The Relationship between Unique Geomagnetic and Auroral Events[1]

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Abstract. From magnetic data obtained at eleven Canadian stations, the ionospheric current patterns in the auroral zone, during several magnetic storms, have been sketched and the predominant current patterns determined for each phase of an 'average' storm. It is found that the auroral displays tend to occur along current lines.

A high correlation is found between the geomagnetic latitudes of the southern extents of auroral displays and the most southerly current lines. When these two sets of data are plotted against a 'storm-phase,' a southward shift of the aurora is seen to accompany the southward motion of ionospheric currents.

INTRODUCTION

An attempt is made, in this paper, to relate individual auroral displays to their simultaneously occurring geomagnetic storms. Following the often quoted concept that the ionospheric currents responsible for magnetic storms are associated with auroras, the data on a number of simultaneous auroras and magnetic storms have been studied to find the dominant patterns of the ionospheric overhead currents.

The magnetic data have been obtained from five permanent observatories and six temporary magnetic stations in Canada (see Figs. 4 and 5) that were operating during the IGY (1957–1958). The distribution of the stations covers a fairly wide range of latitude, including the auroral zone and part of the polar cap, which are of great geomagnetic interest.

Visual auroral observations were made at more than 300 stations distributed all over Canada [*Canadian National Committee for the IGY*, 1959]. The National Research Council of Canada has made one map for each hour of the night during the IGY. Each map contains the auroral information (approximate location, type, color, and brightness, as estimated by observers) from 5 minutes before to 5 minutes after the specified hour on the map.

The analysis is based on data obtained during 20 days, each characterized by the fact that five or more Canadian all-sky camera stations were operating and 75 per cent or more of these showed auroras. These days are: October 1, 20, 21, 1957; November 24, 25, 27, 29, 1957; December 1, 11, 12, 13, 30, 1957; January 13, 1958; and April 15, 16, 17, 18, 19, 21, 24, 1958.

The selection of days was made on the basis of auroral observations only, without reference to the magnetic activity. It later developed, however, that 10 of these days were internationally geomagnetically disturbed (5 days in each month), 7 days were immediately before or after the 5 disturbed days, 3 others had moderate magnetic activity, and none were among the 10 internationally quiet days [see 'Geomagnetic and Solar Data,' *J. Geophys. Research, 63*, 1958].

REPRESENTATION OF MAGNETIC DISTURBANCES

The magnetic data on 5 international quiet days were used to determine the reference line on the magnetograms. The size of a given disturbance was measured as the average departure from the reference line, in 15-minute intervals, for the dark hours. Measurements were taken on three components, either X, Y, and Z or H, D, and Z. The total horizontal disturbance force and its azimuth were then calculated and plotted against Greenwich Mean Time, along with the vertical component of the disturbance (Fig. 1). One chart was made for each of the 20 days and contains the disturbance field for the five permanent observatories only. These diagrams give a vivid discription of the magnetic storm over the range of latitude covered by the stations, and facilitate the sketching of the patterns of the overhead

[1] This work is based on a thesis for the M.A. degree submitted to the Department of Physics at the University of Toronto.

ionospheric currents presumed to be responsible for the disturbance field.

In a statistical sense, at Resolute Bay (geomagnetic latitude 83.2°N) the activity is low. Variations in the field components are slow and take place without any rapid changes. The horizontal component of the disturbance field, starting from the southwest, rotates clockwise and increases very slowly in intensity. Once it reaches northwest, the rotation becomes still slower and within 4 to 6 hours the horizontal component approaches the north, or occasionally reaches the northeast. (It should be noted that Fig. 1 is only a sample and might differ, in some respects, from these general statements.) The vertical component Z, which is usually downward at evening hours, decays gradually and becomes upward after midnight. The low intensity of the Z component, together with its very slow variations, might serve as an indication

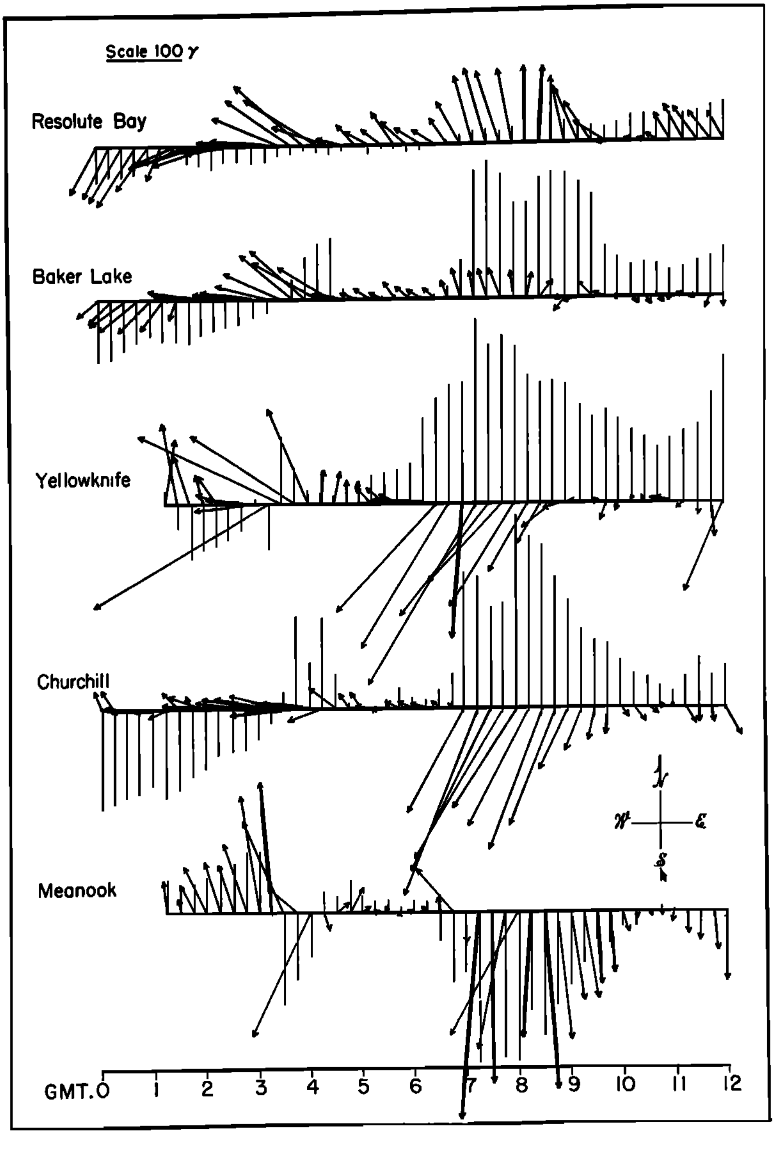

Fig. 1. Horizontal component (arrows) and vertical component (straight lines) of the geomagnetic disturbance field, April 15, 1958.

that the overhead currents can be approximated better by sheet currents than linear ones.

At Baker Lake (geomagnetic latitude 73.0°N) the behavior of a storm is more or less similar to that at Resolute Bay, except that (*a*) the variations in both the H and Z components are more rapid, and (*b*) the intensity of the Z component is larger. These differences might indicate either narrower sheets of ionospheric currents, or sharp bending of current lines in this region, or both.

At Yellowknife (geomagnetic latitude 69.1°N) and Churchill (geomagnetic latitude 68.4°N) the disturbance is most intense. The storm begins with an increase in the H component (first phase) which decays after a while and grows again negatively (main phase). During the main phase, the disturbance is more intense and lasts much longer than in the first phase. The Z component is downward during evening hours, upward for the rest of the night, and is remarkably large.

Meanook (geomagnetic latitude 62°N) has the typical characteristics of a low-latitude station. There is a distinct positive phase in the H component which is followed by an intense negative main phase. The intensity and rapid fluctuations of the H component are comparable to those at Yellowknife and Churchill, but the Z component is less active. It remains mostly downward except during the first phase.

The hypothetical ionospheric current system that would produce these magnetic disturbances would have the following general characteristics: at latitudes such as that of Meanook, just outside the auroral zone, the currents are more intense and concentrated in narrower sheets than they are in the polar-cap region (Resolute Bay and Baker Lake). In the inner portion of the auroral zone, at Yellowknife and Churchill, the large Z component suggests still narrower sheets of currents, probably accompanied by sharp bendings above these stations. However, the abnormal behavior of the Z component within the auroral zone is not well understood, and even circular or semicircular currents (which give the highest Z and lowest H components) fail to explain its peculiar activity.

The magnetic disturbance vectors, for all eleven stations, are shown on the auroral maps (see Figs. 4 and 5) with slight modifications. It was mentioned above that each auroral map contains only the information from 5 minutes before to 5 minutes after the specified hour on the map. To keep the magnetic and auroral data consistent, measurements of the disturbance field were selected for the same intervals as the auroral data. Further, the highest values (rather than the averages) of the disturbance, during these intervals, have been used.

Determination of the Current Systems

If the currents producing the magnetic changes are actually located in the ionosphere, the E layer is the most likely region in which they might exist. *Vestine* [1960], in a discussion of magnetic storms, has concluded that there must be polar electric currents, flowing near or within the E region, that give rise to magnetic storms. *Ratcliffe and Weekes* [1960] have shown that, at places not too near the equator, the ionosphere is highly conducting between about 90 and 140 km (wherein the dynamo region supposedly lies). They also have stated that the calculated dynamo currents, arising from the tidal motion of air, are of the same order as currents deduced from geomagnetic data. *Vegard and Krogness* [1920] found an average height of 107.9 km for the lower borders of 1927 auroral displays. They also have shown that the mean distance from the lower border to the maximum luminosity (which presumably corresponds to the center of the current lines) is about 6 to 9 km. *Weaver and Skinner* [1960], assuming that the ionization within an auroral arc is proportional to the auroral light intensity, have calculated the approximate conductivity of the ionosphere within an auroral arc. They concluded that the maximum conductivity during an active auroral period occurs at a height of about 105 km.

In view of these considerations, an average height of 110 km seems appropriate for ionospheric overhead currents. Figures 2 and 3 illustrate the means used to locate the currents. In Figure 2 the horizontal and vertical components of the magnetic field of sheet currents of various widths are plotted against the distance from the center of those currents. The width of the sheets, $2W$, ranges from 0 to 600 km. In Figure 3, the ratio of Z/H is plotted against the distance. It is apparent that, at distances exceeding about 400 km, the magnetic effects of sheet currents are comparable to those of the linear one.

On the basis of the preceding discussion of the behavior of the disturbance fields at different stations, the following widths were assumed for the current sheets: 300 km for the southern stations, Meanook, Saskatoon, Flin Flon, The Pas, and Winnipeg; 200–300 km for the auroral zone stations, Bird, Churchill, Yellowknife, Ennadai Lake, and Baker Lake; 500 km and over for the polar-cap station, Resolute Bay.

From the ratio Z/H at any station, the curves of Figure 3, and the right-hand rule, the hypothetical current may be located for any observation of the magnetic disturbance. At the southern stations, a correction was made for the effect of the neighboring current, by means of the curves of Figure 2. (The correction was usually small, of the order of a few tens of kilometers.) Inside the auroral zone, however, because of the abnormal behavior of the Z component, the correction did not prove to be useful and seemed to result in more spurious current patterns.

No correction was made for the induced underground currents. The effect of an induced current is to reduce the Z and enhance the H component. Since in the present problem the height of the current is assumed to be fixed, the apparent current thus determined would be closer to the station than the real one. In any event, the

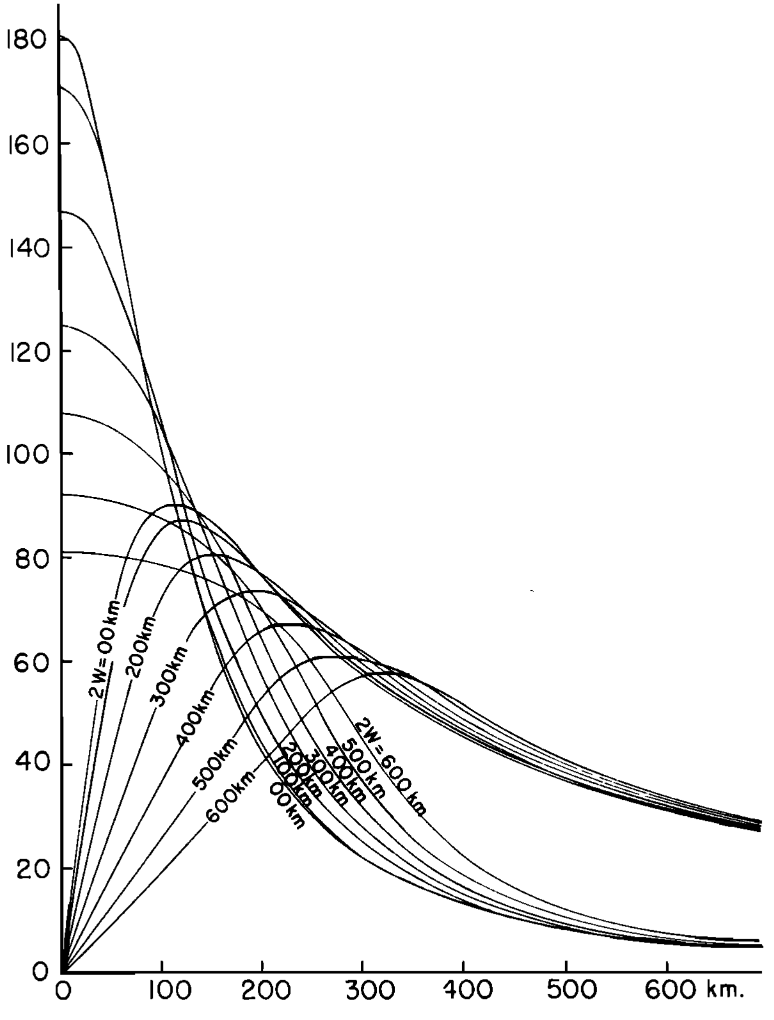

Fig. 2. Horizontal component (H) and vertical component (Z) of the magnetic field of sheet currents plotted against the distance from the center of the sheets. The sheets are assumed to have a width of $2W$ and to be at a height of 110 km. The scale of the magnetic field is arbitrary and we have used only the relative field intensities of the currents.

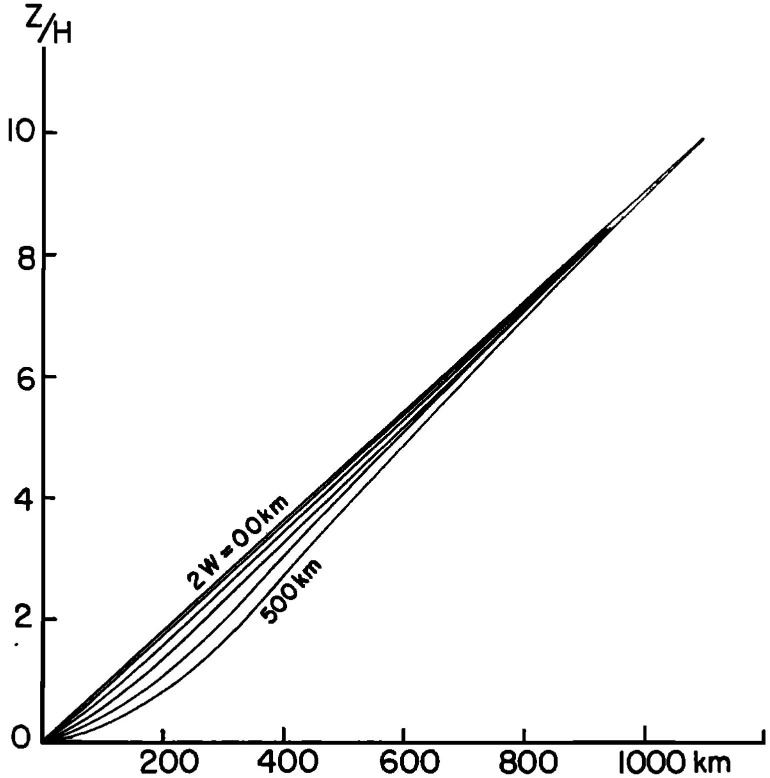

Fig. 3. Ratio Z/H of sheet currents plotted against the distance from the center of the sheets. The sheets are assumed to have a width of $2W$ and to be at a height of 110 km.

induced earth currents probably do not have a serious effect on the results of this analysis. Even if the induced currents contribute one-third of the total disturbance field, they would produce only a small displacement of the ionospheric current patterns, and the shape of the patterns would remain unaltered.

Discussion and Conclusions

In this section we discuss the overhead current patterns and their relation to auroral displays. We present a few sample maps of the superimposed magnetic and auroral data pertinent to several storms and then explain their principal features. Finally, we discuss the correlation of the southern boundaries of the overhead currents with those of the auroral displays during several storms.

(*a*) *Overhead current patterns and auroras.* As a typical example, two current patterns of April 15, 1958, are given in Figure 4. Before discussing these patterns, let us briefly outline the magnetic activity on this particular night (see Fig. 1).

A storm begins to develop slightly before 0100 GMT, with a distinct positive phase (horizontal component), at Meanook, Churchill, and Yellowknife. (It should be noted that at high latitudes—Baker Lake and higher—the morphology of a storm is different from that at lower latitudes, and the distinction of positive and negative phase is for middle and low latitudes only.) The transition to a negative, main phase takes place around 0330, but after a short while this main phase is interrupted by a superposition of the positive phase of a new storm. The latter lasts for a few hours and in turn is followed by a well defined, strong main phase, which lasts until dawn.

The auroral maps and the current patterns corresponding to the positive phase of these storms are not presented here. These patterns, however, were characterized at southern stations by eastward currents that bent northward around

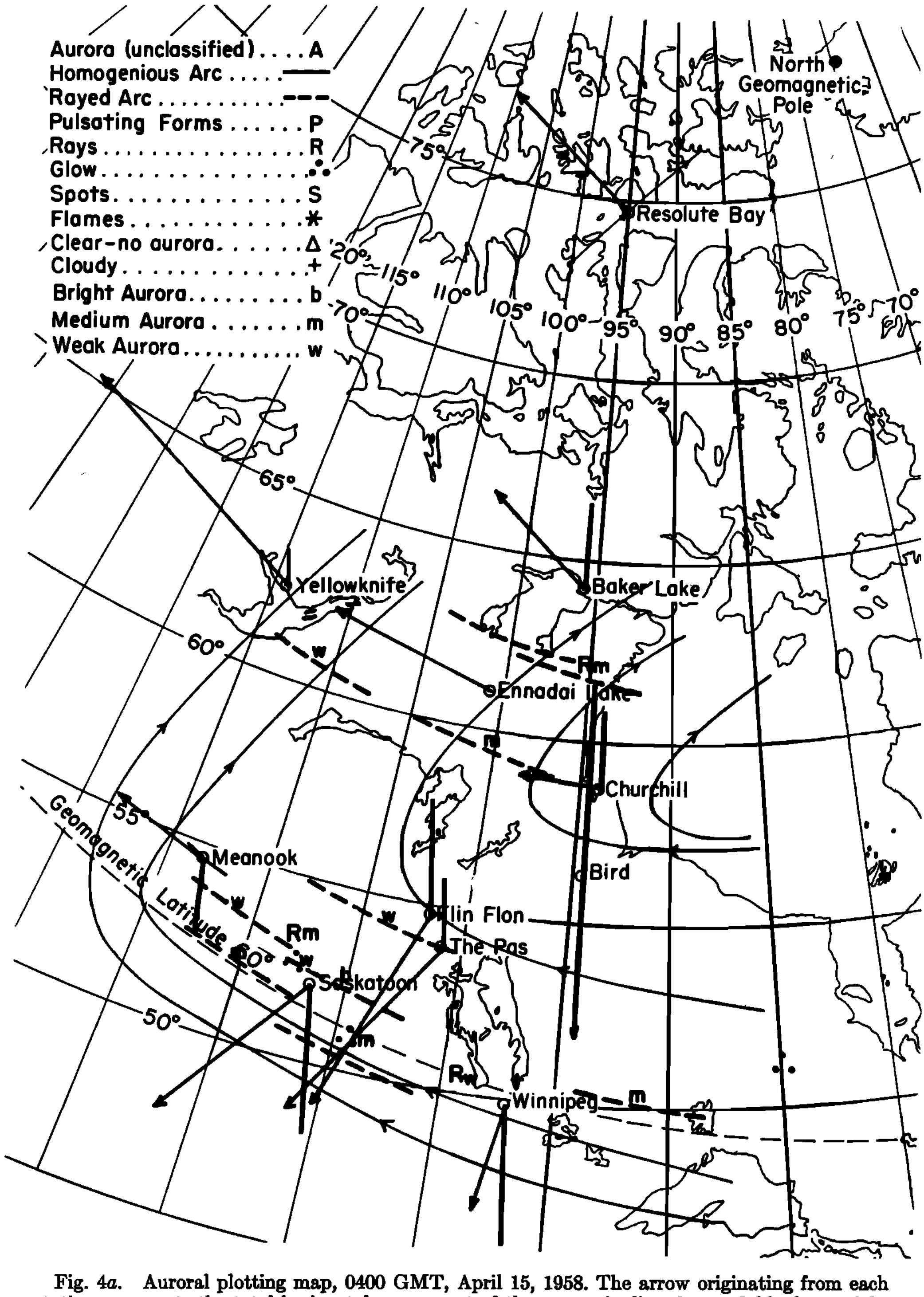

Fig. 4*a*. Auroral plotting map, 0400 GMT, April 15, 1958. The arrow originating from each station represents the total horizontal component of the magnetic disturbance field, the straight line represents the magnitude of the vertical component. The thin lines across meridional lines represent the ionospheric current paths.

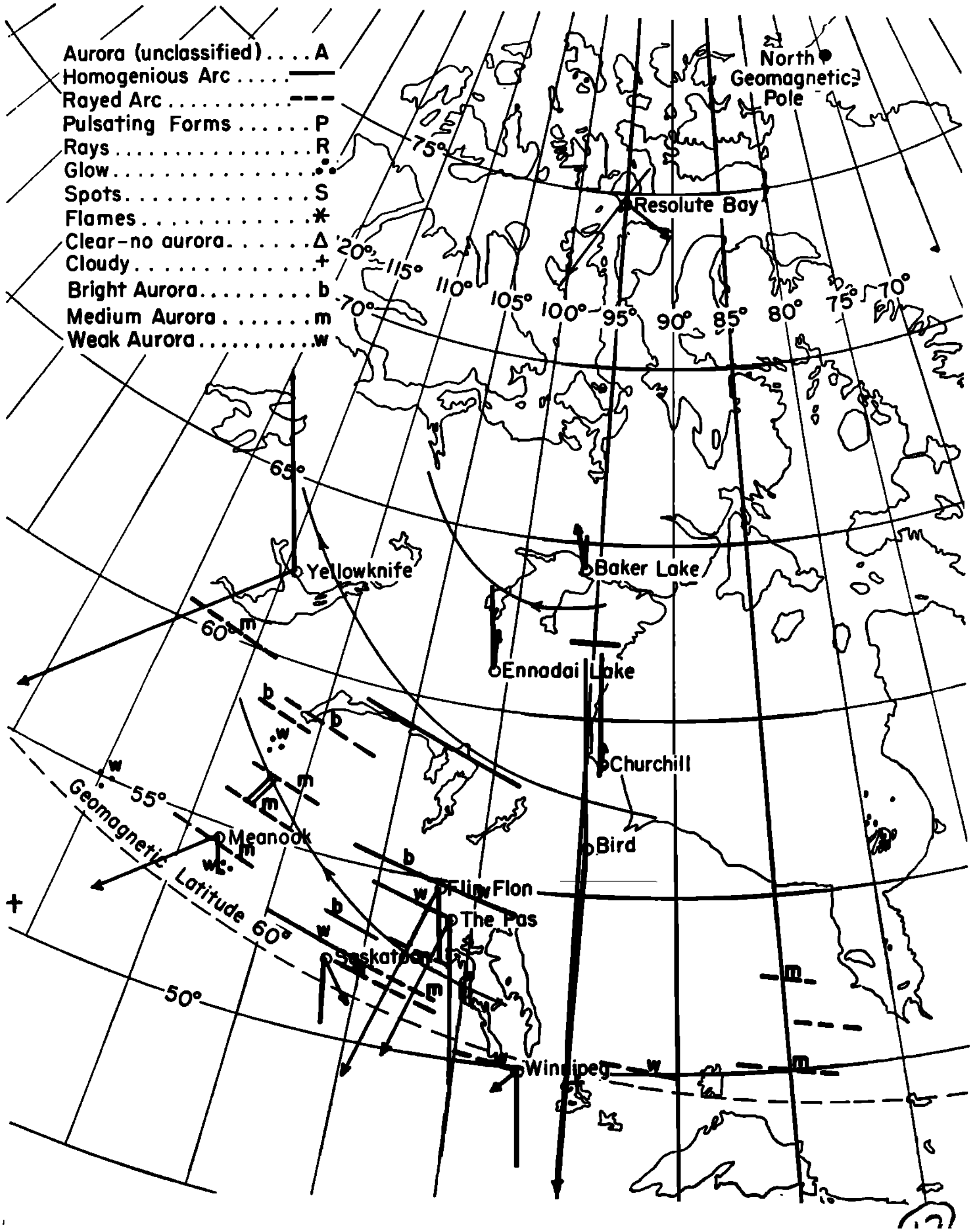

Fig. 4*b*. Auroral plotting map, 0700 GMT, April 15, 1958. (See legend for Figure 4*a*.)

Churchill and Bird. The auroral activity was low during the positive phases of the storms.

Figures 4*a* and 4*b* correspond to the main phase of the storm, characterized by intense southward *H* components at lower latitude stations. The earlier eastward currents are now replaced by currents flowing westward; at higher latitudes they flow either northeast or northwest. The displays occur quite frequently and extend over the more northerly stations. A more detailed discussion of the maps of Figure 4 is presented in the following section.

(*b*) *Superimposed maps.* An inspection of all the patterns at different locations and times, and under various degrees of magnetic activity, revealed that auroras, as a whole, tend to be aligned along the current path. (The alignment of the entire pattern of auroral activity may be different from the direction of orientation of a particular auroral arc or band, which was arbitrarily drawn always along a parallel of geomagnetic latitude.) This statement may be verified by comparing Figures 4*a* and 4*b*.

In Figure 4*a*, the auroras extend east-west over the southern stations, and run from southwest to northeast from Meanook and Saskatoon to Yellowknife and Baker Lake. These two directions happen to be the simultaneous directions of the current lines. In Figure 4*b*, however, there are no auroras over Churchill, Ennadai Lake, and Baker Lake; instead the auroras extend northwest from Saskatoon and The Pas to Yellowknife, which is again the direction of the ionospheric currents. To show this tendency of the aurora to occur along the current patterns in a more striking fashion, a series of superimposed maps (Fig. 5) was made as follows.

The 7 days of April 1958 were selected for this purpose, as the morphologies of the magnetic storms on these nights resemble each other. The maps were inspected, and those having approximately the same distribution of the horizontal disturbance vectors (in direction) were superimposed upon one another. Then all magnetic vectors, current paths, and auroral displays were copied on a blank overlay map. Because the magnetic storms on different nights have different durations, the above procedure does not superimpose maps of equal 'storm-time.' Instead, we may say that it superimposes maps at the same 'storm-phase,' where *phase* signifies a particular distribution of the horizontal disturbance vectors during the development of a storm. According to this definition, all storms belonging to a specified phase will have the same pattern of activity.

These superimposed maps illustrate characteristics that tend to recur in different storms. Figure 5*a* corresponds to the positive phases of the storms. Associated with the low magnetic activity during these phases, few auroras are observed and most of these occur over the southern stations and show a very slight extension toward Churchill. The contrast between the auroral and current patterns of Figures 5*b* and 5*c*, both of which correspond to the negative phases of the storms, is striking. In Figure 5*b* both currents and auroras extend from Winnipeg, Saskatoon, and Meanook to Yellowknife, whereas in Figure 5*c* neither currents nor the auroras show an extension from Meanook to Yellowknife. On both maps the region of Ennadai Lake, Baker Lake, and higher latitudes is clear. Incidentally, the information presented in Figures 5*a*, 5*b*, and 5*c* is less than one-tenth of the total data used in this analysis. This tendency of auroras to occur along current paths was maintained throughout all the data and appears to be statistically significant.

A divergence of current sheets, and consequently a reduction of the current density in higher latitudes, is apparent in Figures 5*a*, 5*b*, and 5*c*, and appears to be associated with the scarcity of auroral displays in these regions.

(*c*) *Low-latitude boundaries of ionospheric currents and auroras.* An auroral display has a rather sharp boundary at its low-latitude extension, whereas its activity diminishes gradually to the north. Hence, the southern limit of a display is much more distinct than the northern limit.

Magnetic storms, and, therefore, ionospheric currents, show this same feature. At their southern limit, the intensities of auroral-zone currents decrease abruptly, while on the northern side, at latitudes as high as that of Resolute Bay, the storm still has a moderate activity.

In order to see whether there is any correlation between the southern limits of auroras and overhead currents, a special analysis was made for Meanook, Saskatoon, and Winnipeg, which are located in the southern part of the auroral zone. (On quiet days the southern boundary of a disturbance may move northward as high as Flin Flon and The Pas.) Geomagnetic latitudes of the central line of the most southerly current

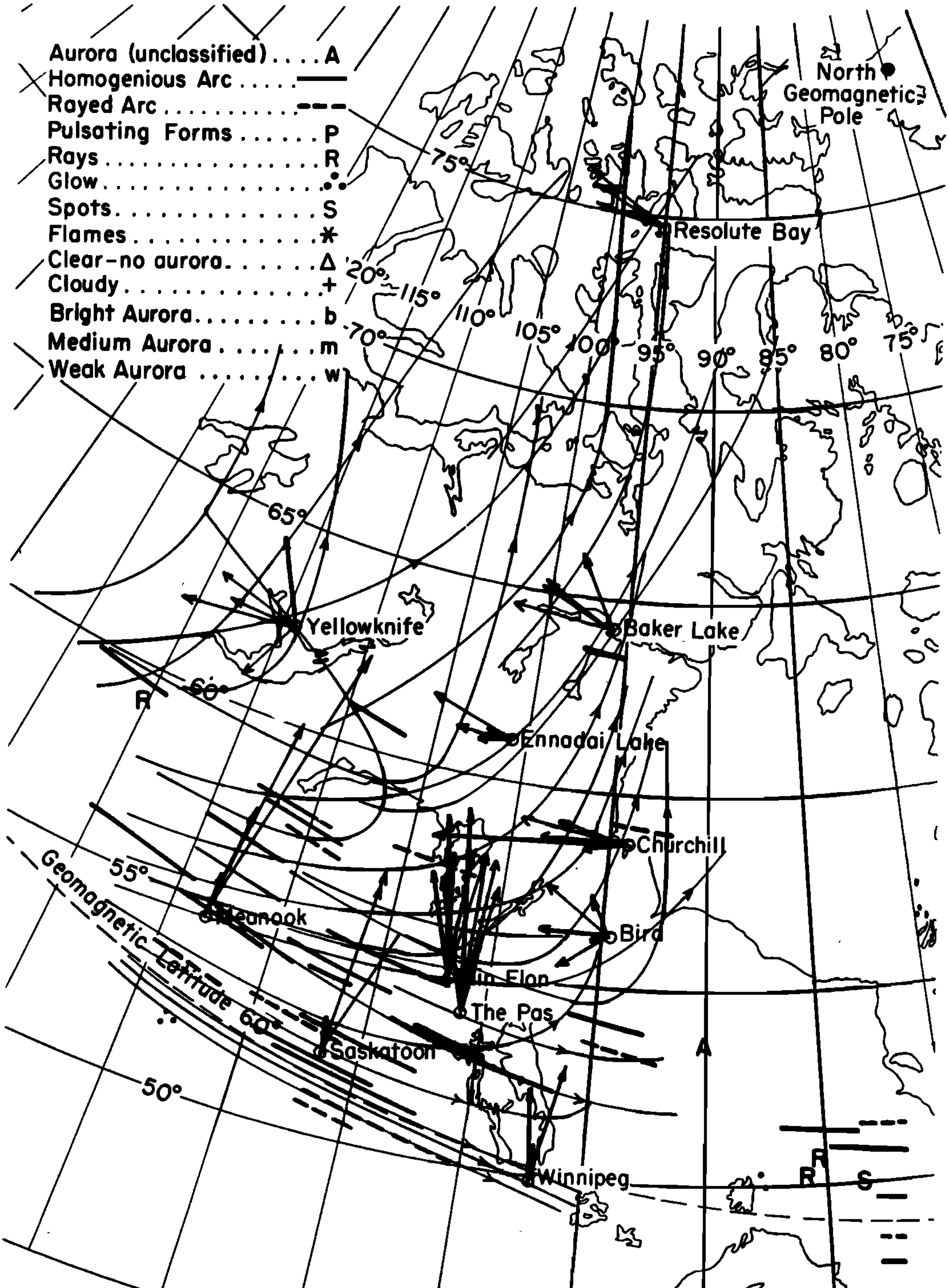

Fig. 5*a*. Auroral plotting map, constructed by superimposing the 5 maps of 0300 April 15, 0500 April 16, 0400 April 17, 0400 April 19, and 0400 April 24, 1958. (See legend for Figure 4*a*.)

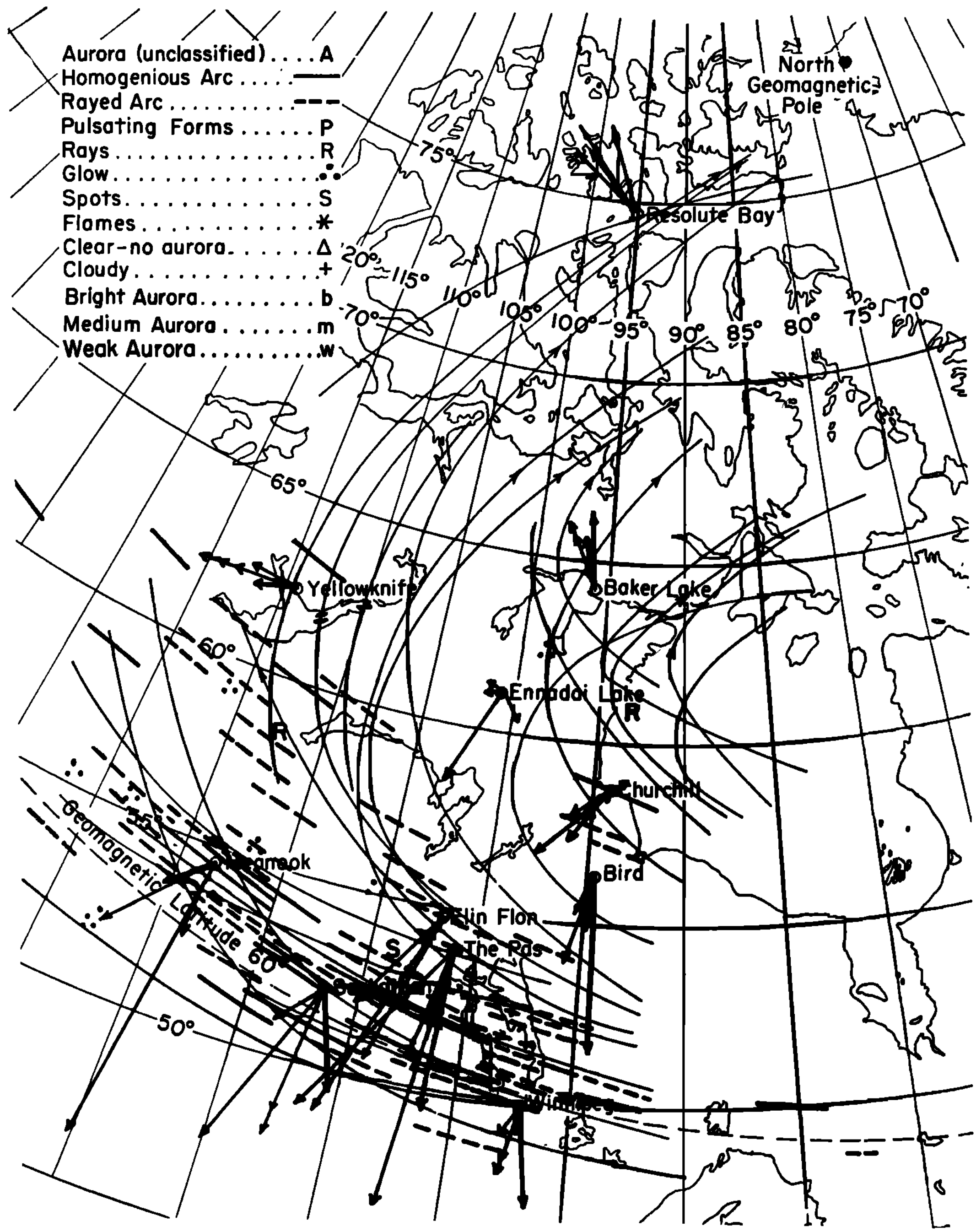

Fig. 5*b*. Auroral plotting map, constructed by superimposing the 5 maps of 0800 April 16, 0700 April 17, 0700 April 18, 0700 April 19, and 0800 April 24, 1958. (See legend for Figure 4*a*.)

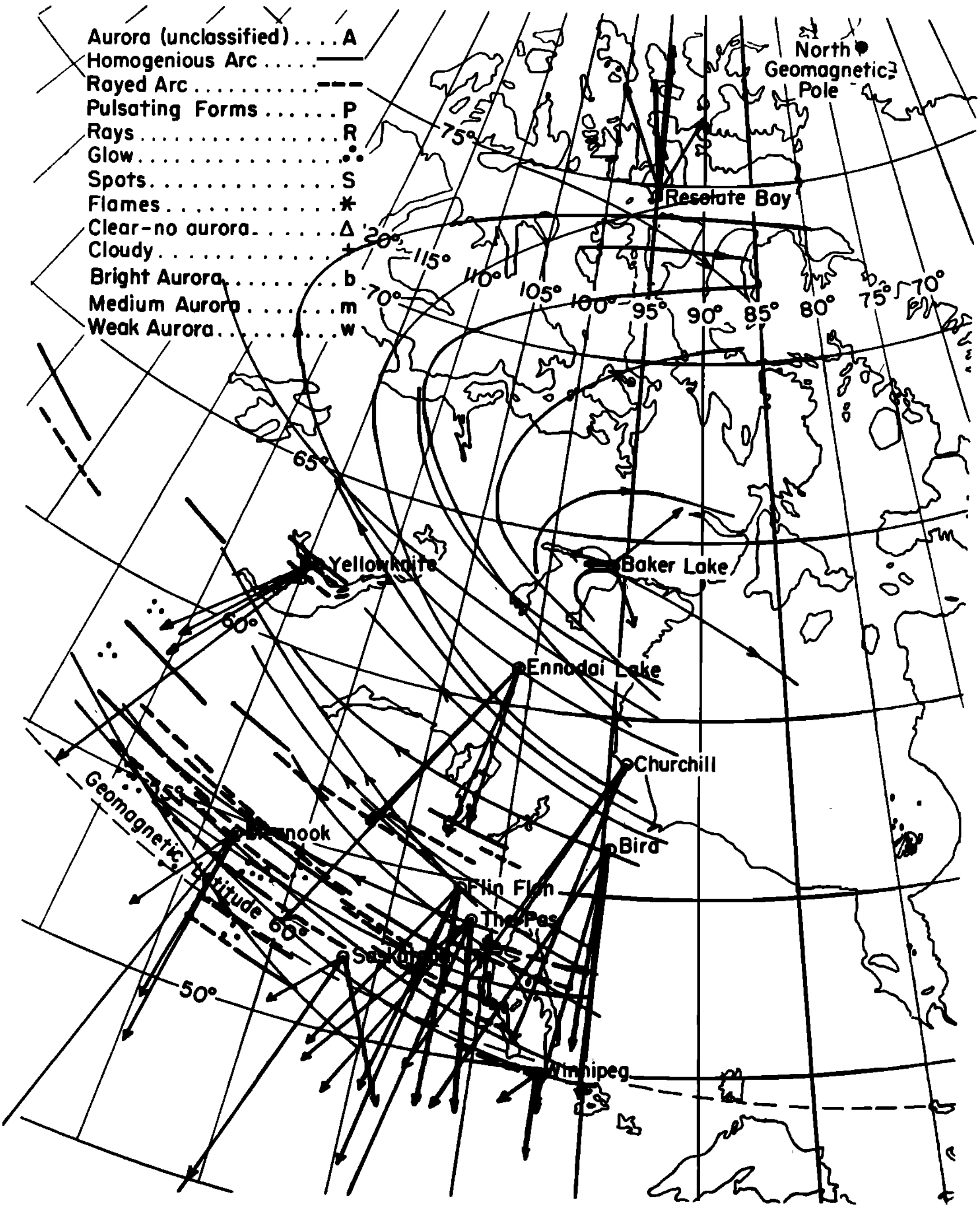

Fig. 5c. Auroral plotting map, constructed by superimposing the 4 maps of 1000 April 16, 0900 April 17, 1100 April 18, and 1000 April 19, 1958. (See legend for Figure 4*a*.)

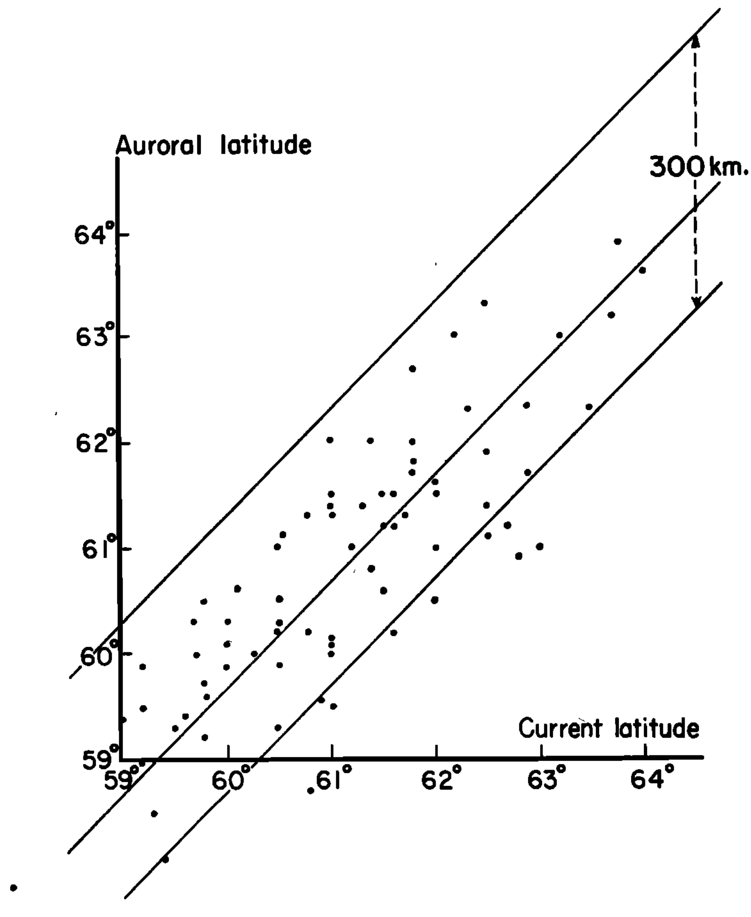

Fig. 6. Geomagnetic latitude of the most southern auroral displays plotted against the geomagnetic latitude of the most southern ionospheric current—April 15, 16, 17, 18, 19, 21, and 24, 1958.

sheets and those of the most southerly auroral displays in the vicinity of these southern stations were measured, with an accuracy of about 0.2°, by overlaying a 'geomagnetic coordinate grid' on the maps. The two sets of auroral and current latitudes thus obtained were compared in two ways.

First, correlation coefficient, $r = 0.85$, was found between the auroral and current latitudes. The 95 per cent confidence limits of r were 0.77 and 0.90.

Indeed, existence of a high correlation is seen from Figure 6, in which the auroral latitudes are plotted against current latitudes. The elongated shape of the cloud of points, along a line inclined at 45 degrees to the axes indicates a high correlation between the two sets of data. This high correlation between the latitudes of currents and auroras on the southern extension of activity suggests that auroras and currents are indeed coincident in time and place.

In view of this evidence a linear relation of the form $Y = X + a$ was assumed between the latitudes of the most southerly current sheets and auroras. From the data of Figure 6, it was found that $a = -0.32° = -36$ km. The line $Y = X - 0.32°$, together with the limits of a 300-km wide hypothetical current sheet, are plotted in Figure 6. The intercept 36 km to the south places an average southern limit for the auroras within this current sheet. However, this 'average' limit has little significance: first, because

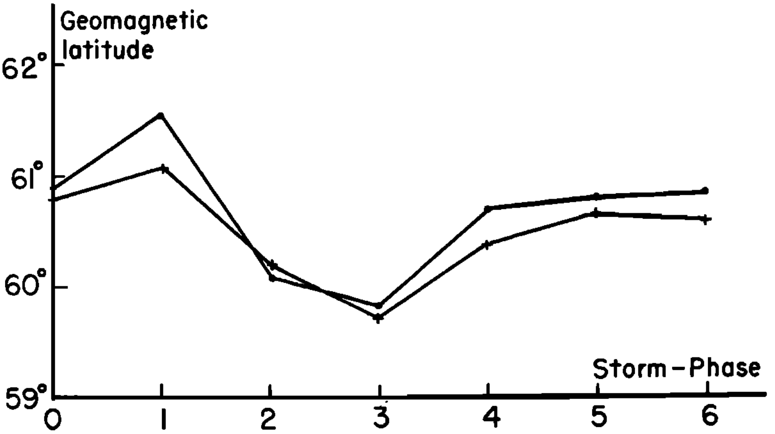

Fig. 7. Geomagnetic latitude of the most southern ionospheric currents and auroral displays at the southern boundary of the auroral zone, plotted against the storm-phase. Averaged data on April 15, 16, 17, 18, 19, 21, and 24, 1958. (·) current latitude, (+) auroral latitude. The duration of all phases (0–6) is roughly 6 hours.

of a fairly large spread of data of Figure 6 around this line and, second, because of a probable displacement of the current patterns caused by neglecting the magnetic effects of the induced earth currents. It should be emphasized here that the width of the currents may not be inferred from this 36-km intercept.

The second comparison of the current and auroral latitudes was made as follows: the two sets of latitudes of the most southerly currents and auroras were classified according to their corresponding 'storm-phase' (as defined above). The averages of all data having the same storm-phase are plotted against storm-phase in Figure 7. The outstanding features of this graph are:

(*a*) The graph of auroral latitudes is parallel to that of current latitudes; i.e., the auroras tend to appear within the sheets of ionospheric currents.

(*b*) The southward shift of the current system of the auroral zone is clearly demonstrated in Figure 7. During the positive phase of the storm (0 and 1 on the graph), currents and auroras both have high latitudes. As the storm develops and reaches its most intense negative phase (2 and 3 on the graph) currents and auroras move southward and again gradually back to north, as the storm decays and vanishes.

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