THE SOUTHERN AURORAL ZONE AS DEFINED BY THE POSITION OF HOMOGENEOUS ARCS

By F. JACKA*

[*Manuscript received December* 4, 1952]

Summary

Observations on homogeneous arcs (H.A.) made at Macquarie Island (geomagnetic coordinates 60·7 °S., 243·1 °E.) are examined. The latitude of H.A. is found to be significantly dependent on the geomagnetic planetary disturbance index K_p and the time of day. For given values of K_p and time the probability distribution of latitude of H.A. has a sharply defined mode about 0·5° north of the mean.

I. INTRODUCTION

The main features of the frequency distribution of geographic position of auroras in the northern hemisphere are well known from the work of Fritz (1881) and Vestine (1944). The first comprehensive study of this distribution in the southern hemisphere was made by White and Geddes (1939) who found the zone of maximum frequency of occurrence to be roughly circular with a radius 18° about a point (75 °S., 129 °E.) near the magnetic axis pole. Vestine and Snyder (1945), from an analysis of the disturbance daily variation (S_D) of the Earth's magnetic field and comparison with northern hemisphere observations, estimated the positions of the zone of maximum frequency and other isochasms (lines of equal frequency of occurrence of auroras). Their estimates show only very rough agreement with the observed frequencies of occurrence of auroras up to that time (cf. Fig. 1). In all of these studies the data were taken from various periods in the sunspot cycle, and the auroral observations referred to auroras of all forms.

In the present paper attention is confined to just one type of aurora, viz. homogeneous arcs (H.A.) (see Atlas of Auroral Forms 1930), and the latitude of the southern auroral zone as defined by the most frequent position of H.A. on the 243 °E. geomagnetic meridian is determined by an examination of the records of 211 H.A. observed by Parsons and Fenton (1953) at the Australian National Antarctic Research Expedition Station at Macquarie Island during the period May 1950 to April 1951. The geographic coordinates of Macquarie Island are 54° 29′ S., 158° 58′ E., the geomagnetic coordinates being 60·7° S., 243·1° E. The data used are the observers' estimates of the elevation above the southern horizon of the apex of the lower border of the H.A., the fraction in eighths of the sky which was cloud covered, the hour (G.M.T.) during which the observation was made, and the value to the nearest integer of K_p (geomagnetic planetary disturbance index) associated with the 3-hr. period including the hour of observation.

* Antarctic Division, Department of External Affairs, Melbourne.

The observations on H.A. were selected for the following reasons :

(1) The orientation and simple shape of H.A. permit of fairly accurate visual estimation of the elevation of the apex of the lower border which was in all cases approximately in the magnetic meridian plane. The observers consider that errors of more than 5° in these estimates are rare.

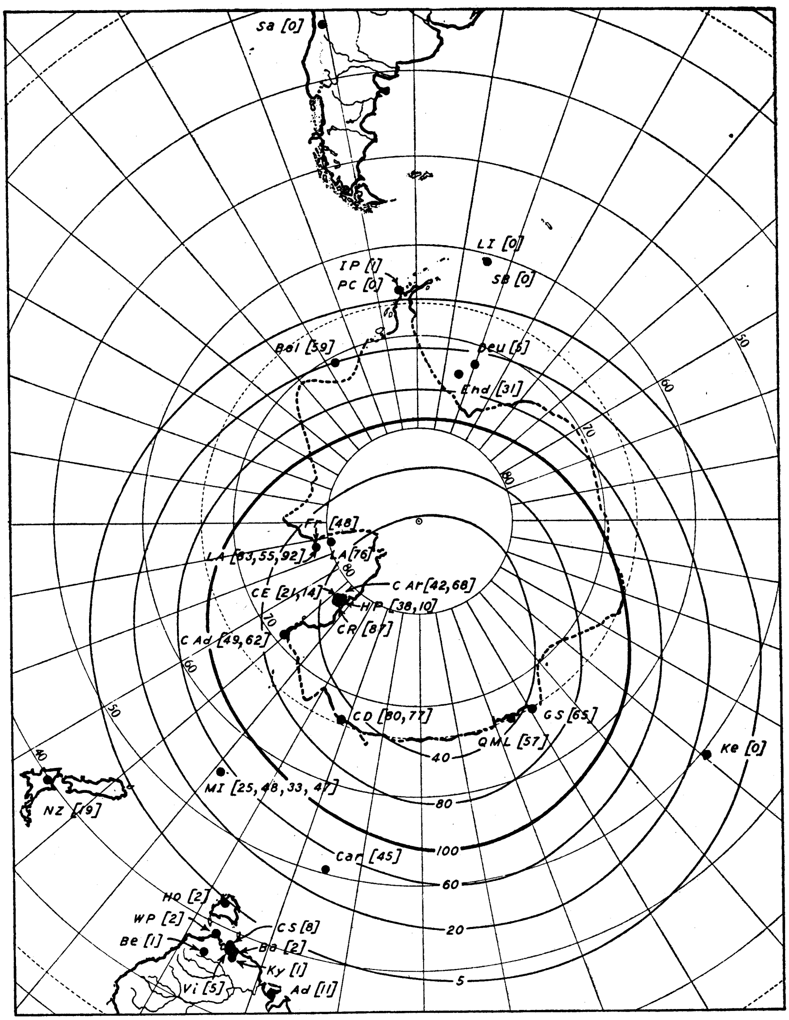

Fig. 1.—Diagram by Vestine and Snyder (1945) showing estimated percentage frequency of days with occurrence of aurora on clear dark nights at high latitudes, southern hemisphere. Figures in square brackets are observed values.

(2) H.A. appear to be due to a quiet discharge (as distinct from a constricted discharge which may remain fixed in the atmosphere for long periods). This has also been suggested by Alfvén (1950) who considers H.A. to define the position of the " *A* curve " of his theory.

The latitude departures L°, measured positive to south (see Fig. 2), of the H.A. from Macquarie Island were calculated from the relation

$$\cos(L+a)=(1+h/R)^{-1}\cos a, \quad \text{................} \quad (1)$$

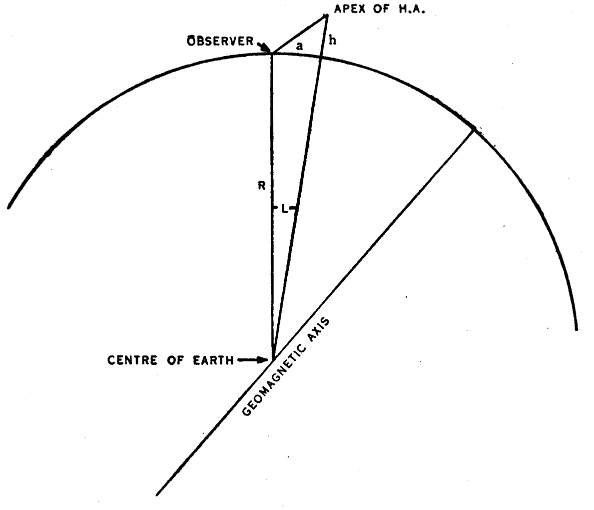

Fig. 2.—L is the latitude departure of the H.A. from the observer at Macquarie Island.

where a=elevation of H.A., R=radius of the Earth ($6{\cdot}36\times10^3$ km.), h=height of the lower border of H.A., taken as 105 km. (near the most frequent value found in the northern hemisphere (cf. Harang 1951)).

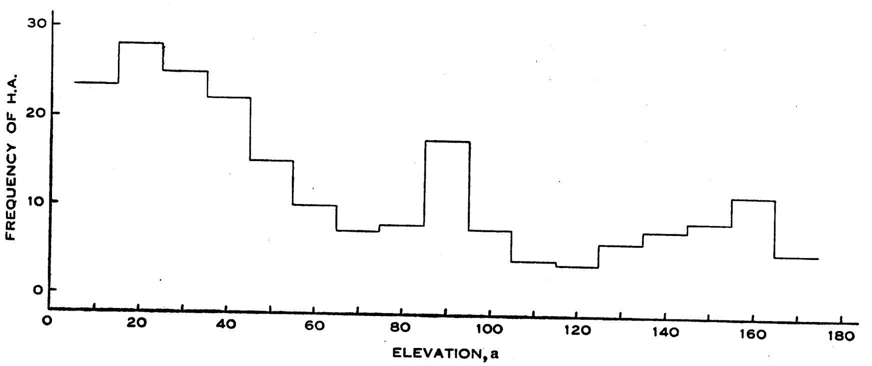

Fig. 3.—Observed frequency of H.A. in 10° intervals of elevation measured from the southern horizon.

The observed frequency of H.A. in 10° intervals of elevation is shown as a function of elevation in Figure 3. In Figure 4 (a) the relative frequency of H.A. per degree of latitude is shown as a function of L. This curve clearly shows two maxima, one at $L\simeq1^\circ$ and one at $L=0^\circ$. The possibility has been considered that the decrease in relative frequency south of $L=1^\circ$ may be due to the effect of cloud obscuring the sky at low elevations. The unimportance of

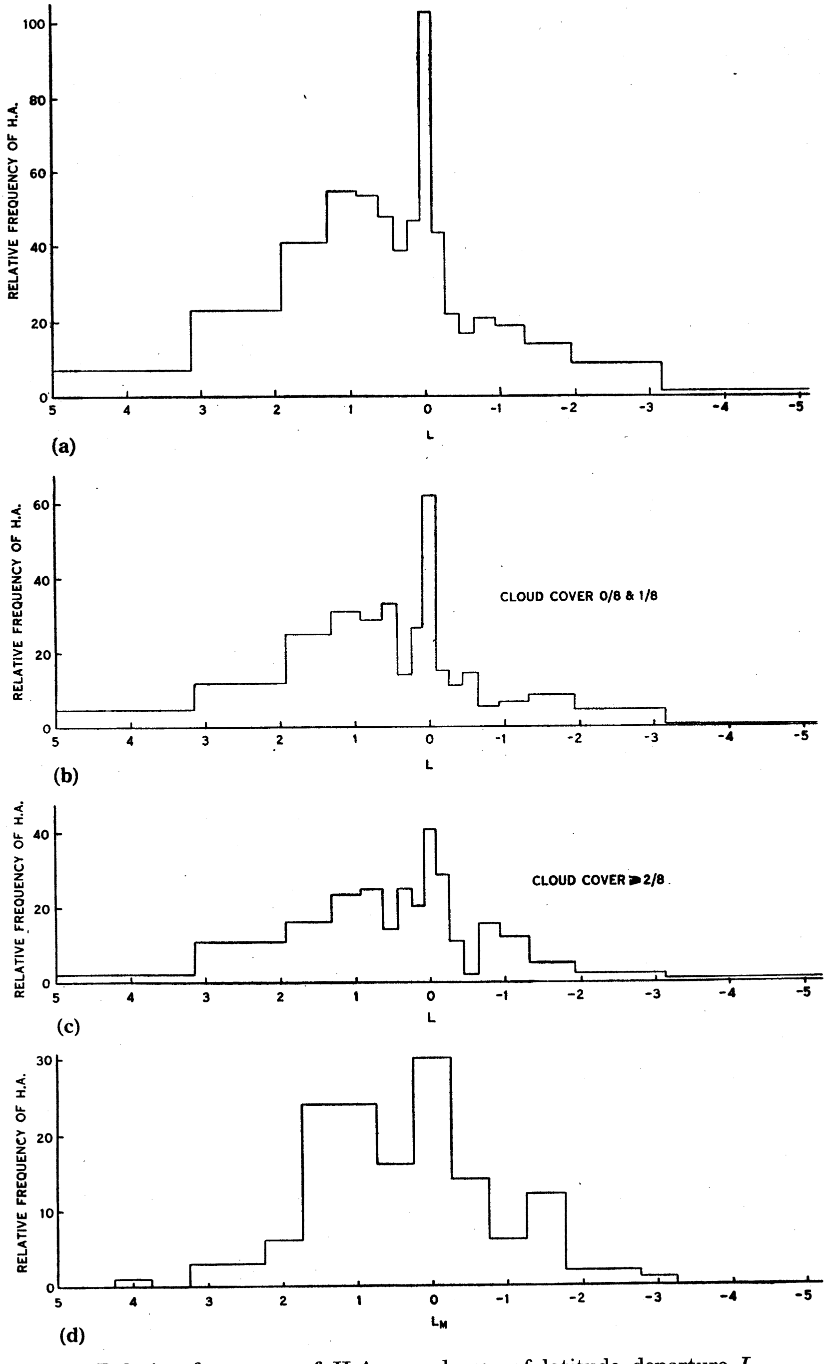

Fig. 4.—Relative frequency of H.A. per degree of latitude departure L.
(a) Derived from all observations; (b) derived from observations made at times when the cloud cover was 0/8 or 1/8; (c) derived from observations made at times when the cloud cover was $\geqslant 2/8$; (d) calculated from observed values of K_p and t using equation (5).

cloud effects is, however, clearly demonstrated by the similarity of Figures 4 (*b*) and 4 (*c*), which were derived from observations made at times when the cloud cover was 0/8 or 1/8 and $\geqslant$2/8 respectively.

II. Latitude of H.A. and Geomagnetic Disturbance

Several workers in the northern hemisphere have shown that the auroral zone expands with increase in geomagnetic activity. Among them Røstad (1935) found a roughly linear relation between auroral zone radius and magnitude of the perturbing magnetic vector at Potsdam and Rude Skov. Nagata (1950), from an examination of magnetic records of a number of stations at different times during one magnetic storm, found the mean radius of the auroral zone, as defined by the line of maximum geomagnetic north component of the D_{st} field ΔX_m, to increase during the development of the storm and to be related to the mean equatorial ΔX_m. This relation was interpreted using Störmer's auroral theory and found consistent with the view that increase in auroral zone radius is due to modification of the Earth's field associated with the development of an equatorial ring current of radius about 20 Earth radii. The solar particle stream was assumed to consist of Ca^+ ions moving with velocity 1000 km./sec., the particle trajectories being determined by the magnetic field of the Earth.

According to Martyn's (1951*a*, 1951*b*) theory one would expect the radius of the outer edge of the auroral zone to increase with increase in kinetic energy density of the solar particle stream. Also Alfvén's (1950) theory indicates an increase in mean radius of his " *A* curve " with increase in velocity of the stream.

The geomagnetic planetary disturbance index K_p was devised to measure the intensity of the solar particle stream by its geomagnetic effects (cf. Bartels and Veldkamp 1949 ; Bartels 1949). For this reason it was considered desirable to examine the relation between latitude of H.A. and K_p.

Figure 5 shows the mean latitude of H.A. associated with each value of K_p, the straight line

$$L_E = 2 \cdot 95 - 0 \cdot 605 K_p \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

through the points being fitted to the raw data by the least squares method. One of the assumptions on which the validity of the least squares method is based is that successive errors are distributed independently of one another. When this condition is violated the estimates of the regression coefficients, though unbiased, need not have least variance and the t and F tests generally used for making confidence statements are not valid.

In the present case the observations were ordered chronologically and where several observations occurred during the same hour these were shuffled so that their ordering was random. The deviations from the regression equation (2) then show positive serial correlation significant at the 1 per cent. level. This is indicated by the statistic $d = \Sigma(\Delta Z)^2/\Sigma Z^2 = 1 \cdot 43$ being less than $d_L(1\%) > 1 \cdot 52$ as given by Durbin and Watson (1951). (Z is deviation from regression, ΔZ's are first differences of Z). Consequently the usual test of significance of the correlation coefficient r_{LKp}, according to which in this case the value found is significant at the 1 per cent. level, is not valid. The deviations Z from regression show, on the average, a systematic non-linear variation with time of day as shown in Figure 6. A regression equation linear in K_p and quadratic in time t was therefore fitted, the equation found being

$$L_E=2\cdot72-0\cdot72K_p+0\cdot06(t-12\cdot5)+0\cdot104(t-12\cdot5)^2. \quad \ldots.(3)$$

The value used for t is the mid-point of the hour (G.M.T.) of observation. In this case, too, the deviations from regression show positive serial correlation significant at the 1 per cent. level; $d=1\cdot52<d_L(1\%)\simeq1\cdot60$. An examination of the values of ΔZ shows that in a number of places several small values follow one another, these being associated mainly with the occurrence of several observations during the same hour.

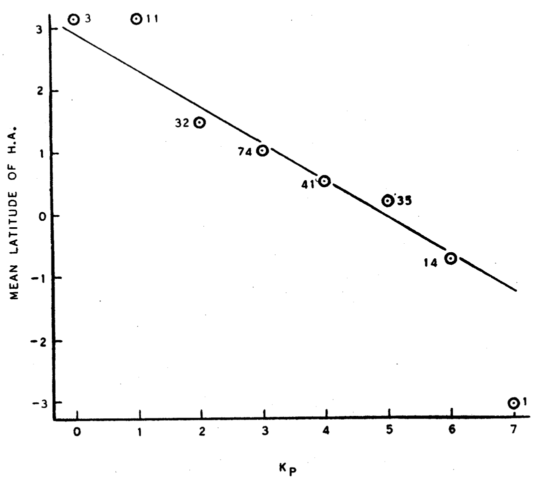

Fig. 5.—Dependence of latitude of H.A. on K_p. (The figures near the points indicate the number of observations used in computing the point.)

For this reason a regression equation linear in K_p and quadratic in t was fitted, taking as dependent variable the mean latitude L' of all H.A. observed during the same hour. Cases where several observations were made during the same hour are mainly those where several H.A. occurred simultaneously. The observations were again ordered chronologically. The regression equation obtained is

$$L'_E=2\cdot98-0\cdot79K_p+0\cdot06(t-12\cdot5)+0\cdot11(t-12\cdot5)^2. \quad .. \text{(4a)}$$

The deviations from regression in this case show no serial correlation significant at the 5 per cent. level; $d=1\cdot781>d_U\simeq1\cdot780$. Equation (**4a**) may be rewritten in the form

$$L'_E=2\cdot97-(0\cdot79\pm0\cdot20)K_p+(0\cdot11\pm0\cdot05)[t-(12\cdot2\pm0\cdot8)]^2, \quad \ldots\ldots\ldots\ldots\ldots \text{(4)}$$

in which the limits shown are the 95 per cent. fiducial limits.

All of the above statistical tests involve the assumption that the errors (departures from regression in the population) are normally distributed with constant variance. An examination of the frequency distribution of $L-L'_E$ (Fig. 7) suggests that this is not so in the present case; however, this is not likely to affect the conclusions here.

The quadratic form of equation (4) was chosen purely on the grounds of simplicity to fit the data which cover the range $K_p=0$ to 7, $t=7\cdot5$ hr. to $17\cdot5$ hr. G.M.T.; it is not inconsistent with the view that the auroral zone is a closed curve, as is required by Alfvén's and Martyn's theories.

From equation (4) it can be seen that for any K_p, L'_E has a minimum value at $t_{min}=12\cdot2\pm0\cdot8$ hr. G.M.T. which is not significantly different from mean magnetic midnight ($12\cdot4$ hr. G.M.T.) as defined by McNish (1936). This result

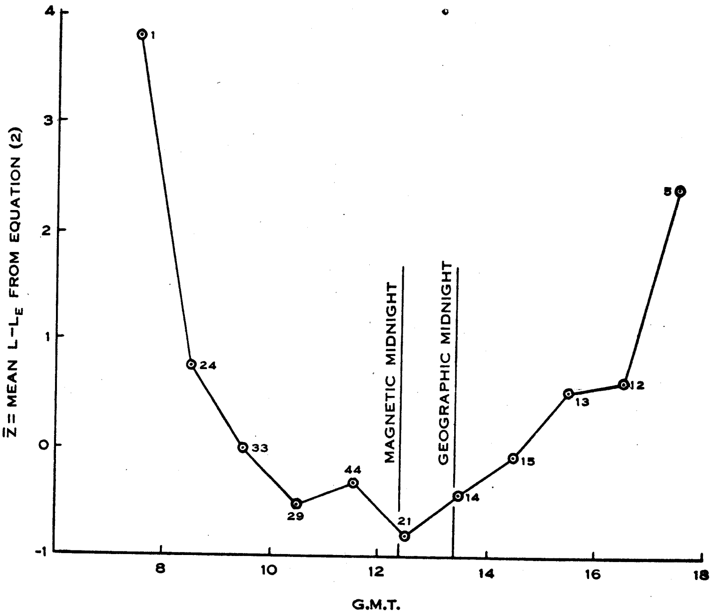

Fig. 6.—Nocturnal variation of deviation of observed L from equation (**2**). (The figures near the points indicate the number of values used in computing the point.)

is in fair agreement with observations on arcs in the northern hemisphere summarized by Alfvén (1950). According to Alfvén's theory, however, the minimum L'_E should occur 6 hr. before magnetic midnight. Martyn's theory, on the other hand, indicates no dependence of L'_E on time of day.

In Figure 7 is shown the frequency distribution of deviations $L-L'_E$ of the observed latitudes of H.A. from the regression equation (4). The smooth curve estimates the probability distribution of latitude of H.A. at constant K_p and t; but it definitely underestimates the probability at each end of the curve, especially for $L>L'_E$. This is caused by the limitation in range of L over which H.A. may be observed from a single station.

At this stage it may be pointed out that when several H.A. occur simultaneously their latitudes are not independently distributed. This is shown by the fact that the deviations of observed L from regression equation (**3**) show significant positive serial correlation while the deviations of observed L' from regression equation (**4**) do not.

Figure 7 shows that the auroral zone is extremely sharply defined especially on its northern edge where the probability of occurrence of an H.A. decreases from its maximum to half the maximum over a range of less than $1\frac{1}{2}°$ of latitude. This result is of course not inconsistent with any of the auroral theories proposed by Störmer, Alfvén, or Martyn but the general shape of the curve (Fig. 7) is relevant to considerations of the accuracy of Alfvén's and Martyn's theories.

According to Martyn's theory the auroral zone is an annular ring about 6° wide. On the outside of this ring positive ions impinge on the upper atmosphere while on the inside edge electrons enter. If now we assume that both positive ions and electrons produce H.A. we would expect the distribution of L at constant

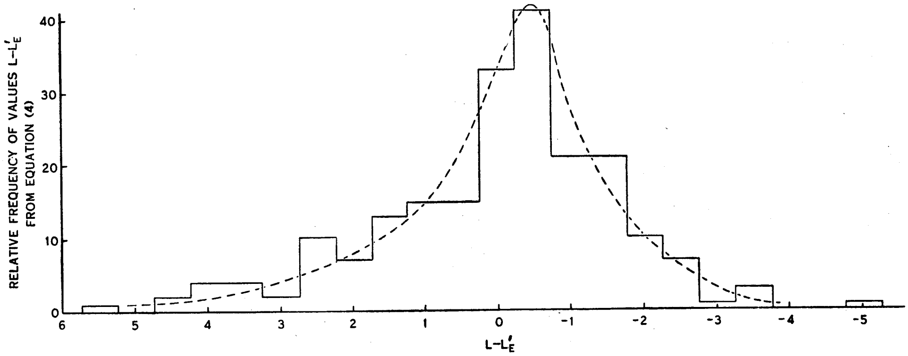

Fig. 7.—Frequency distribution of deviations L–L'_E of observed latitudes of H.A. from equation (**4**). The dotted curve estimates the probability distribution of latitude of H.A. at constant K_p and time of day.

K_p and t to be rectangular with a width of about 6° or bimodal with the modes separated about 6°. Figure 7 is not consistent with either case. The presence of the $H\beta$ line in the spectrum of H.A. (see, for example, Dahlstrom and Hunten 1951) demonstrates that protons do occur in the streams of particles producing this phenomenon. If, then, we assume that electrons do not produce H.A. we may identify the line of maximum frequency of occurrence of H.A. with the outer edge of Martyn's auroral zone.

According to Alfvén's theory the auroral zone has a well-defined outer edge only, the day side being produced by positive ions, the night side by electrons. The results of this work, then, are consistent with Alfvén's theory only if electron streams do produce H.A.

Vestine (1944) estimated the probability distribution of latitude of the aurora in the northern hemisphere. His result is shown in Figure 8. The extreme difference between this curve and Figure 7 is largely explained by the following features of the data used by Vestine :

(1) Since the ordinate represents the probability that the aurora will be within " seeing range " from a given point the latitude resolution is about 10–12°.

(2) The curve is derived from observations associated with various values of K_p and t.

(3) The observations used refer to auroras of all forms while the probability distribution may be different for different forms. This is certainly the case at Macquarie Island where pulsating and flaming auroras occur almost invariably north of all H.A. visible.

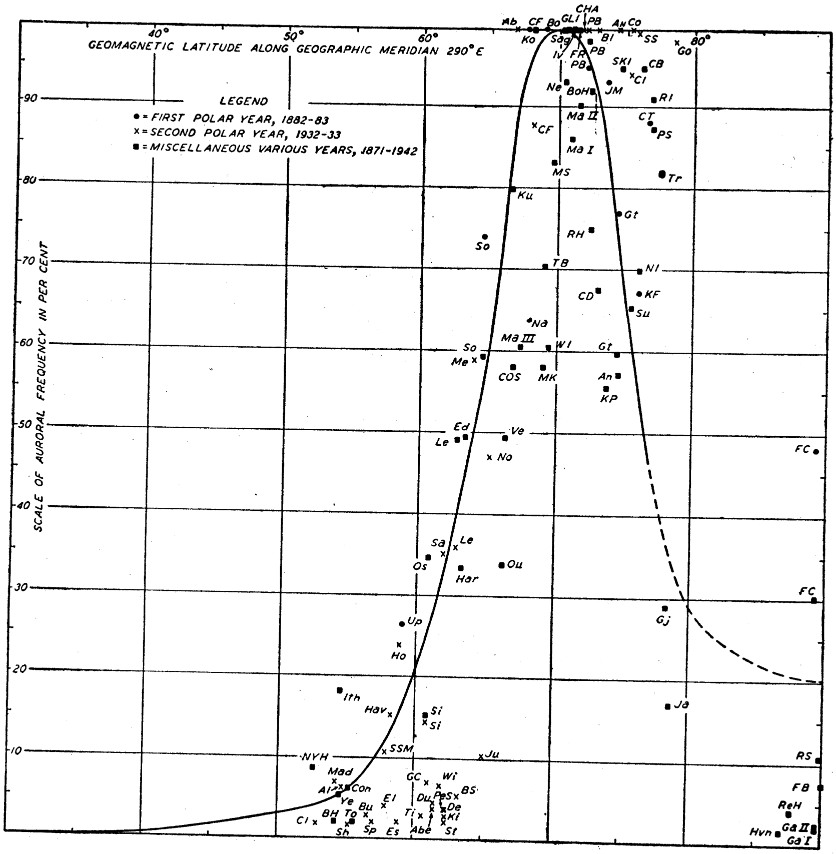

Fig. 8.—Estimated average auroral percentage frequency on clear dark nights, meridian 290 °E. ; adjusted to circular zone of maximum auroral display in geomagnetic latitude 69 °N. (after Vestine 1944).

(4) Vestine assumes the mean auroral zone (Alfvén's "*M* curve") to be circular with its centre on the magnetic axis pole. Owing to the local irregularities of the Earth's magnetic field this is unlikely to be an accurate assumption.

From an examination of the distribution given in Figure 7 it can be seen that the most probable latitude L_M of an H.A. is about $0\cdot5°$ less than the expected value L'_E given by equation (4). The equation

$$L_M = 2\cdot47 - 0\cdot79K_p + 0\cdot11(t - 12\cdot2)^2 \quad \ldots\ldots\ldots\ldots \quad (5)$$

then predicts the most probable position of an H.A. given that an H.A. occurs. The frequency distribution of L_M (calculated from values of K_p and t) is given in Figure 4 (*d*). This clearly shows the main features of the observed distribution (Fig. 4 (*a*)).

Summarizing then: the expected value of the mean latitude L' of all H.A. visible from Macquarie Island at the one time is given by equation (4), while the latitude of the southern auroral zone as defined by the line of most frequent occurrence of H.A. is given on the 243 °E. geomagnetic meridian by equation (5).

III. Acknowledgments

The author wishes to express thanks to Mrs. U. Brent for her assistance with numerical computations, to Mr. N. R. Parsons and Mr. K. B. Fenton for discussions on their observations, and to Dr. D. F. Martyn who read the manuscript and offered valuable comments on it.

IV. References

Alfvén, H. (1950).—" Cosmical Electrodynamics," Ch. 6. (Oxford Univ. Press.)

Atlas of Auroral Forms (1930).—(Int. Un. Geod.: Oslo.)

Bartels, J. (1949).—Geomagnetic indices, *K* and *C*, 1948. Appendix B: The standardised index K_s and the Planetary index K_p. Association of Terrestrial Magnetism and Geophysics (Int. Un. Geod.) Bulletin No. 12b.

Bartels, J., and Veldkamp, J. (1949).—International data on magnetic disturbances. First quarter, 1949. *J. Geophys. Res.* **54**: 295-9.

Dahlstrom, C. E., and Hunten, D. M. (1951).—O_2^+ and H in the auroral spectrum. *Phys. Rev.* **84**: 378-9.

Durbin, J., and Watson, G. S. (1951).—Testing for serial correlation in least squares regression. II. *Biometrika* **38**: 157-78.

Fritz, H. (1881).—" Das Polarlicht." (F. A. Brockhaus: Leipzig.)

Harang, L. (1951).—" The Aurorae." Ch. 2. (Chapman and Hall: London.)

McNish, A. G. (1936).—Geomagnetic coordinates for the entire Earth. *Terr. Magn. Atmos. Elect.* **41**: 37-43.

Martyn, D. F. (1951*a*).—Magnetic storms and aurorae. Solar particles at the Earth. Mixed Commission on Ionosphere, Int. Coun. Sci. Un., Proc. 2nd Meeting, Brussels, 1950, pp. 49-58.

Martyn, D. F. (1951*b*).—The theory of magnetic storms and auroras. *Nature* **167**: 92-4.

Nagata, T. (1950).—Development of a magnetic storm: the southward shifting of the auroral zone. *J. Geophys. Res.* **55**: 127-41.

Parsons, N. R., and Fenton, K. B. (1953).—Observations of the Aurora Australis, Macquarie Island, May 1950-April 1951. Aust. Nat. Antarctic Res. Expedition Interim Report No. 5.

Røstad, A. (1935).—Beziehungen der Nordlichterscheinungen zu den weltweiten magnetischen Störungen. *Geofys. Publ.* **10** (10): 1-10.

Vestine, E. H. (1944).—The geographic incidence of aurora and magnetic disturbance, Northern Hemisphere. *Terr. Magn. Atmos. Elect.* **49**: 77-102.

Vestine, E. H., and Snyder, E. J. (1945).—The geographic incidence of aurora and magnetic disturbance, Southern Hemisphere. *Terr. Magn. Atmos. Elect.* **50**: 105-24.

White, F. W. G., and Geddes, M. (1939).—The Antarctic zone of maximum auroral frequency. *Terr. Magn. Atmos. Elect.* **44**: 367-77.