will correspond to the projection of the corresponding one in the other hemisphere along the geomagnetic field lines.

The only assumption made in the foregoing is that an electron or an ion moves from the equatorial plane to one of the auroral zones along a geomagnetic field line or on the surface defined by those field lines which cross the equatorial plane along one and the same circle and which contain the location of the particle in the equatorial plane. Such an assumption seems to be well founded. No other details of the actual physical processes are involved.

The projections of circles in the equatorial plane to the earth's surface along the real field lines, were calculated by Hultqvist (1958) for purposes of comparison with experimental isochasms.

Hultqvist (1958) traced the geomagnetic field lines from the geomagnetic equator plane outside the earth to their intersections with the earth's surface. A perturbation method was used consisting of integration along the dipole line of the deflection from dipole field line of the higher approximation line due to the effect of the second to the fifth terms in the spherical harmonic development of the earth's magnetic field. The calculations yielded deflection vectors for a large number of dipole lines. These gave the deflection for the point of intersection of the higher approximation field line—coinciding with the pertinent dipole line in the equatorial plane well outside the earth's surface—and the earth's surface from the corresponding point of intersection of the dipole line itself.

§ 2. Review of Observational Results Concerning the Locations of the Auroral Zones

The northern auroral zone delineation of Fritz (1881), and Vestine's (1944) modification of it are shown in Fig. 1 together with a zone determined by Feldstein (1960) on the basis of photographic recordings taken at 39 Arctic stations and visual observations made three sites during the International Geophysical Year, 1957–58.

While Fritz's auroral zone was based almost entirely on unsystematic auroral observations from several hundred years B. C. up to about 1878, Vestine had at his disposal more systematic observations, particularly those from the two polar years 1882–3 and 1932–3. Both delineations, however, are based on material obtained over very long periods of time with secularly changing geomagnetic fields, varying solar activity, partly unknown meteorological conditions, etc. In contrast, Feldstein's (1960) curve is based on observations made within two years with the use of a uniform technique at all stations. The auroral indices employed in his determination are more accurate than those previously used, and only the aurora in the zenith has been utilized.

It seems reasonable, therefore, to attribute greater physical significance to Feldstein's (1960) auroral zone. Although its exact polar distance is representative only for periods of high solar activity (*cf.* Sheret and Thomas, 1961), the configuration is probably valid for all levels of solar activity.

The greatest difference between Vestine's (1944) and Feldstein's (1960) northern auroral zones is in the region of Hudson Bay, in

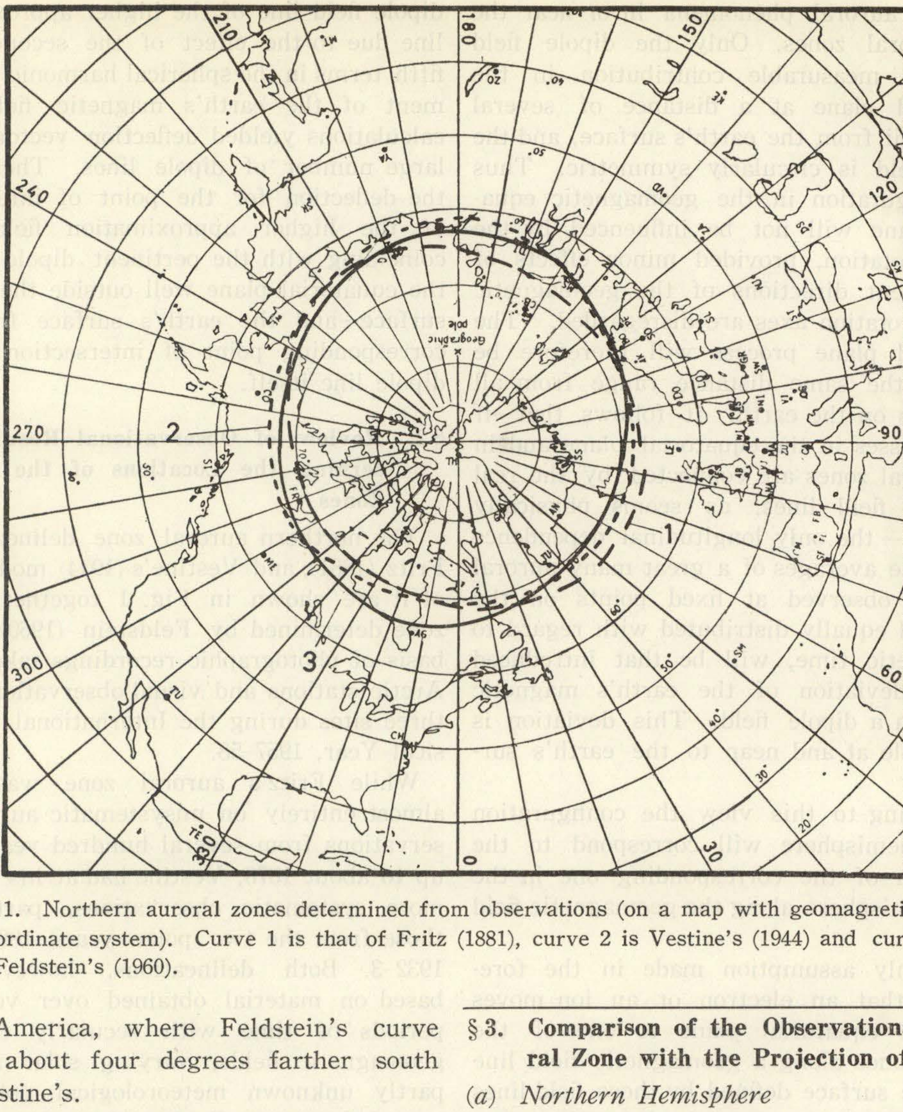

Fig. 1. Northern auroral zones determined from observations (on a map with geomagnetic coordinate system). Curve 1 is that of Fritz (1881), curve 2 is Vestine's (1944) and curve 3 Feldstein's (1960).

North America, where Feldstein's curve reaches about four degrees farther south than Vestine's.

The first important investigation of aurora in the southern hemisphere was conducted by Boller in 1898. White and Geddes (1939) estimated the location of the southern auroral zone on the basis of scattered visual observations of aurora australis, and Vestine and Snyder (1945) defined a zone based on geomagnetic observations in the Antarctic. These two zones are shown in Fig. 2 together with that of Bond and Jacka (1960) and Feldstein's (1960) International Geophysical Year zone. The IGY material used was taken at 20 stations on the Antarctic continent and at two stations on islands situated south of Australia. The technique employed in the evaluation was the same as that used in the Arctic.

§ 3. Comparison of the Observational Auroral Zone with the Projection of Circles

(a) *Northern Hemisphere*

Hultqvist (1958) pointed out that the experimental northern auroral zone of Vestine (1944) accorded well with the circle projections except over the North American continent, where the calculated curve extended about 4 degrees farther south than the observational one.

Some preliminary isochasms prepared by Gartlein (1959) on the basis of visual observations in North America during the International Geophysical Year agreed well with the computed circle projections (Hultqvist, 1959). It seemed probable, therefore, that Vestine's auroral zone required a correction for the Hudson Bay area.

These preliminary results are verified by the IGY data as presented by Feldstein

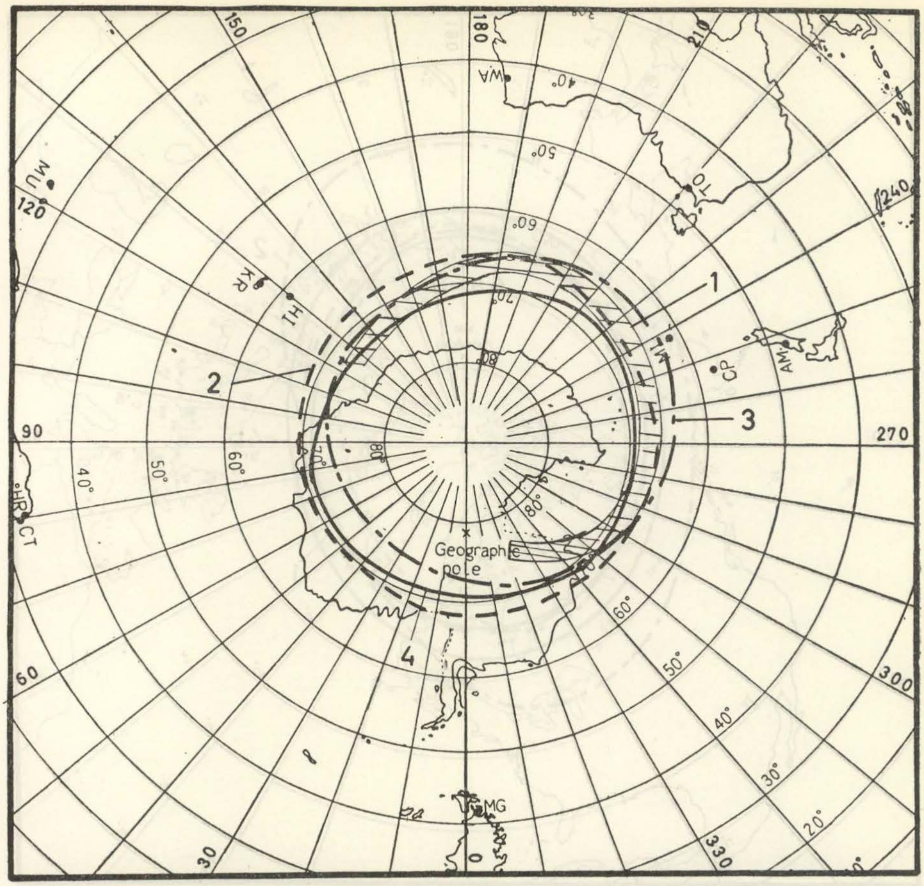

Fig. 2. Southern auroral zones determined from observations (on a map with geomagnetic co-ordinate system). Zone 1 is according to White and Geddes (1939), zone 2 to Vestine and Snyder (1945), zone 3 to Bond and Jacka (1960), and zone 4 to Feldstein (1960).

(1960). From Fig. 3 it is evident that the configurational agreement between the IGY northern auroral zone and the projections of circles is excellent. The maximal difference in latitude between Feldstein's zone and the projection which conforms best to it amounts to about one degree (in the region of Scandinavia).

Fig. 3 includes, for purposes of comparison, curves showing two other types of more or less theoretical auroral zones: the zone suggested by Gartlein and Sprague (1960) which is almost identical with the isocline 76 degrees, and Quenby and Webber's (1959) curve which was based on calculations of vertical cut-off rigidities for cosmic ray particles in the earth's magnetic field, and took into account both the dipole and the nondipole parts of the internal field. Neither of these two curves conforms as closely to observed data as do the circle projections.

Vestine and Sibley (1960) evaluated curves nearly identical with the circle projections discussed above by computing lines of constant integral invariant.

The very good agreement observed indicates that the precession of the geomagnetic axis around the geographic one has no major effects on the statistical parameter discussed.

(*b*) *Southern Hemisphere*

Feldstein's auroral zone in the southern hemisphere is shown in Fig. 4 together with the projections of the circles of radii 5.60 and 7.13 earth radii.

The experimental curve differs quite significantly from the computed ones. While it follows the course of the latter in the geomagnetic longitude range of 320°E–90°E, it is much nearer to the Antarctic continent for the rest of the longitude circle, where

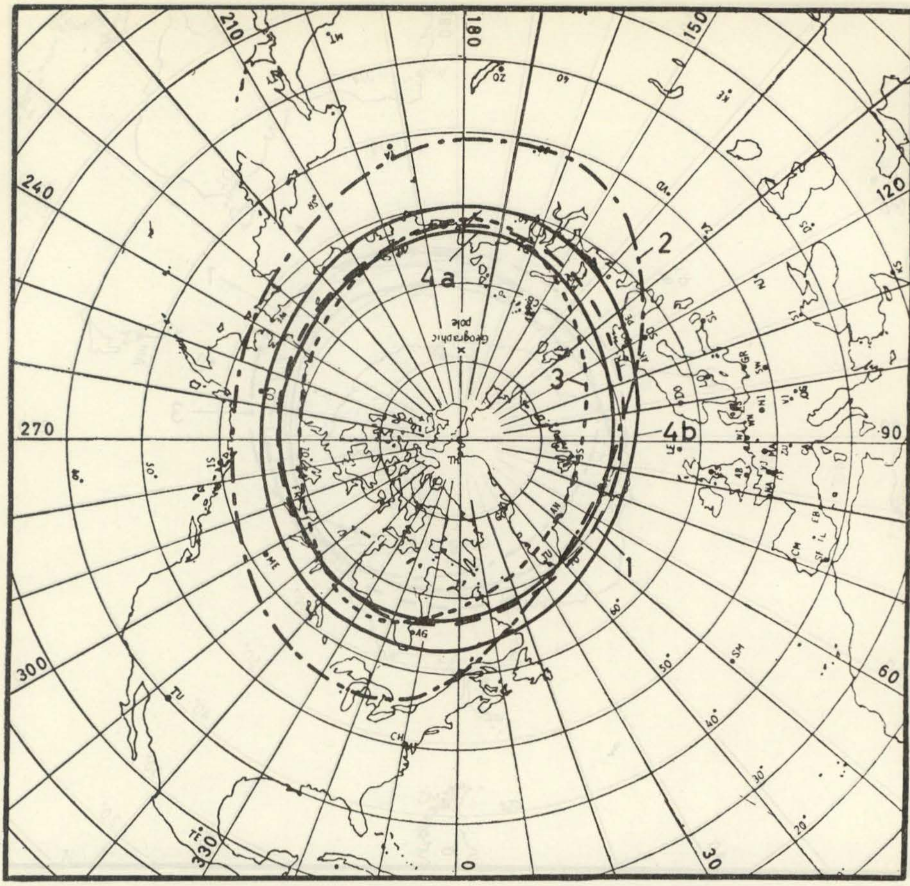

Fig. 3. Comparison of Feldstein's (1960) northern observational zone (curve 1) with a number of "theoretical" auroral zones: 2 is according to Gartlein and Sprague (1960), 3 to Quenby and Webber (1959), and 4a and b are projections of two circles in the geomagnetic equatorial plane (corresponding to colatitudes 22 and 25 degrees respectively; Hultqvist, 1958).

it is located over the sea.

The important question is whether the discrepancy between the IGY southern auroral zone and the projections of circles is a real one or attributable merely to inaccuracy of the observational data and/or of the computed curves.

The errors of data are certainly greater for the Antarctic than for the Arctic. As mentioned earlier, the computations of circle projections were based on Vestine *et al.*'s (1947) harmonic analysis of the geomagnetic field for epoch 1945, when the southern hemisphere data were very sparse. Although this fact may partially account for the discrepancy, it seems unlikely that the six latitude degrees difference over the sea is primarily attributable to errors in the harmonic analysis of the geomagnetic field.

All observational stations in the discrepant region are situated on or close to the coast of the Antarctic continent far inside the auroral zone. This means in effect that the aurorae occurring in the auroral zone are visible from these stations at a low elevation, a circumstance which implies considerable error in the observational results.

Indeed, since publication of Feldstein's paper, Bond and Jacka (1960) have communicated a report in which they note that the latitude of the auroral zone in the region of Macquarie Island south of Australia (point 15 on Fig. 4), is only one or two degrees less than that of the station. A small part of their auroral zone—the one near Macquarie Island—is shown in Fig. 4 as curve No. 2. Taking this and the above-mentioned considerations into account, it would appear

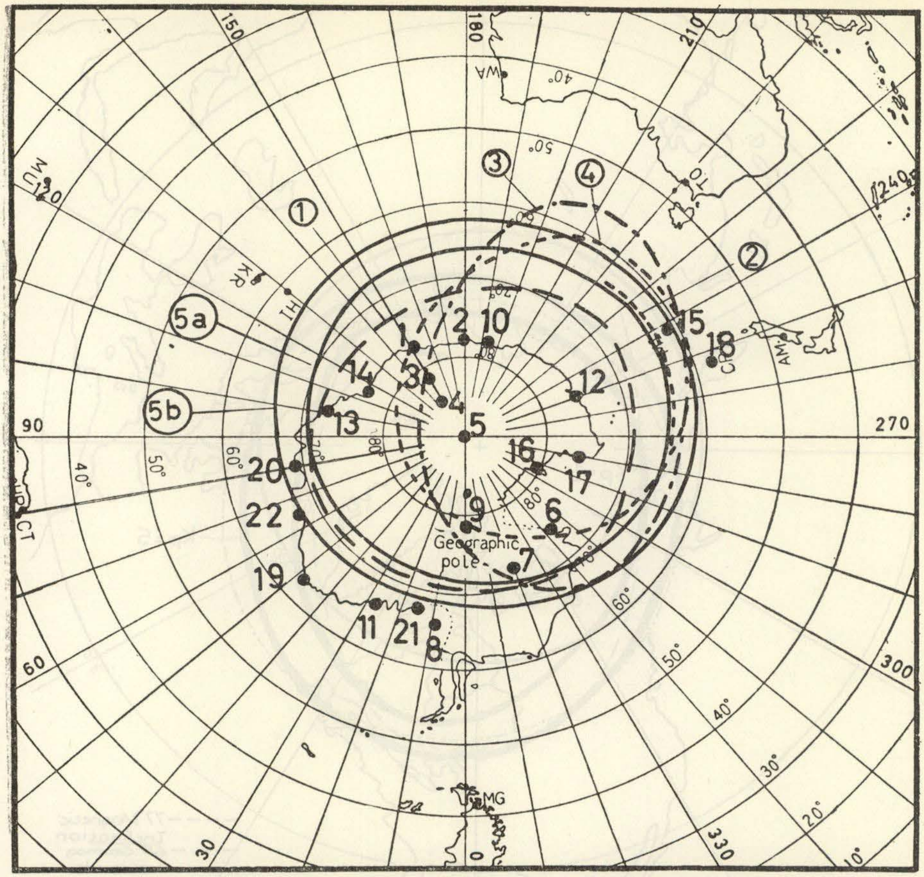

Fig. 4. Comparison of Feldstein's (1960) southern observational zone (curve 1) and that of Bond and Jacka (1960) (curve 2) with different "theoretical" auroral zones: 3 is according to Gartlein and Sprague (1960), 4 to Quenby and Webber (1959), and 5a and b are projections of two circles in the geomagnetic equatorial plane (corresponding to colatitudes 22 and 25 degrees, respectively; Hultqvist, 1958). The numbered points show the approximate locations of the stations at which the IGY observational material—the basis of Feldstein's auroral zone—was collected. The numbering is that of Feldstein (1960).

that the auroral zone is fairly consistent with the computed curves, with which it shows agreement over the Antarctic continent. This seems so much the more plausible in view of the close accord between observed auroral zone and circle projections for the northern hemisphere. Indeed it would be surprising if the two hemispheres showed entirely different degrees of agreement between the two types of curves. Fig. 4 contains two other theoretical auroral zones corresponding to the northern hemisphere zones of Gartlein and Sprague (1960) and of Quenby and Webber (1959).

§ 4. Other Evidence of Circular Symmetry in the Geomagnetic Equatorial Plane

Hitherto it is only the observed in relation to the computed form and location of auroral zones that have been discussed. There are, however, other statistical parameters which, according to the considerations in the introduction, should show circular symmetry. One is the average southern extent of the aurora at a definite degree of magnetic disturbance. Such curves have been evaluated by Gartlein, Gartlein and Sprague (1960). They can be studied in Fig. 5. On close examination the curves are seen to coincide almost exactly with circle projections.

In the author's opinion it is highly probable that the northern and southern auroral zones are geomagnetically conjugated curves and are projections of circles in the geomagnetic equatorial plane on to the earth's surface along the real geomagnetic field lines.

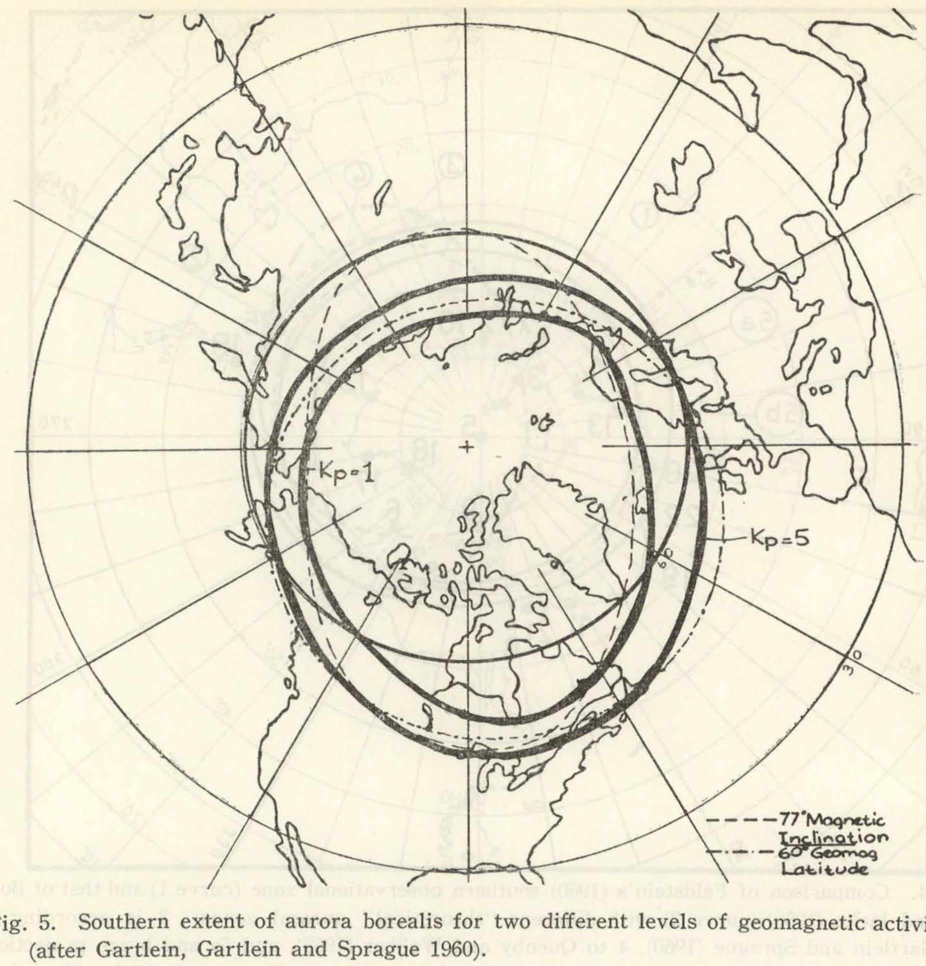

Fig. 5. Southern extent of aurora borealis for two different levels of geomagnetic activity (after Gartlein, Gartlein and Sprague 1960).

In the southern hemisphere more accurate data are still required for those parts of the zone which lie over the ocean.

§ 5. Regularities in the Average Direction of Auroral Arcs

As mentioned in the introduction, considerable data on the average directions of auroral arcs have been obtained by averaging all available determinations irrespective of the time of night to which they are referable. Differences between investigators as respects the observation time scheme are undoubtedly reflected in the results due to the existence of a diurnal variation in the direction, which will be discussed.

A fairly extensive collection of such data is contained in Fig. 6. Also included are a number of computed projections of circles in the equatorial plane on to the earth's surface along the geomagnetic field lines (*cf.* Hultqvist, 1958).

Despite the above-mentioned reservations concerning the observational material, it is evident from Fig. 6 that, in general, the alignment of the arcs conforms to the direction of the relevant circle projection quite closely, and that the agreement with the circle projections is better than with the geomagnetic latitude circles.

For instance it has been verified experimentally that on the eastern and western coasts of Greenland the observed average azimuths deviate in opposite directions from 90 degrees, as to the azimuths of the circle projections.

The available observational results for the southern hemisphere are of course relatively exiguous. A collection of IGY and subsequent data is contained in Fig. 7. The arrows indicate results of observations of directions, as sighted to the auroral point

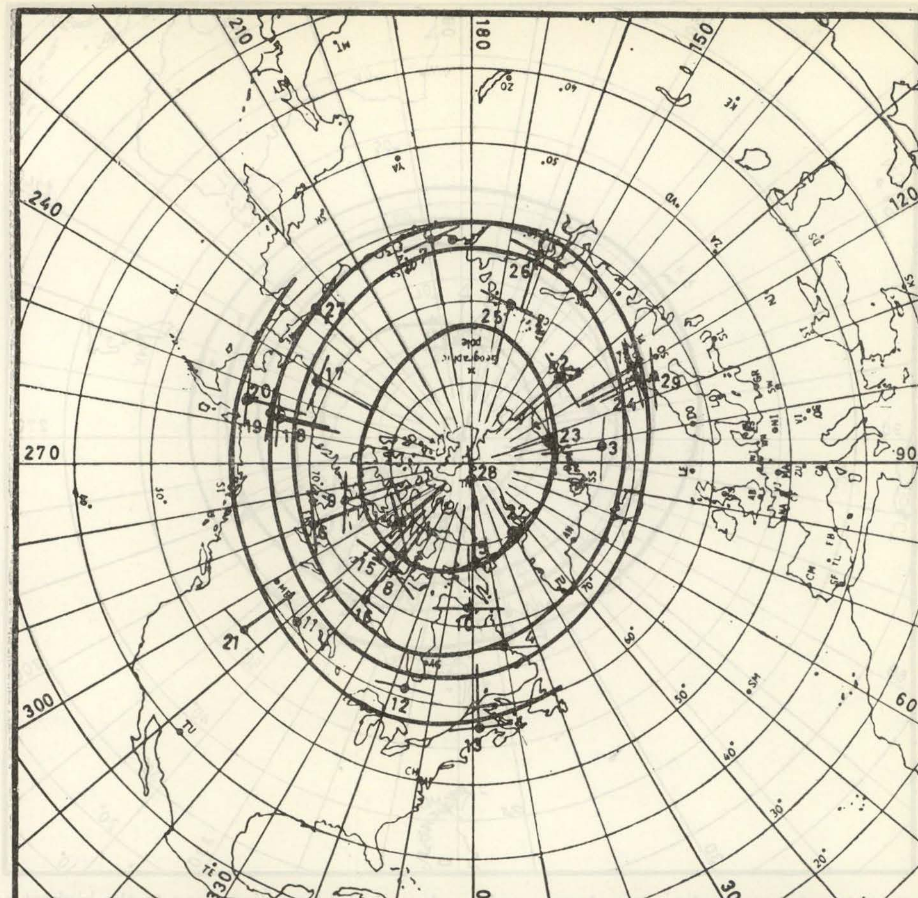

Fig. 6. Directions of quiet auroral arcs and bands in the northern hemisphere. 1. Haldde and Bossekop; 2. Cap Thordsen; 3. Jan Mayen; 4. Nain; 5. Kingua Fjord; 6. Fort Rae; 7. Sagastyr—(the data for points 1-7 are after Vegard and Krogness, 1920)—; 8. Chesterfield; 9. Coppermine; 10. Cape Hope's Advance; 11. Saskatoon; 12. Coral Rapids; 13. Aroostook; 14. Gjöahavn—(the data for points 8-14 are taken from Currie and Jones, 1941; the dotted lines at Chesterfield and Coppermine refer to all types of aurora)—; 15. Baker Lake; 16. Churchill; 17. Barrow; 18. Fort Yukon; 19. College; 20. Farewell; 21. Choteau—(the data for points 15-21 are taken from Davis; 1961; the values are averages for the hour around geomagnetic midnight)—; 22. Godhavn (the data are after Lassen, 1959, and refer to the early morning hours); 23. the region of Micardbu (approximate data after Störmer, 1944); 24. Tromsö (the data are after Harang, 1945, and refer to geomagnetic midnight); 25. Wiese; 26. Dixon; 27. Cape Schmidt—(data for points 25-27 are after Feldstein, 1960, and refer to local midnight); 28. Thule (data of Harang, taken from Störmer, 1955); 29. Kiruna (refers to geomagnetic midnight). The map has a geomagnetic coordinate system.

of highest elevation. Two arrows for any single station represent the results of observations during each of the two years 1957 and 1958. The differences in direction of the arrows for the two years demonstrate the uncertainty of the results.

As will be seen from Fig. 7, the agreement between observed directions with those of the projected equator plane circles is fairly good for all places except Byrd (No. 9), and the agreement is certainly better than for the geomagnetic latitude circles.

Because of the existence of a pronounced diurnal variation in the orientation of the auroral arcs as discussed earlier, increased accord between the directions of the arcs and of the circle projections is to be expected if values for a short period (*e.g.* one hour)

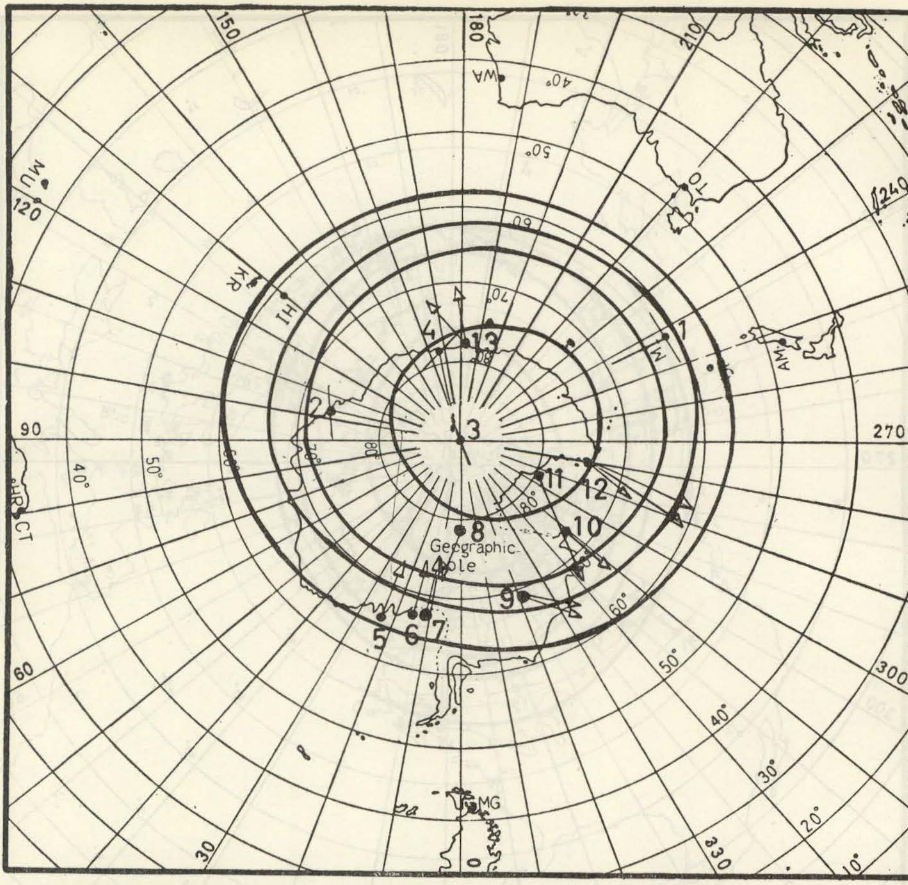

Fig. 7. Directions of quiet auroral arcs and bands and sighting directions to the highest points of quiet arcs and bands (arrows) in the southern hemisphere. 1. Macquarie Island; 2. Mawson (data taken from Bond and Jacka, 1960); 3. Vostok; 4. Oasis (the data, after Feldstein, 1960, refer to local midnight); 5. Halley Bay; 6. Shackleton (data from Evans and Thomas, 1959); 7. Ellsworth; 8. South Pole; 9. Byrd; 10. Little America; 12. Hallett (short arrow); 13. Wilkes—(the data for points 7-13 are from Gartlein, Nack and Sprague, 1960; the two arrows at points 9 and 13 show the average directions for the two years 1957 and 1958, the 1957 arrow being the one nearest the meridian at both points); 11. Scott Base (the long arrows at points 11 and 12 are after Hatherton and Salmon, 1959). The map has a geomagnetic coordinate system.

of the night are compared. The results of such a comparison for local midnight at 12 stations, most of them in or near the northern auroral zone, are presented in Table I and Fig. 8. A comparison with Fig. 6 clearly shows that the concordance of the arc directions with the circle projections is better for the selected material of Fig. 8 than for the unselected values of Fig. 6.

§ 6. Observations of Diurnal Variation in the Orientation of Quiet Auroral Arcs at Kiruna

Although it was evident from the observations of Bravais at Bossekop in northern Norway as early as 1838-40 that the directions of the arcs and bands show a diurnal variation, very little attention was paid to this phenomenon until the nineteen-thirties (Vegard, 1939; Harang 1945), and even now only few studies exist. It was stated as recently as 1953 that no diurnal variation exists (Jensen and Currie, 1953). From all-sky-camera recordings taken at Kiruna Geophysical Observatory in the period December 1958 to March 1961, the directions of 366 quiet auroral arcs were estimated.

The result of the alignment investigations

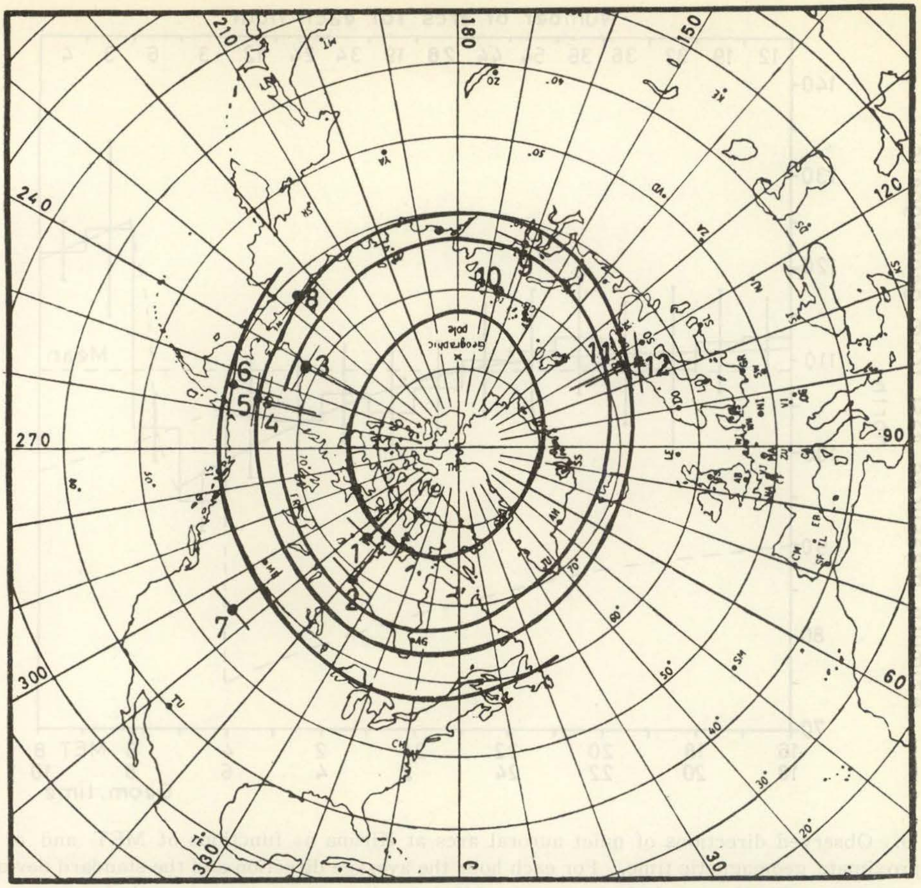

Fig. 8. Directions of quiet auroral arcs and bands at local midnight in the northern hemisphere. 1. Baker Lake; 2. Churchill; 3. Barrow; 4. Fort Yukon; 5. College; 6. Farewell; 7. Choteau —(data for points 1-7 taken from Davis, 1961)—; 8. Cape Schmidt; 9. Dixon; 10. Wiese (data taken from Feldstein, 1960); 11. Tromsö (after Harang, 1945); 12. Kiruna. The map has a geomagnetic coordinate system.

is shown in Fig. 9.

For each hour of MET the average direction and the standard deviation were computed, for which procedure the direction value of each arc was weighted with the arc's duration.

At the top of Fig. 9 is shown the number of arcs used for each hour. The number is maximal around geomagnetic midnight. In the morning hours the aurora is usually unsuitable for direction determination—as a rule, it is diffuse and situated far to the north. It is therefore not astonishing that the observational material is smallest for that part of the night.

The observational material, while not extensive for the interval 0400–0800 MET, suffices to demonstrate that the very rapid increase of the azimuth occurring between 05 and 06 MET is certainly significant.

The azimuth change in the morning is so rapid as to resemble a discontinuity of the type predicted by the Alfvén theory (*cf.* Alfvén, 1950). No such marked " discontinuity " has, to the author's knowledge, been observed before. Lassen (1959) found at Godhavn a rapid change in direction at approximately the same local time, but the amplitude of the change was lower (20 degrees as compared to 30 degrees in Kiruna).

In fact, the " discontinuity " can probably be observed only in longitudes where geomagnetic time runs ahead of local time, since daylight will preclude auroral observations until 8 or 10 o'clock geomagnetic time in other longitudes.

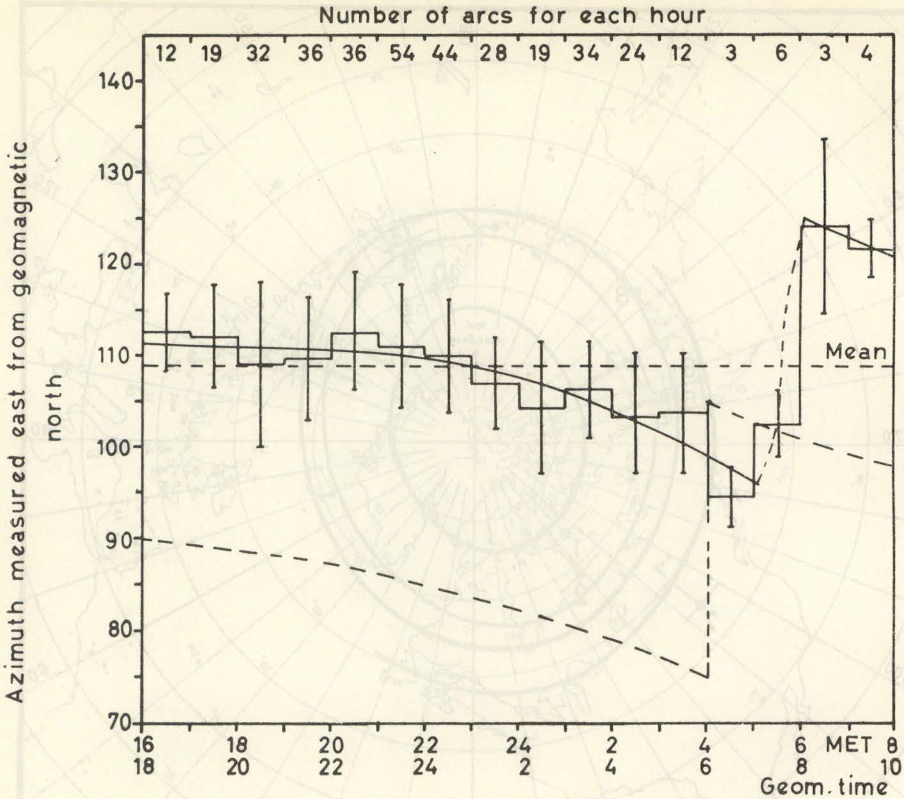

Fig. 9. Observed directions of quiet auroral arcs at Kiruna as functions of MET and of approximate geomagnetic time. For each hour the average direction and the standard deviation are given. The lower, dashed curve is Alfvén's theoretical diurnal variation curve (*cf.* Alfvén, 1950).

In order to ascertain the degree to which the differences between the observational and theoretical curves in Fig. 9 could be attributed to referral of the direction to the geomagnetic meridian, *i. e.* to overlooking of the effect of the non-dipole part of the geomagnetic field, a correction was made for this factor. The direction, instead of being referred to the geomagnetic meridian, was referred to the perpendicular to the projection of circles in the geomagnetic equatorial plane on to the earth's surface along higher approximation geomagnetic field lines, as calculated by Hultqvist (1958). By changing the time scale to the geomagnetic one, the Kiruna curves of Fig. 10 were obtained. This figure also shows transformed diurnal variation curves for a number of other stations near the northern auroral zone.

The "discontinuity" observed at Kiruna has the same amplitude as that on the theoretical curve but is displaced about one and a half hours in the positive time direction.

The broad experimental picture accords remarkably well with the theoretical one, considering the very simple model on which the latter is based.

From the observed diurnal variation curves of Fig. 10 the auroral curve — corrected for the effects of the non-dipole part of the geomagnetic field — corresponding to Alfvén's theoretical *I* curve can be evaluated by integration.

From the Kiruna diurnal variation curve of Fig. 10 the *I* curve of Fig. 11 has been derived. The whole curve, as will be seen, is situated outside the circle with which it coincides at 1800, in contrast to the theoretical curve, which is inside the circle. The difference between the experimental and theoretical curves varies between 7 and 9 degrees, which means that the theoretical curve is situated outside the standard deviation "region" of the observational material.

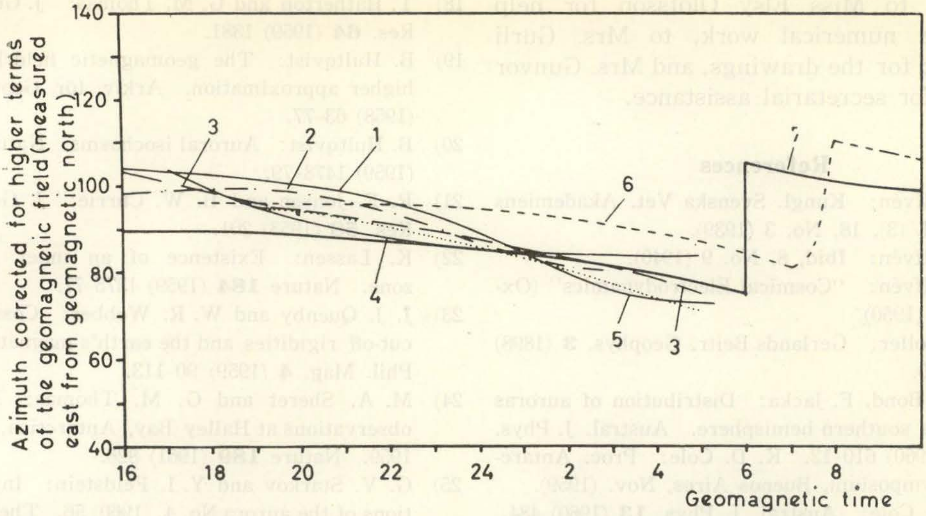

Fig. 10. Observed diurnal variation curves (smoothed) for the direction of quiet arcs and bands, corrected for the non-dipole part of the geomagnetic field, given as a function of geomagnetic time for a number of stations situated in or near the northern auraral zone. 1. Barrow (geom. lat. 67°); 2. Fort Yukon (geom. lat. 67°); 3. College (geom. lat. 65°); 4. Farewell (geom. lat. 61°)—(curves 1-4 are based on data taken from Davis, 1961)—; 5. Cape Schmidt (geom. lat. 63°; based on a curve presented by Feldstein, 1960); 6. Kiruna (geom. lat. 65°); 7. Alfvén's theoretical diurnal variation curve (*cf.* e.g. Alfvén, 1950).

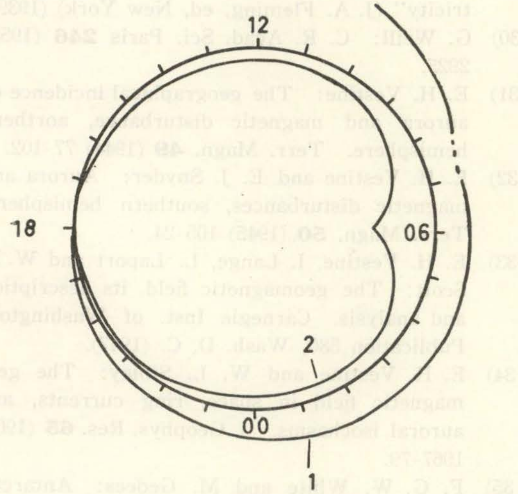

Fig. 11. Curve 1 is the auroral zone corresponding to Alfvén's I curve, evaluated from the Kiruna curve of Fig. 1 for diurnal variation in the orientation of quiet auroral arcs. It is corrected for the non-dipole part of the geomagnetic field. Curve 2 is Alfvén's theoretical I curve, (*cf.* e.g. Alfvén, 1950).

Therefore the difference is most probably a real one, which is not surprising in view of the fact that the theoretical curve is based on a highly idealized model.

Fig. 11 shows that the experimental *I* curve is not symmetric with regard to the line 18–06 but is elongated on the day side, over most of which it has, of course, not been determinable.

Very high amplitudes of the diurnal variations have been found for high latitude stations (cf. *e.g.* Davis, 1961). This cannot be explained by the Alfvén theory, according to which the greatest deviation of the arc azimuth from 90 degrees should be at 0600 geomagnetic time, where the *I* curve has a singular point. The theoretical azimuth is almost independent of geomagnetic latitude. It varies from 75 to 76 degrees when the latitude varies from about 65 to more than 80 degrees.

Thus it may appear that the mechanisms determining the alignment of arcs in and near the auroral zones correspond to those postulated by Alfvén, but there seems to be some difficulties for this theory to account for the phenomena over the polar caps.

Acknowledgement

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References

1) H. Alfvén: Kungl. Svenska Vet. Akademiens Handl. (3), 18, No. 3 (1939).
2) H. Alfvén: Ibid, 8, No. 9 (1940).
3) H. Alfvén: "Cosmical Electrodynamics" (Oxford) (1950).
4) W. Boller: Gerlands Beitr. Geophys. **3** (1898) 56,550.
5) F. R. Bond, F. Jacka: Distribution of auroras in the southern hemisphere. Austral. J. Phys. **13** (1960) 610-12. K. D. Cole: Proc. Antarctic Symposium, Buenos Aires, Nov. (1959).
6) K. D. Cole: Austral. J. Phys. **13** (1960) 484.
7) B. W. Currie and C. K. Jones: Terr. Magn. **46** (1941) 269.
8) T. N. Davis: J. Geophys. Res. **65** (1960) 3497.
9) T. N. Davis: Geophysical Institute, College, Scient. Report No. 1, NSF Grant No. G. 14782 (1961).
10) J. V. Denholm, F. R. Bond: Austral. J. Phys. **14** (1961) 1.
11) S. Evans and G. M. Thomas: J. Ghophys. Res. **64** (1959) 1381.
12) Y. I. Feldstein: Geographical distribution of aurora and azimuth of auroral arcs. Investigations of the aurora, The Academy of Sciences of the USSR, Moscow No. 4, (1960) 61-78.
13) H. Fritz: Das Polarlicht. Leipzig (F. A. Brockhaus) (1881).
14) C. W. Gartlein, B. Nack and G. Sprague: IGY WDC, A, U. S. National Acad. of Sci. IGY General Report No. 12, (1960) 38.
15) C. W. Gartlein, H. E. Gartlein and G. Sprague: The aurora and the local magnetic field. IGY WDC A, U.S. National Academy of Sciences, IGY General Report No. 12, (1960) 57-67.
16) C. W. Gartlein and G. Sprague: Auroral occurrence. IGY WDC A, U.S. National Academy of Sciences, IGY General Report No. 12, (1960) 68-73.
17) L. Harang: Terr. Magn. **50** (1945) 297.
18) T. Hatherton and G. M. Thomas: J. Geophys. Res. **64** (1959) 1381.
19) B. Hultqvist: The geomagnetic field lines in higher approximation. Arkiv för Geofysik **3** (1958) 63-77.
20) B. Hultqvist: Auroral isochasms. Nature **187** (1959) 1478-79.
21) R. E. Jonsen and B. W. Currie: J. Geophys. Res. **58** (1953) 201.
22) K. Lassen: Existence of an inner auroral zone. Nature **184** (1959) 1375-77.
23) J. J. Quenby and W. R. Webber: Cosmic ray cut-off rigidities and the earth's magnetic field. Phil. Mag. **4** (1959) 90-113.
24) M. A. Sheret and G. M. Thomas: Auroral observations at Halley Bay, Antarctica, during 1959. Nature **189** (1961) 826.
25) G. V. Starkov and Y. I. Feldstein: Investigations of the aurora No. 4, (1960) 56. The Academy of Sciences of the USSR, Moscow.
26) C. Störmer: Geofysiske Publikasjoner XII, No. 13 (1944).
27) C. Störmer: "The Polar Aurora" (Oxford) (1955).
28) L. Vegard and O. Krogness: Geofysiske Publikasjoner I, No. 1 (1920).
29) L. Vegard: "Terrestrial Magnetism and Electricity" (J. A. Fleming, ed, New York) (1939).
30) G. Weill: C. R. Acad. Sci. Paris **246** (1958) 2925.
31) E. H. Vestine: The geographical incidence of aurora and magnetic disturbance, northern hemisphere. Terr. Magn. **49** (1944) 77-102.
32) E. H. Vestine and E. J. Snyder: Aurora and magnetic disturbances, southern hemisphere. Terr. Magn. **50** (1945) 105-24.
33) E. H. Vestine, I. Lange, L. Laport and W. E. Scott: The geomagnetic field, its description and analysis. Carnegie Inst. of Washington, Publication 580, Wash. D. C. (1947).
34) E. H. Vestine and W. L. Sibley: The geomagnetic field in space, ring currents, and auroral isochasms. J. Geophys. Res. **65** (1960) 1967-79.
35) F. G. W. White and M. Gedees: Antarctic zone of maximum auroral frequency. Terr. Magn. **44** (1939) 367-77.

Discussion

Nagata, T.: It makes me rather surprised to see that you have got so good agreement even in detail between southern auroral zone and your theoretical one which is based on the existing analysis of the earth's magnetic field. Because the real geomagnetic field in the southern hemisphere, especially around Antarctic, is much different from that known in the existing charts. It is about 3% less than the published value.

Hultqvist, B.: The only estimations of the accuracy of the circle projections I have obtained from comparing the coefficients of Vestine's analysis for epoch 1945 with those of the earlier analysis. From such a comparison would expect the circle projections to be correct in latitude within a few degrees.

Hines, C.O.: Does Dr. Hultqvist not accept observations of the type reported by Davis, or is he simply saying he has not had time to consider them relative to his description? In particular, does not the observation of Sun-Earth aligned arcs over the polar cap differ from Hultqvist's conclusions and theory?

Hultqvist: The situation over the polar caps is far from clear. There are a number of inconsistencies between different investigators. I have not claimd to give any theory for the processes determining each single configuration in the equator plane or at the earth's surface, but has only shown that a several parameter representing statistical averages for the physical processes are circularly symmetric in the geomagnetic equatorial plane.

Cole, K.D.: Dr. Hultqvist's thesis is basically one of axial symmetry (about the magnetic axis). This is a geometrical thesis. It seems that symmetry about the magnetic equator would have more physical significance. This latter approach would link magnetic-disturbance current-systems in the ionosphere with aurora in the manner suggested by their association. Geomagnetic disturbance reported by Fukushima at this Conference indicates equatorial symmetry.

Hultqvist: What I have tried to show is that there is circular symmetry in the geomagnetic meridian plane for such distance parameters which are statistical averages for the processes in the equator plane associated with the occurrence of aurora and magnetic storms at the earth's surface. No details has been assumed concerning the physical processes other than that the electrons and the ions follow the magnetic field lines from the equator plane through the surface. I have in no way excluded possible symmetry with regard to the equator plane, and the single configuration in the equator plane may very well differ from that of the arc of a circle. The circular symmetry is found in averaging over a large many cases.

Chamberlain, J.W.: I think the most immediate application of this type of analysis of isoauroras is to indicate whether aurora results from direct entry of particles, (in the manner suggested by Alfvén or Martyn) or from leakage of geomagnetically trapped radiation. In the former case one would expect Dr. Hultqvist's analysis to predict the isoauroras. In the case of trapped particles, the application of the second adiabatic invariant by Vestine and Sibley should predict them. In fast, both analyses give an adequate representation of the observations. My question is this: Is the agreement between the predictions fortuitous, or should we have anticipated it *a priori* because of heavy weighting of the equatorial field in the second adiabatic invariant?

Hultqvist: Firstly, I have only been discussing statistical averages over a large many processes and not each single configuration in the equator plane which may very well differ considerably from the form of an arc of a circle. Secondly, I believe that the surface of constant adiabatic invariant intersects the equator plane along a curve which is a circle within the limits of accuracy of observation and analysis.

Dungey, J.W.: Does not Dr. Davis' analysis give the detail required for discussion of the physical processes?