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The Harang Discontinuity in Auroral Belt Ionospheric Currents*

by

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(1) Introduction

In 1946 L. Harang published a study of high latitude magnetic disturbances which ranks with the works of Birkeland [1908, 1913], Chapman [see Chapman and Bartels, 1940], Vestine [see Vestine, et al., 1947], and their co-workers in setting the stage for describing the latitude vs. local time pattern of the disturbances and the inferred ionospheric currents. Although for many years eclipsed in journals by references to Chapman and Vestine and their co-workers, and later Nagata [e.g., 1963] and his associates and students, Harang's study was singularly significant in recognizing and emphasizing the midnight (or pre-midnight, see later discussion) discontinuity in the auroral zone. His statements in the 1946 paper indicate that he expected the discontinuity in the magnetic disturbance and inferred currents to also appear as a discontinuity in the auroral activity. For example, he states "it would be of special interest to follow the variations in the auroral luminosities during the hours when the storminess in H changes from positive to negative values---" and "it would be of great interest to decide whether there is a parallel discontinuity in the mean movements of the auroras." These expectations were borne out. Heppner [1954] demonstrated that the reversal of E-W currents as indicated by the magnetic disturbance was in space-time coincidence with a transition from comparitively quiet, usually homogeneous, arcs to more active rayed forms with the major change in activity occurring at the time the lowest latitude auroral arc near midnight broke into bright, rapid moving, rayed aurora (i.e., auroral break-up). Davis [1962] demonstrated that the discontinuity was in space-time coincidence with a reversal in auroral motions from E to W at local times preceding the discontinuity to W to E at local times following the discontinuity.

Harang [1946] also expressed views on ionospheric closure of the electrojet currents. Relative to return currents through the lower latitude ionosphere "the hypothesis that perturbing currents flowing in the ionosphere are closed is untenable" and relative to closure over the polar cap "the material is, however, not sufficient to support the view that the perturbing currents as a whole are closed over the polar cap." These are modern views that mesh with journal articles being published today. Particularly because it has become recognized that the most dynamic processes within the magnetosphere (e.g., partial collapse of the magnetospheric tail, major particle energizations, redistributions of trapped particle populations, etc.) occur coincident with sudden changes in the midnight discontinuity, often referred to as substorm onsets, Harang's [1946] diagrams for the disturbance patterns merit more attention than they have received. These patterns can be identified with convective motions; in fact, the basic correctness of the form of Harang's patterns is indirectly confirmed by numerous recent electric field measurements. Nevertheless only a few of the many investigators concerned with high latitude phenomena and their magnetospheric implications have recognized or ascribed any importance to the configuration of the discontinuity where auroral break-up, and associated changes, first appear.

The principal intent of this paper is to direct attention to Harang's contribution by bringing together observations which illustrate the reality and form of the discontinuity near midnight, which we appropriately have named the "Harang discontinuity." In presenting this subject the author is going to draw heavily on his own, and co-workers, observations. A literature review is not attempted. Hopefully others will be motivated to compare their observations with Harang's patterns.

(2) Harang's Discontinuity

High latitude magnetic disturbances and auroral displays have never been found to be completely identical on any two days. Nevertheless, at any single observatory repetitious similarities as a function of local time are immediately obvious. Harang analyzed this diurnal variation in magnetic records as a function of latitude by using a latitudinal distribution of eleven observatories in a small longitudinal sector covering Scandinavia. To see if the diurnal characteristics were dependent on the degree of storminess he separated days into four classes, I-IV, based on the daily sum of the hourly values of the perturbation in the horizontal component, H, at Tromsö. Diurnal curves for each observatory within each class were obtained for each component (H, D, Z) by averaging hourly means. To graphically illustrate the diurnal variation equal values of the perturbations (ΔH, ΔD, ΔZ) were contoured on a conical projection of geomagnetic latitude vs. local time. Figure 1 illustrates the result for one of the four levels of disturbance analyzed. In more recent years it has become well known that longitudinal differences in the diurnal pattern are largely removed by using geomagnetic local time (MLT) in place of solar local time. Thus to make Harang's diagrams applicable to other longitudes the time scale has to be changed. In Figure 1 the change is indicated by tic marks giving the MLT at Tromsö (magnetic latitude = 67.2°). As MLT is not independent of latitude the change in the local time scale is not exact for other magnetic latitudes but the differences are small enough to not affect major characteristics.

The principal feature that made Harang's disturbance pattern distinct from others is that it showed that the reversal in the sign of ΔH in the nightside auroral belt occurred at different local times as a function of latitude as shown in Figure 1. The coincident pattern in ΔZ was consistent with interpreting the ΔH discontinuity in terms of ionospheric currents flowing eastward and westward, respectively, in the southern and northern parts of the auroral belt prior to the reversal becoming complete across the entire belt between 22^h and 23^h MLT. A similar but less striking discontinuity appeared near 10^h MLT on the dayside. Harang [1946] did not emphasize the 10^h discontinuity--possibly because of the weaker magnitudes and its location above 70^o magnetic latitude where his observatory coverage was more limited. Thus, in naming the E-W current reversal the "Harang discontinuity" the term is applied here only to the night time discontinuity. Also, recent investigations of both electric and magnetic field variations have shown the reversal near 10^h to be highly complex, usually involving multiple reversals, such that a simple latitudinal overlap of E-W currents derived from averages is not likely to be as representative of individual cases as it is during the night hours.

It is appropriate to ask why most other analyses of high latitude magnetic disturbance patterns have not shown the latitudinal overlap of + and -ΔH regions (or equivalent E-W currents) in the pre-midnight sector. The answer lies in the averaging and smoothing techniques used relative to how combinations of factors such as the observatory distribution, the mixing of days with different degrees of disturbance, sampling intervals, the universal time distribution of the data, etc. relate to the large spatial asymmetries in magnitude and abrupt changes in sign of the parameters being analyzed. This is easy to recognize which makes it remarkable that the Silsbee and Vestine [1942] analysis has been so widely referenced. Their analysis contained most of the obvious pitfalls and thus is illustrative: for example, between 44^o and 88^o magnetic latitude only 5 observatories were used, individual samples were 3 hour averages, the analysis was based on 9 hours of Universal Time corresponding to times when no auroral belt data below 70.8° was available in the local time sector 18^h - 24^h, and, as Silsbee and Vestine [1942] state, the selection of bays for study was biased toward large values of $-\Delta H$. As to be expected the resulting Silsbee and Vestine [1942] current pattern does not provide a representation of auroral belt disturbance that fits other data in the afternoon and pre-midnight sectors of the auroral belt. Many analyses appear to miss the form of the Harang discontinuity simply because the data is greatly smoothed in space and time; however, some suggestion of Harang's discontinuity has appeared even in highly smoothed representations [e.g., Nagata 1963]. There are also numerous analyses of selected times which give the impression that the pattern of high latitude disturbances is extremely variable and thus might suggest that average patterns such as Harang's are without meaning. In most cases detailed examination of these analyses reveals that the instantaneous distributions are greatly affected by the observatory distribution and the interpolation between widely spaced observatories when the representation is in terms of equivalent currents closed within the ionosphere. Examined critically, the patterns drawn by Grafe [1969] illustrate this point; the techniques in many other analyses have been similar.

The next question is 'how well do Harang's patterns represent the spatial distribution of individual disturbances?' From magnetograms it is obvious that neither positive or negative bays reach maximum intensities at identical magnetic local times on different days even when the days are selectively grouped as in Harang's analysis. Thus the smoothing effect of averaging different days produces a local time distribution with less contrast in magnitude as a function of local time than is present in individual cases. A more subtle effect occurs relative to the location of the nighttime $+\Delta H \rightarrow -\Delta H$ discontinuity. Because negative bay, post-break-up values for $|-\Delta H|$ are in most cases 2 to 8 times greater than ΔH in the pre-breakup positive bay sector, the discontinuity that appears in averages is disproportionally biased toward earlier local times by a small number of individual cases where the discontinuity occurs at an abnormally early MLT. Thus, in the majority of individual disturbances the $+\Delta H \rightarrow -\Delta H$ discontinuity will be located at a somewhat later MLT than the discontinuity that appears in Harang's patterns. Similarly in the pre-midnight sector where $+\Delta H$ and $-\Delta H$ regions overlap in latitude (e.g., between 20^h and 22^h MLT in Figure 1) the discontinuity is shifted slightly toward lower latitudes in the averaging process. These biasing effects, illustrated in more detail by Heppner [1954], are unavoidable when averages are used. A more recent study [Heppner, 1967], involving computer generated movies of the simultaneous disturbance vectors at 25 observatories at 2.5 minute intervals throughout several weeks, showed that the biasing effects in Harang's analysis do not appreciably alter the principal features of the distribution (e.g., to represent a greater fraction of individual disturbances the shift in the MLT of the $+\Delta H \rightarrow -\Delta H$ discontinuity would be approximately one hour). In fact with allowance for these biases and ignoring local enhancements in magnitude (which are obviously obliterated in Harang's averages), the movies show that Harang's average patterns for classes II, III, and IV provide a remarkably good representation of the distribution of the instantaneous disturbance most of the time.

In addition to the four classes, or levels, of disturbance I-IV, Harang [1946] analyzed the nine most intense storms at Tromsö recorded between 1932 and 1937. He found no fundamental differences between these storms and his

Class IV days. In effect because the basic form of his patterns changed very little between Classes II, III, and IV the pattern was basically the same for all Classes II and above. His Class II corresponds roughly to $Kp = 3^-$. His Class I pattern (corresponding roughly to $Kp < 2^-$) differs in that overlapping $+\Delta H$ and $-\Delta H$ regions do not appear and the MLT of the night-time discontinuity is displaced toward earlier hours. Except for this apparent difference for Class I, his finding that the form of the pattern is independent of disturbance level was confirmed by the movie analyses of Heppner [1967]. As the movie analyses did not indicate any basic differences for very weak disturbances, and electric field directions in the auroral belt between 18^h and 22^h appear to be independent of disturbance level, it is likely that Harang's averages for ΔH for very weak disturbances, Class I, may have been influenced by a small baseline error or one of numerous other factors which can influence averages when dealing with small quantities. This is suggested also by the fact that his ΔD and ΔZ diagrams for Class I do not differ appreciably from those for other classes. Thus no significance should be attached to his ΔH difference for Class I. Like all other analyses Harang found that the region of disturbance extended to lower latitudes with increasing disturbance.

(3) The Auroral Discontinuity

Much of the apparent complexity of magnetic disturbances at auroral latitudes becomes less mysterious when the simultaneous auroral behavior is observed in detail. Heppner [1954] was able to demonstrate repetitive relationships between the magnetic disturbance and sequences of occurrence of different auroral forms and the distribution of these sequences in local time and latitude. The typical diurnal behavior during the night hours between 60° and

70° magnetic latitude was illustrated in terms of two patterns, Figure 2. Pattern I (Figure 2) was regarded as the basic pattern; pattern II was included to cover cases, usually of weak disturbance, in which the disturbance and aurora temporarily died out instead of being continuous through the night. Although not drawn in an idealized pattern, highly complex disturbances were shown to result when new bay activations occurred before a previous disturbance died out. The auroral symbolism describes the visible auroral forms which characterize the auroral activity in terms of magnetic local time and latitude and the related stage of development of simple positive and negative bays. The dominant auroral transition is clearly the break between homogeneous forms, usually appearing comparatively stable, and rayed forms, usually brighter, more rapidly moving, and more transient in duration. In Figure 2, Pattern I, this break is indicated by the dotted line AB. Davis [1962] used a similar representation to show the local time vs. magnetic latitude distribution of directions of auroral motions. Figure 3 is an example for a highly disturbed day in which the aurora extended to latitudes $< 60^{\circ}$. The character of the pattern is clearly dominated by the reversal of east-west motions along the line AA' which Davis identified as corresponding to Heppner's line AB, indicated in Figure 2. Davis [1962] found that this reversal was characteristic of every auroral display observed independent of the level of activity. Over 44 nights at College, Alaska (mag. lat. = 64.7°) the total range of local times for the reversal was nearly 6 hours with the average "approximate geomagnetic time" of the reversal falling near 23^{h}. Davis [1962] also found large variations in the alignment of auroral forms associated with the reversal.

Both Heppner [1954] and Davis [1962] found that the simultaneous magnetic disturbance was consistent with ionospheric currents directed eastward before and westward after the local time of the AB (or AA') auroral discontinuity. A station, such as College, Alaska, located near but slightly to the south of the center of maximum activity (most often 66° - 68° in the mid-night hours) is frequently situated such that the magnetic disturbance observed between the local times of B (or A') and A (Figures 2 and 3) is a superposition of effects from westward currents to the north and eastward currents overhead and to the south. As the westward current in the high latitude part of the auroral belt (following AB or AA') is usually more intense than the eastward current in the low latitude part of the auroral belt (preceding AB or AA') the superposition usually gives a small, but variable, $-\Delta H$ at these times. The College magnetograms, H trace, between magnetic times 23^h and 0^h (or local 150th meridian times near 01^h) in Figure 3 provides a typical example. This tendency for the superposition to produce a slightly negative ΔH illustrates the latitudinal bias in Harang's averages, noted in the previous section.

The analyses which showed the AB, or AA', discontinuities coincident with the ionospheric current reversals were performed for a large number of individual nights and disturbances. Thus, they illustrated the reality of Harang's discontinuity independent of statistical averages.

(4) Convection at the Harang Discontinuity

The motions of visual aurora, described by Davis and others, and the motions of auroral ionization irregularities by radio techniques, by Kaiser [1958] and Harang and Tröim [1960], were used by Axford and Hines [1961] as observational evidence for their convective model of high latitude disturbances. This is equivalent to stating that the ionospheric currents are Hall currents and numerous electric field measurements, beginning with the Ba^+ motion studies of Föppl, et al. [1968] and Wescott, et al [1969], have since confirmed that the auroral electrojets are Hall currents. Thus it would appear that convection patterns can be deduced from either the magnetic disturbance [see, e.g., Heppner, 1969] or the auroral motion [see, e.g., Davis, 1971]. The limitations of these procedures are, however, evident. In the case of the magnetic disturbance it is well known [Haerendel and Lüst, 1970; Wescott, et al., 1970] that the intensity of the ionospheric current is more closely related to the ionospheric conductivity than to the magnitude of the electric field. When this consideration is coupled with the fact that the surface magnetic observatory is seeing the integrated effect of the regional ionospheric current it is clear that abrupt changes within the convection pattern cannot be spatially resolved. Contributions from non-ionospheric currents also introduce uncertainties and in regions displaced from the principal auroral currents, such as the polar cap, it has been found [Heppner, et al., 1971] that the magnetic disturbance cannot be related to the overhead ionospheric convection. The limitations in deducing convection from auroral motions are quite different and fall into two general categories: (a) ionospheric irregularities associated with aurora can arise from a variety of mechanisms and without knowledge of cause one cannot be sure that the motions are truly convective, and (b) the particles producing visual aurora are subject to non-convective drifts in the magnetosphere (e.g., from magnetic field curvature and gradients) and thus the precipitation patterns are not necessarily along convective shells and changes in magnetospheric magnetic fields, precipitation energies, etc. will cause apparent motions of aurora that are not closely related to the convection.

Barium release experiments have clearly shown both the applicability and the pitfalls of using magnetic disturbance vectors and auroral motions to deduce convective patterns. For example, there have been a number of cases

[Wescott et al., 1969 and unpublished observations] where the motions of barium ion clouds were almost exactly parallel to auroral arcs and perpendicular to the surface magnetic vector. However, there are other cases [Wescott et al., 1970 and unpublished observations] where the motion of auroral forms has been at a large angle to the Ba^+ cloud motion and their paths have crossed. These obvious exceptions have been observed in association with break-up aurora and transitions in the magnetic disturbance that can be identified with the Harang discontinuity. Thus they illustrate that the discontinuity is a region of instability whose instantaneous form and location is frequently shifting as discussed in Section (5).

Because of the shifting of the discontinuity, the uncertainties in using auroral motions and magnetic vectors, noted above, and the limitation of having a finite number of Ba^+ clouds to observe at one time, it is not possible to obtain a complete instantaneous picture of convection at the discontinuity. However, the Ba^+ motions observed slightly before, during, and shortly after, times when the presence of the discontinuity is indicated by the local magnetic disturbance and aurora, suggest several features that may be general (i.e., each has been observed more than once and each case involves multiple Ba^+ clouds). (1) At local times slightly before (e.g., 0 to 30 min.) the local time of the beginning of a negative bay, convective motions are westward and closely parallel to lines of constant invariant latitude. (2) In space-time coincidence with the beginning of a $-\Delta H$ disturbance and the development of bright rays, rapidly moving within unstable, moving auroral forms, convective motions toward the equator are observed. (3) At local times slightly after the local time of the beginning of a negative bay, while $|-\Delta H|$ is increasing, eastward convective motions are dominant but there is also a significant equatorward component transverse to lines of constant invariant latitudes (examples in Wescott et al., 1969). The observations are idealized in Figure 4(a) by referencing them in local time to a discontinuity arbitrarily drawn to resemble AB in Figure 2 (Note: plotting actual local times and mixing observations from different nights would introduce an unreal randomness relative to the discontinuity location as a consequence of the discontinuity displacements between nights of observation). In Figure 4(b) the idealization is carried one step further by drawing continuity for the convection in this region. Using Ba^+ observations at earlier and later MLT's and in the polar cap, together with the extensive electric field measurements of OGO-6 [Maynard, 1972; Heppner, 1972] the convection pattern could be extended to show its typical form at all local times. This is beyond the scope of the present paper but a point to note is that one of the principal uncertainties in the pattern occurs at local times and latitudes (usually $\geq 69^{\circ}$) where the auroral belt discontinuity merges with the anti-solar polar cap convection. The OGO-6 data in this region frequently suggest the existence of eddy-like flow structures with dimensions of several tens of kilometers to several hundred kilometers. The double reversal of the highest latitude Ba^+ track in Figure 5(a) could be related to such an eddy structure rather than distinct time shifts in the discontinuity as discussed for the examples in Figure 5(b) and 5(c) in the next section. Harang [1946] was perhaps prophetic when he stated "we get the impression that the currents producing the geomagnetic disturbances on the southern edge of the zone move regularly, whereas on the northern, or inner, edge of the auroral zone the currents move more irregularly often forming systems of whirls."

Despite the short-comings of deducing the convection near the Harang discontinuity from magnetic vectors, auroral alignments, and auroral motions, noted above, the results resemble Figure 4(b) [see, e.g. Davis's (1962) contours]. In essence this means that they yield statistically reasonable results when allowance is made for spatial resolution in the case of magnetic field analyses and the possibility of misleading auroral motions and alignments in individual cases.

(5) Time Variability of the Harang Discontinuity

The previous sections have emphasized a picture in which the Harang discontinuity appears to have a fixed location and form in magnetic time and latitude. Dynamic characteristics of the discontinuity were noted primarily to explain how individual events bias averages or typical distributions. The "fixed" picture is necessary to show the form and the most common location of the discontinuity. Next, the variability, particularly as related to initial stages of negative bay development, has to be examined (Note: the term "substorm" or Birkeland's term "polar elementary storm" can be used interchangeably with "bay." The term bay can be used somewhat more precisely to describe individual activity increases within a stormy interval and when needed reference can be made separately to positive and negative bays. It is, of course, even more precise to refer to $\underset{\sim}{\Delta}H$ directly and avoid the semantic confusions that have accompanied these names).

Most descriptions of the near midnight auroral and magnetic activity center on the dynamics accompanying the sudden onset of a large negative bay and a visually impressive auroral breakup (e.g., the extensive descriptions of Akasofu et al., 1964-1966). The attention given these events is understandable because correlations with other observations are the most distinct. However, clearly identified sudden onsets seldom occur more than eight times per 24 hours of UT and the associated duration of outstanding change (i.e., time for $|-\Delta H|$ to reach large values) is usually less than one hour. This means that these descriptions apply less than 8 out of 24 UT hours---and more typically less than 4 out of 24 hours. Thus in describing the variability of the Harang discontinuity it would appear that distinctions might be needed between: (a) universal times displaced from the UT intervals of maximum change accompanying a sudden activation, (b) universal times when magnetograms collectively show growing bay disturbances of considerable magnitude, either or both + and -, but when there is a lack of evidence that the growth involves an identifiable activation time, and (c) universal time intervals embracing the UT's of sudden activations but restricted to the periods of maximum change. In principal the (b) intervals are included under (a); however, it is quite likely that some of the (b) intervals are related to (c) but an activation time is not recognized as a consequence of the discontinuity (i.e., onset location) not being near an observatory at the UT of onset. The ambiguity of (b) has the same implication as noting that there are cases where onsets are not detected and treating (b) as part of (a).

Despite expectation that the sudden bay activations, (c) above, would produce larger shifts in the discontinuity location than shifts at other times, this was not borne out in the movie analyses of $\underset{\sim}{\Delta H}$ by Heppner [1967]. Particularly with recognition that the bias effects in a $\underset{\sim}{\Delta H}$ analysis are largest at the time of negative bay increases only a questionable tendency for larger shifts in MLT was evident. In essence, this confirms Harang's finding relatively little difference in pattern as a function of disturbance level but applies it to a dynamic condition (i.e., the variability during times of large change is not greatly different than the variability observed at other times). The most characteristic behavior in the movie analysis was that the transition from + to -ΔH disturbance progressed rather smoothly, moving successively from one auroral belt observatory to the next as the earth rotated. In several longitudinal sectors the observatory separations were 1 to 2 hours in MLT which meant that the MLT shifting of the discontinuity was confined to less than 2 hours of MLT much of the time. However, intermittently superimposed on this general behavior, discrete jumps, in which the shifting between observatories took place within 10 to 20 minutes, were evident. In total these observations indicated that there could be considerable small scale motion of the discontinuity, apparently independent of disturbance level, but that major sudden shifts over ranges as large as 3 hours in MLT must be rare. A different form of exception to a completely fixed pattern was noted following some of the sudden shifts to earlier MLT's; in effect, the discontinuity gradually returned to later MLT's at approximately the earth's rate of rotation. This implies that to some extent the pattern tries to rotate with the earth but that the forces involved are apparently weak compared to the forces that give the basic pattern.

The variability of the discontinuity in terms of auroral forms and motions [Heppner, 1954; Davis, 1962] appears compatible with the ΔH movie analyses. Segments of the lines AB or AA' in Figures 2 and 3 in some cases correspond to a slow east to west progression of the auroral transformation across the observers sky (e.g., most apparent when the east end of a homogeneous arc bends northward to form a partial loop open toward the west). In select cases the transformation within an east-west arc appears to take place over its visible length within periods as short as 10 minutes. The latter cases suggest sudden shifts of the discontinuity $\geq$ 2 hours in MLT at the arc latitude; however, they must be interpreted with caution in view of recent findings of non-convective auroral motions during the break-up phase (noted below). In general, however, auroral observations used with the magnetic data improve the resolution for studying the shape of the discontinuity (i.e., its trace in magnetic local time vs. latitude projection) over that possible using only magnetic data. In extreme cases MLT differences ranging up to 5 hours have been observed between points B and A in representations like Figure 2 (Pattern I) with A occurring well after magnetic midnight. A speculative point for investigation is whether or not these cases are indicative of the tendency for the pattern to rotate with the earth, as mentioned previously. The other extreme that of zero time difference between B and A cannot be proven in terms of magnetic field and auroral observations as it involves prediction in regions where aurora is absent (e.g., Figure 2, Pattern II). It is significant, however, that there are not any documented cases of B (or A') (Figures 2 and 3) occurring at a later MLT than A. Neglecting the uncertain zero time difference cases, values of 30 minutes to 3 hours between B (or A') and A are characteristic. Figure 5(c) is an attempt to be more statistical between magnetic latitudes 60 and 70°. Based primarily on the observations of Heppner and Davis a conservative estimate is that at least 66% of the time both points B (or A') and A fall between the lines 2 and 3 and at least 95% of the time between lines 1 and 4.

Two examples of the motions of Ba^+ clouds (Figure 5, b and c) illustrate apparent stability and shifting, respectively, of the Harang discontinuity. Both illustrate non-convective auroral motions. In Figure 5(b) the two lowest latitude clouds, labelled I1 and I2 at the release points, moved southward as well as westward in invariant latitude during the first 10 minutes of observation. Simultaneously: (a) auroral arcs in the same vicinity showed rapidly moving rays and progressed poleward across the magnetic shells of the Ba^+ clouds and

(b) the magnitude of the existing $+\Delta H$ disturbance of an observatory at the right edge of the figure near $\Lambda = 66.6^{\circ}$ decreased to values near zero. After this initial period the clouds moved westward parallel to invariant latitude lines. The higher latitude cloud, I3, moved principally southward throughout observations. These motions suggest a highly stable discontinuity location passing through I3 but with I1 and I2 on the westward fringe of the discontinuity such that the initial westward component progressively moved them away from the discontinuity.

Figure 5(c), in contrast to Figure 5(b), illustrates a shifting discontinuity. In this case the dominantly westward early motion (beginning at release points I1, I2, I3, and I4) turned southward between 49^m (I1) and 54^m (I4). At 51^m: (a) ΔH at the earth's surface began a rapid change toward large $-\Delta H$ values, and (b) auroral arcs to the south brightened and moved poleward. The poleward moving aurora later crossed the magnetic shells of the Ba^+ clouds as in the previous case. The latest observations shown (e.g., I3 at 02^m) indicate that the motion was turning from southward to eastward. As the initial westward motion was faster than the earth's rotation the discontinuity had to rapidly shift toward an earlier MLT to reach the Ba^+ cloud positions.

(6) Continuity of Current at the Harang Discontinuity

As quoted in the Introduction, Harang [1946] considered it untenable that the auroral belt currents closed their circuit through lower latitudes and stated that closure over the polar cap could not be supported in terms of the limited data available. These opinions came from examination of the pattern of current vectors using Birkeland's technique of drawing these vectors perpendicular to the horizontal disturbance vectors with magnitudes proportional to the disturbance. He did not speculate further on the closure and as late as 1966 (personal communication) still regarded this as an unresolved problem. In 1946 he did, however, pursue the question one step beyond the current vectors by drawing the indicated directions of current flow to and from the auroral belt. As shown in Figure 6 for Class IV disturbances this flow was drawn relative to center lines of the evening eastward and morning westward currents. As indicated in his other diagrams, center lines for all classes of disturbances were constructed from both ΔH and ΔZ and tested for compatibility. The dominant characteristic of Figure 6 is the outflow of current on the nightside with the distribution of outflow centered on the region of latitudinal overlap of eastward and westward currents (i.e., the discontinuity).

Recently in seeking explanation for disagreement between the convective motion of Ba^+ clouds in the polar cap and the existence of current closure via the polar cap ionosphere Heppner et al. [1971] concluded: (a) that neither the middle latitude night-side ionosphere nor the polar cap ionosphere was sufficiently conducting to provide continuity for the auroral electrojets, (b) that variations in the ratio of (grad N)/N to (grad $\underset{\sim}{E}$)/$\underset{\sim}{E}$ in sub-zones of auroral precipitation were such that the ionospheric Hall currents would close via field-aligned current flows to and from the magnetosphere (N = lower ionosphere plasma density, $\underset{\sim}{E}$ = electric field intensity), (c) that the magnetic disturbance vectors in both the polar cap and regions adjacent to the low latitude boundary of auroral activity could be explained in terms of two sheet currents flowing "out of" and "into" the auroral belt ionosphere, respectively, in the magnetic local time sectors 20 - 24^h and 8^h - 12^h, and (d) that a distribution of precipitation which would give maximum ionization in the region of electrojet current reversal would also make this region the mean location of a net field-aligned current. In essence, when idealized further the magnetic time vs. latitude trace of the Harang discontinuity became the horizontal intercept of a field-aligned current sheet. The sheet associated with the Harang discontinuity represented a net inflow of electrons. A net outflow of electrons (or inflow of ions) in the 8 - 12^h sector was required for continuity and explanation of the $\underset{\sim}{\Delta H}$ vector in adjacent regions but the sheet configuration was less certain. Between these sectors field aligned currents were flowing "in" and "out" but the net current was small compared to that near the regions of current reversal when viewed in terms of widespread effects.

Unfortunately, the authors (Heppner et al., 1971) had forgotten Harang's "lack of continuity" diagram (Figure 6) at the time of the above study and it is not referenced. It would have geometrically supported the conclusions reached. Converted to field aligned flow the arrows on the night side would leave the ionosphere in the regions where they depart significantly from E-W flow. This gives outflowing currents distributed toward earlier and later MLT, respectively, in the higher and lower latitude portions of the auroral belt--i.e., a mean distribution following the discontinuity.

(7) Related Topics

Detailed studies contrasting the energy spectra and composition of particles precipitating at and on opposite sides of the Harang discontinuity have apparently not been carried out for ionospheric altitudes. Through association with stages of auroral and magnetic activity some information is potentially available from rocket and satellite measurements. Indirectly from radio wave absorption, sporadic-E, and auroral photometric studies it is known that the precipitation during and following breakup must be more intense and penetrating than prior to breakup; however, more subtle differences should be sought. At synchronous satellite altitudes the reality of a discontinuity has been apparent in a number of studies [e.g., Lezniak and Winckler, 1970; DeForest and McIlwain, 1971] but its L vs. MLT form is not revealed at a constant distance.

Because the magnetosphere and ionosphere form a feedback system it has been impossible to distinguish whether events such as sudden bay onset have a magnetospheric or ionospheric origin point. Thus, magnetospheric events can be treated as the logical consequence of an ionospheric short-circuiting (e.g., Heppner et al., 1967) in the reversal region but this does not specify the cause of the short-circuiting which is likely to be closely tied to conductivity changes resulting from a change in the precipitating particle flux from the magnetosphere. One important point, consistent with the feedback characteristic, is that sudden bay onsets of appreciable magnitude occur only when aurora is already present. Another important point is that electric field measurements [Heppner, 1972] are not consistent with invoking major changes in the global electric field as a cause of bay activations. Similarly, as discussed here, the basic properties of the Harang discontinuity do not change with the level of disturbance. The Harang discontinuity is, however, the ionospheric locus of initial sudden change when a bay activation occurs. This suggests that the search for instability mechanisms should be directed to the conditions found at the location of the discontinuity. Equatorward convection, transverse to L shells, and the presence of auroral forms predominantly aligned parallel to L shells are two such conditions. Thus at the Harang discontinuity the conditions are optimum for obtaining a mixing of plasma populations having distinctly different energy spectra. Detailed time-space mapping at and near the discontinuity for all particle energies, including the cold plasma, is difficult to achieve operationally for the scale involved and the difficulty is compounded by a need for selecting the most appropriate times. However, this is an objective worthy of pursuit that could be approached in a limited way using existing particle data relative to auroral and magnetic field determination of the instantaneous location of the discontinuity--with careful attention to the limitations of these techniques. Simultaneous electric field (i.e., convection) mapping would be required for the ideal experiment.

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FIGURE CAPTIONS

Figure 1 : Contours of equal ΔH, ΔD, ΔZ for Harang's [1946] Range III disturbance levels: Solid lines (+ ΔH, + ΔZ, West dec.), dotted lines (- ΔH, - ΔZ, East dec.), heavy dashed lines for ΔH and ΔZ indicate the center of the current system. Original coordinates are magnetic latitude and solar local time. The magnetic local time scale is added for ΔH.

Figure 2 : Idealized patterns of simultaneous auroral and magnetic activity from Alaska observations of Heppner [1954]. The line AB (Pattern I) represents the Harang discontinuity.

Figure 3 : Directions of auroral motions with simultaneous College, Alaska magnetogram for one night from Alaska observations of Davis [1962]. The line AA' corresponds to the Harang discontinuity.

Figure 4 : (a) convective motions of Ba^+ clouds relative to the Harang discontinuity, idealized from northern Norway observations of Wescott, Stolarik, and Heppner (see text), (b) convective continuity indicated for the region of the Harang discontinuity, (c) ranges of variability in the location of the Harang discontinuity (see text): coordinates are magnetic local time and invariant latitude.

Figure 5 : Horizontal tracks of Ba^+ clouds projected along magnetic field lines to the 100 Km altitude level. Invariant latitude lines ( ) are superimposed on the geographical grid. Numbers along tracks are minutes of the hour in (c) (2 digits) and minutes and seconds in (a) and (b) (4 digits).

From rocket release experiments at Andennes, Norway by Wescott, Stolarik, and Heppner.

Figure 6 : Harang's [1946] representation of directions of in-flow and out-flow of currents from the center of the auroral belt currents, indicated by the dashed lines. His coordinates were magnetic latitude and solar local time. An approximate magnetic local time scale has been added (outer time scale).

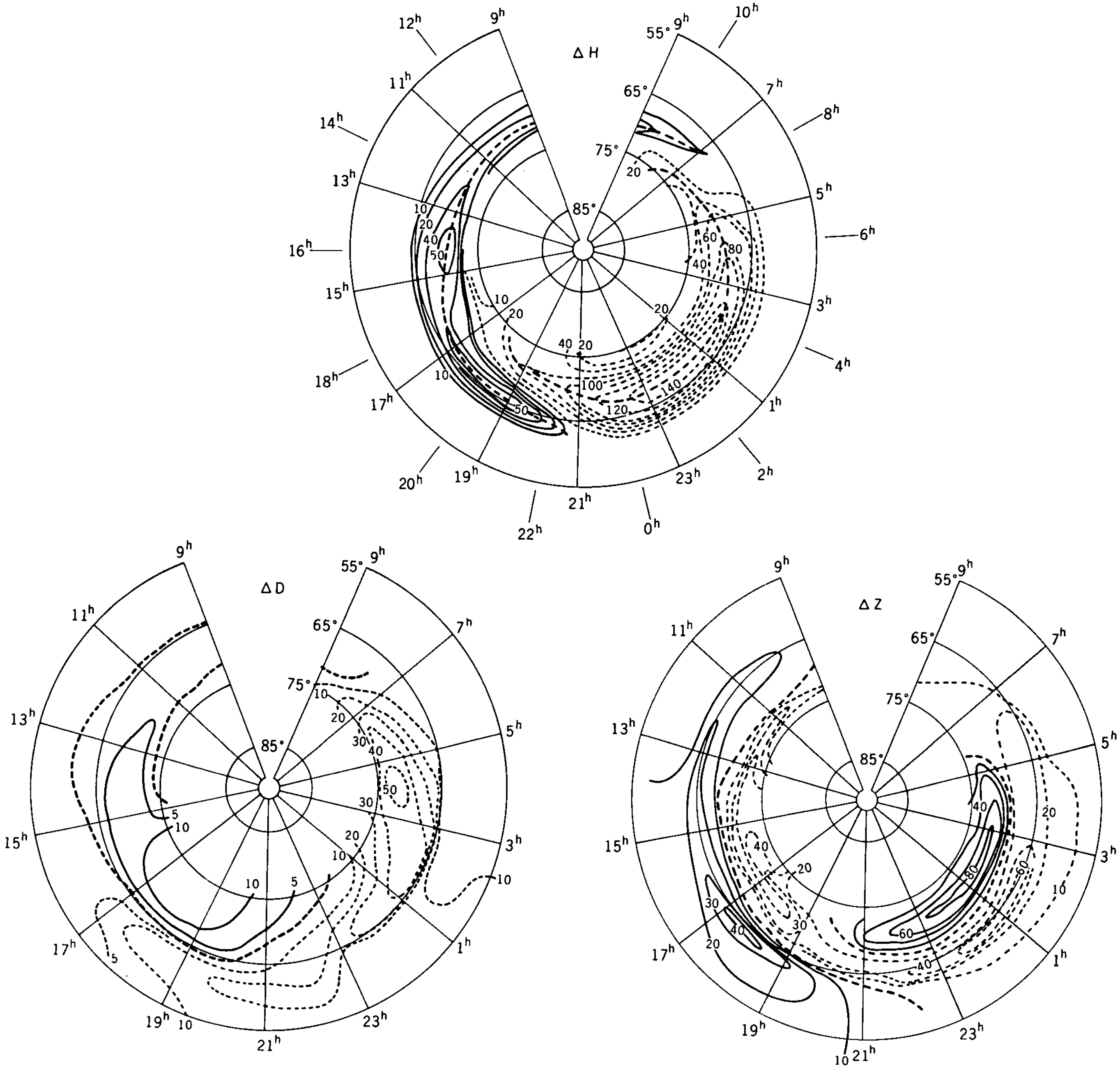
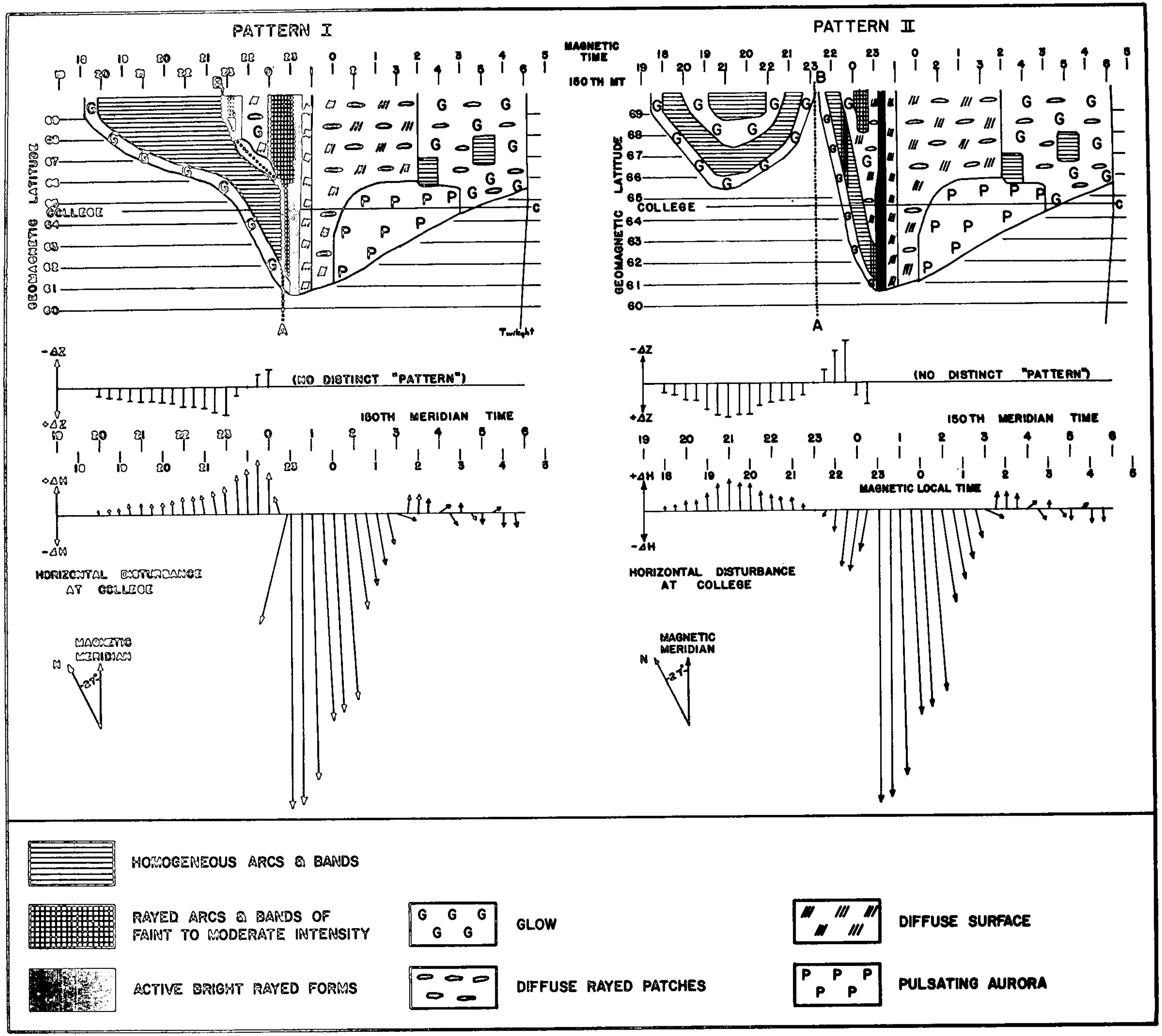

ΔH
ΔD
ΔZ
55°
65°
75°
85°
9h
10h
11h
12h
13h
14h
15h
16h
17h
18h
19h
20h
21h
22h
23h
0h
1h
2h
3h
4h
5h
6h
7h
8h

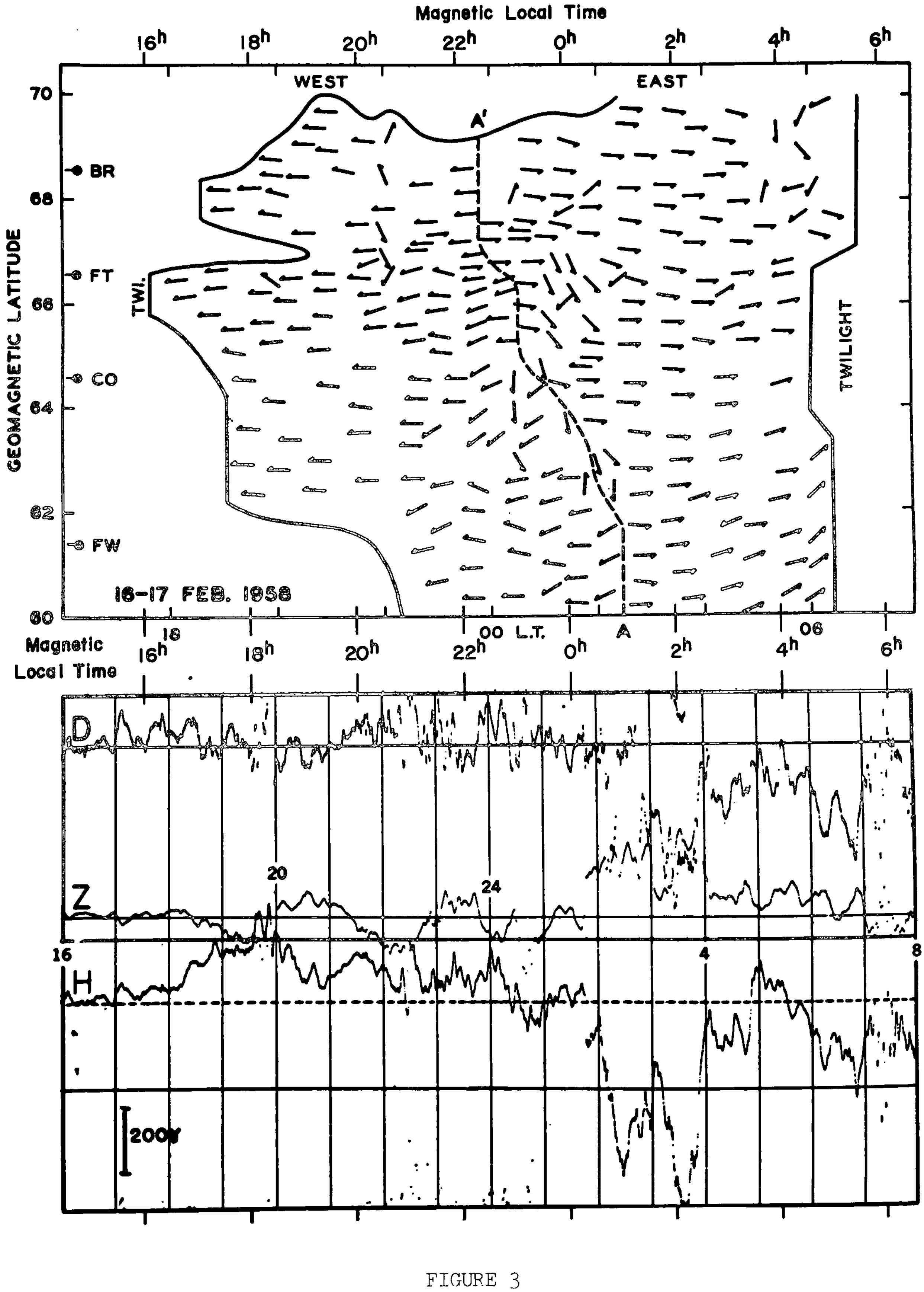
FIGURE 1



PATTERN I
PATTERN II
MAGNETIC TIME
150TH MT
GEOMAGNETIC LATITUDE
COLLEGE
Twilight
(NO DISTINCT "PATTERN")
150TH MERIDIAN TIME
MAGNETIC LOCAL TIME
HORIZONTAL DISTURBANCE AT COLLEGE
MAGNETIC MERIDIAN
HOMOGENEOUS ARCS & BANDS
RAYED ARCS & BANDS OF FAINT TO MODERATE INTENSITY
ACTIVE BRIGHT RAYED FORMS
GLOW
DIFFUSE RAYED PATCHES
DIFFUSE SURFACE
PULSATING AURORA

FIGURE 2

28



Magnetic Local Time
16h
18h
20h
22h
0h
2h
4h
6h
WEST
EAST
A'
A
70
68
66
64
62
60
BR
FT
CO
FW
GEOMAGNETIC LATITUDE
TWI.
TWILIGHT
16-17 FEB. 1958
18
00 L.T.
06
Magnetic
Local Time
D
Z
H
20
24
16
4
8
200γ

FIGURE 3

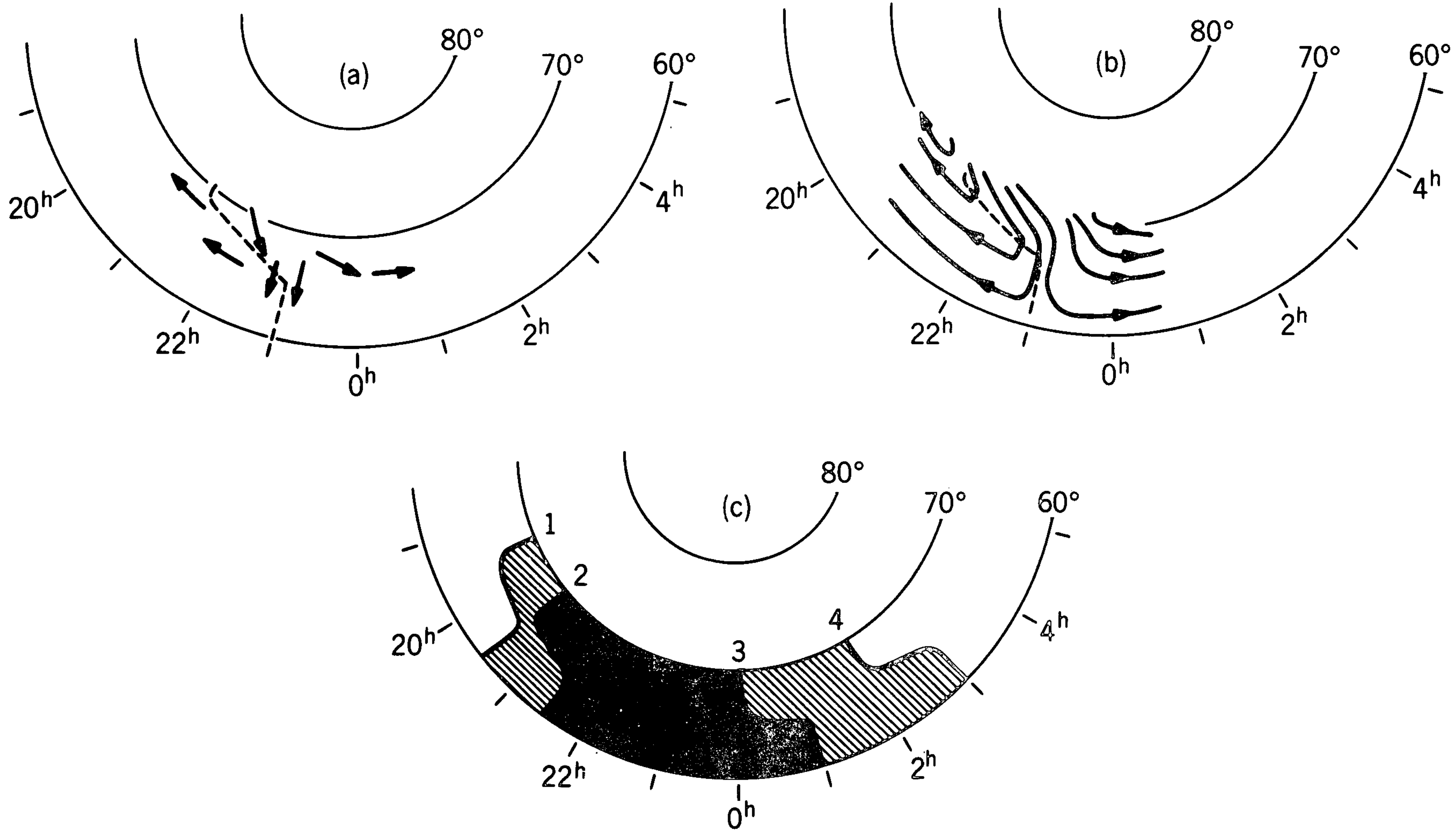

(a)
80°
70°
60°
20h
22h
0h
2h
4h
(b)
80°
70°
60°
20h
22h
0h
2h
4h
(c)
80°
70°
60°
1
2
3
4
20h
22h
0h
2h
4h

FIGURE 4

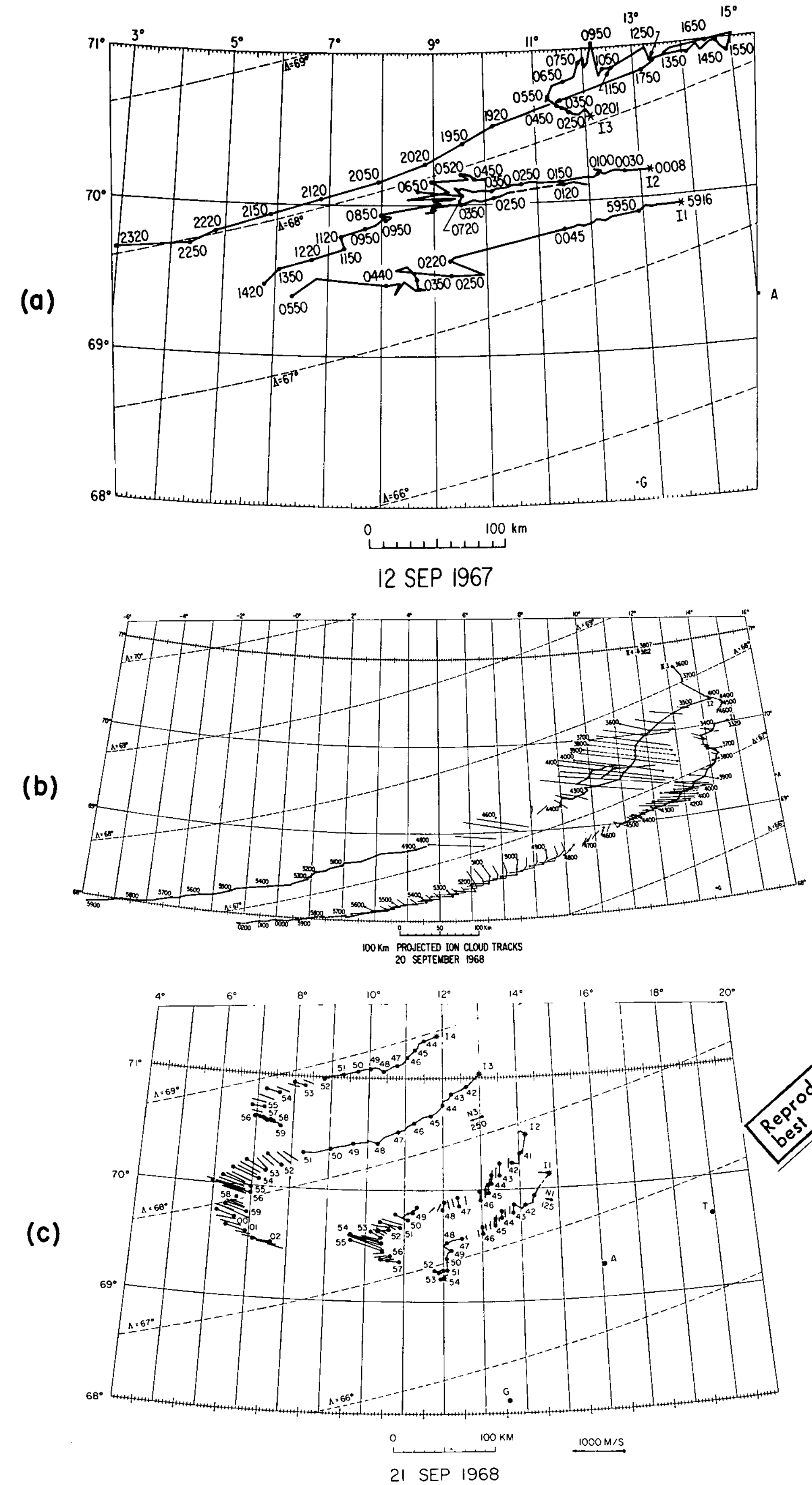

(a)
12 SEP 1967
0 100 km
(b)
100 Km PROJECTED ION CLOUD TRACKS
20 SEPTEMBER 1968
(c)
0 100 KM
1000 M/S
21 SEP 1968

FIGURE 5

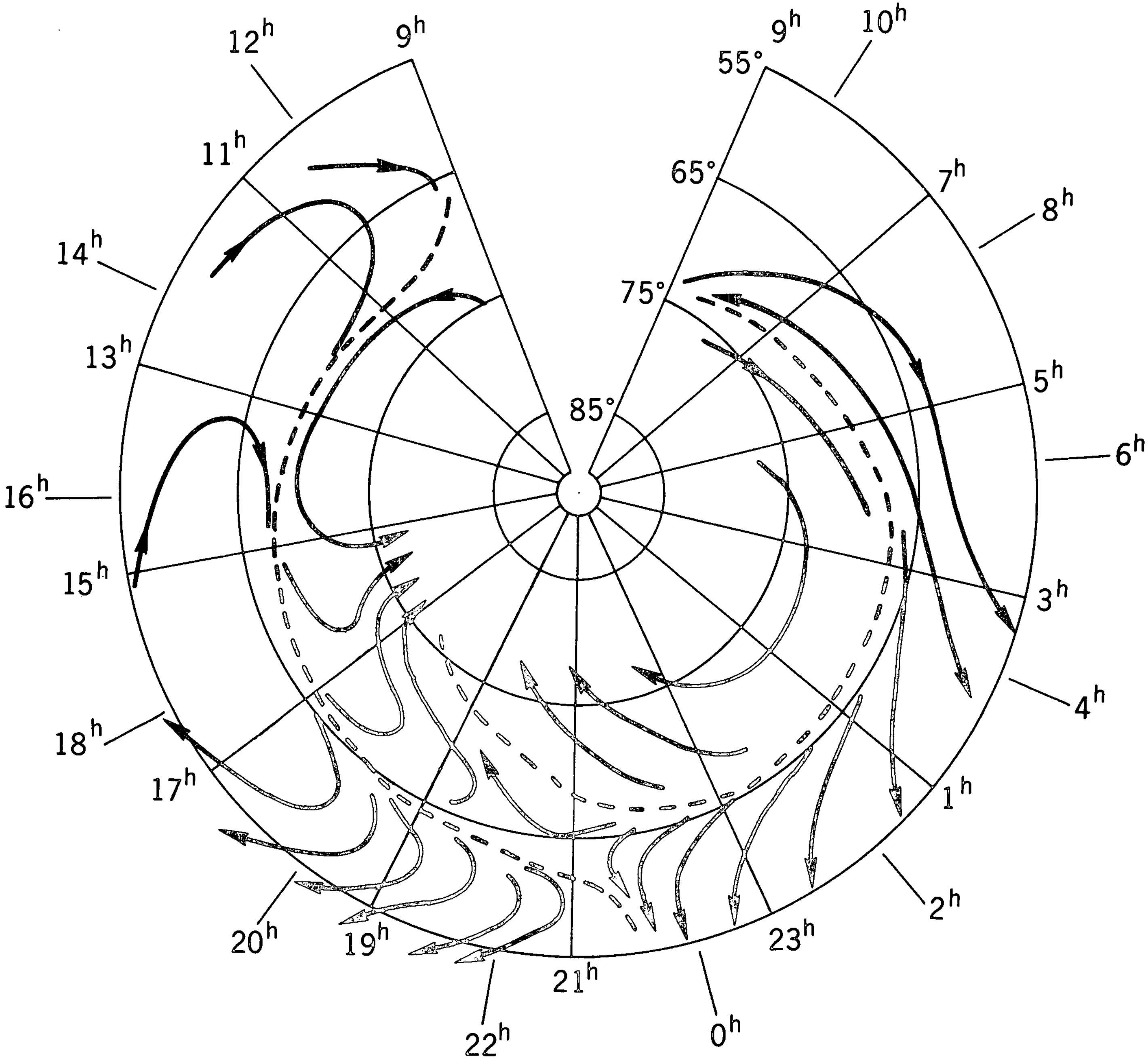

12h
9h
55°
9h
10h
11h
65°
7h
8h
14h
75°
13h
5h
85°
6h
16h
15h
3h
4h
18h
17h
1h
2h
20h
19h
23h
21h
22h
0h

FIGURE 6