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magnetic substorms, december 5, 1968

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Contents

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Abstract. Magnetograms from 26 auroral and polar cap observatories and total intensity data from Ice Island T3 were used in the analysis of an intense polar magnetic substorm which developed at 08 U.T. on December 5, 1968. The magnetic effects were interpreted as resulting from a double substorm. The changing orientation of the equivalent current vector at Thule, close to the geomagnetic pole, was found to represent very closely the time development of the storm.

Equivalent currents, calculated from both the horizontal and vertical components of the magnetic perturbation vector, supported the Akasofu model of the auroral oval for the expansion and early recovery phases of the storm. Prior to the westward surge and following the end of the substorm there was some evidence for an SD-type (two-celled) current system, but the available data were insufficient to verify this. A velocity of 1.1 km/sec for the westward surge and an expansion of the auroral oval by about 15° in the midnight sector were inferred from the magnetic effects. The direction of current flow in the oval was parallel to the auroral zone a few hours after local midnight. The poleward contraction of the oval was very rapid in the recovery phase of the storm, with the storm centre returning to a position considerably east of the local midnight meridian.

A class of intense substorms for the years 1962 – 1969 was identified from the occurrence on the Mould Bay magnetograms of indented positive H bays around local midnight. These substorms occurred mainly in the winter and equinox, and were most numerous in the years immediately preceding sunspot minimum. No clear relationship was found between the occurrence and intensity of these substorms and the Dst index.

Résumé. Des enregistrements magnétiques provenant de 26 observatoires de la zone aurorale et de la calotte polaire et les données sur l'intensité totale provenant de l'île de Galce T3 ont servi à l'analyse du sous-orage magnétique polaire intense du 5 décembre 1968 à 8 heures (heure universelle). On a interprété les effets magnétiques comme le résultat d'un sous-orage double. L'orientation changeante du vecteur du courant équivalent à Thule près du pôle géomagnétique a presque coïncidé avec l'évolution de l'orage.

Les courants équivalents calculés à partir des composantes horizontales et verticales du vecteur de perturbation magnétique sont conformes au modèle d'Akasofu de l'ovale auroral des phases d'expansion et de diminution de l'orage. Avant la poussée vers l'ouest et après le sous-orage, certaines indications portaient à croire qu'il existait un réseau de courant de type SD (à deux cellules), mais il a été impossible de procéder à une vérification en raison de l'insuffisance de données. On a déduit d'après les effets magnétiques que la poussée vers l'ouest avait une vitesse de 1.1 kilomètre à la seconde et qu'il y avait eu une expansion d'environ 15° dans le secteur de minuit de l'ovale auroral. La direction du courant dans l'ovale était parallèle à la zone aurorale quelques heures après le minuit local. La contraction de l'ovale vers le pôle a été très rapide pendant l'accalmie de l'orage dont le centre est revenu à une position considérablement à l'est du méridien local de minuit.

Une variété de sous-orages intenses entre 1962 et 1969 a été identifiée grâce à l'inversion du sens de la variation H autour du minuit local sur les enregistrements magnétiques de Mould Bay. Ces sous-orages ont eu lieu principalement l'hiver et au temps de l'équinoxe et sont plus fréquents au cours des années précédant immédiatement les périodes de faible activité solaire. On n'a trouvé aucun lien entre la fréquence et l'intensité de ces sous-orages et l'index Dst.

Introduction

One of the most spectacular features of auroral zone and higher latitude magnetograms is the frequent occurrence during the night hours of large negative bays, lasting about an hour, in the horizontal component. Detailed studies of these disturbances, known as polar substorms, or polar elementary storms in the older terminology of Birkeland, show that they occur along the belt which contains the active aurora (Akasofu, 1968). If it is assumed that the geomagnetic disturbances are due to electric currents flowing in the ionosphere, it is found that the currents generally coincide with visible aurora, in position, direction and intensity (Walker, 1964; Kim and Wang, 1967). The belt containing the active aurora is approximately an oval, eccentric about the dipole axis pole and elongated toward the equator in the local midnight sector (Feldstein, 1963). The auroral zone at 67° dipole latitude is now seen to be the locus of the midnight position of the auroral oval. The polar magnetic substorm itself is only one manifestation of the more general magnetospheric substorm which includes also auroral and ionospheric substorms, and well-defined micropulsation, cosmic noise, and x-ray disturbances.

It is probable that the currents which give rise to polar magnetic substorms are three-dimensional and flow along field lines as well as in the ionosphere (Akasofu and Meng, 1969; Bostrom, 1967). Results of a rocket-borne experiment at Fort Churchill on February 26, 1969 have been interpreted as showing the existence of field-aligned sheet currents associated with the visible auroral arc (P.A. Cloutier *et al.*, 1970). Fukushima (1969) has shown that it is not possible using only geomagnetic data observed on the ground, to determine whether the current system responsible for polar elementary storms flows only in the ionosphere or along field lines as well. However, it is useful in studying the form of the oval and its changes with time, to determine an equivalent current system in the ionosphere (not the actual current system) which could give rise to the observed magnetic effects.

Essentially two models have been used to represent the equivalent flow pattern of the auroral electrojet in the ionosphere which causes polar magnetic substorms: a modification of the Silsbee and Vestine (1947) SD current system, and the Akasofu and Feldstein models (Akasofu, Chapman and Meng, 1965; Feldstein and Zaytsev, 1965). The first is a two-celled model in which an intense electrojet flows westward along the auroral zone in the dark sector. The circuit of each electrojet is completed by return currents flowing across the polar cap toward the dawn sector. Akasofu and Feldstein represent the electrojet as flowing westward all around the oval. In Akasofu's representation, the eastward flowing currents in the afternoon and evening hours are explained as leakage currents from the westward electrojet, whereas Feldstein interprets these currents as forming an independent system. The co-existence of the auroral electrojet and the twin-vortex current in the polar region has been postulated by Iijima and Nagata (1968) and Fukushima (1969).

In view of the unresolved problems concerning the generation of polar magnetic substorms and the existence of several conflicting models of the ionospheric and field-aligned currents which give rise to the magnetic effects, it is important to study the development in time and space of many individual substorms. From such studies it may be possible to synthesize a model magnetic substorm, or at least to recognize a limited number of classes of such storms, in order to test existing theories in a more rigorous fashion. The present paper analyzes the intense substorm which developed at 08 U.T. on December 5, 1968, with particular emphasis on the observed morphology of the auroral oval.

Analysis of magnetic data

Magnetograms from 26 auroral and polar cap observatories and total intensity data from Ice Island T3 were used in this analysis. These stations are shown on the map in Figure 1. Geomagnetic co-ordinates, the angle Ψ between the geographic and geomagnetic meridians, and the Universal Time of local midnight, are listed in Table I for each station.

Deflections of H, D (X, Y) and Z from the baseline were measured at approximately nine-minute intervals from 0624 to 1339 U.T. Perturbations from the midnight level of the quiet day December 14 (or December 2 in a few cases) were then expressed in the geomagnetic co-ordinate system X′, Y′, Z. Plots of magnetic perturbation vectors ΔX′, ΔY′ ΔZ, contours of ΔZ, and equivalent line currents, calculated from the three perturbation vectors for a height of 112 km (equivalent to one degree of latitude), were drawn for a number of instants of time during the storm.

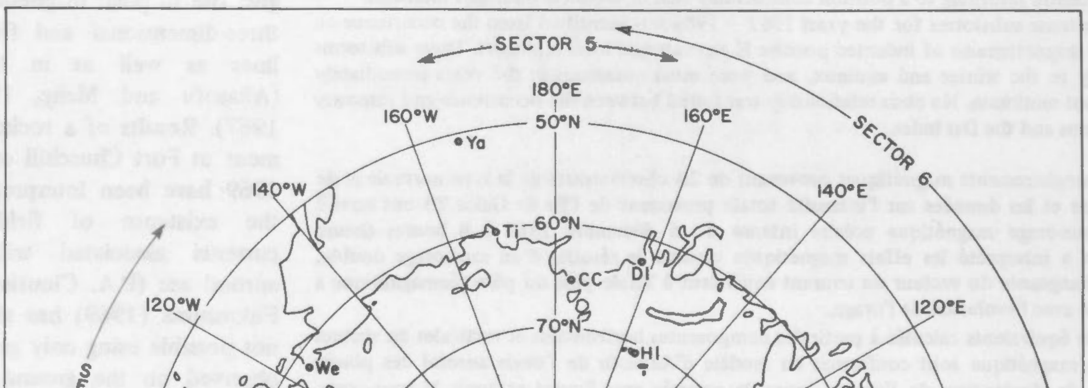

Figure 1. Map in geomagnetic co-ordinates showing the stations used for this analysis and their grouping into six sectors.

Table I

		Geomag.Co-ords. Lat.N	Long. E	ψ_E	U.T. of local midnight (hrs)			Geomag.Co-ords. Lat.N	Long.E	ψ_E	U.T. of local midnight (hrs)
Th	Thule	89.2	357.4	2.4	04.61	Ab	Abisko	65.9	115.3	330.2	22.75
Al	Alert	85.7	168.7	197.7	04.17	Co	College	64.6	256.1	27.6	09.86
RB	Resolute Bay	83.1	287.7	47.1	06.33	DI	Dixon Is.	62.8	161.7	347.0	18.63
Go	Godhavn	80.0	33.1	341.8	03.56	Le	Lerwick	62.5	89.0	336.0	00.07
MLB	Mould Bay	79.1	255.4	55.3	07.96	Me	Meanook	61.9	300.7	17.5	07.55
BL	Baker Lake	73.9	314.8	19.4	06.40	We	Welen	61.6	236.8	24.8	11.32
Na	Narssarssuaq	71.4	37.3	345.2	03.02	Ti	Tixie Bay	60.3	192.6	351.9	15.40
HI	Heiss Is.	71.1	156.3	330.0	20.13	Si	Sitka	60.0	275.0	21.8	09.02
Leir	Leirvogur	70.3	71.6	333.8	01.45	Nu	Nurmijarvi	59.6	114.4	336.4	22.36
Ch	Fort Churchill	68.8	322.5	13.8	06.27	St. J	St. John's	58.7	21.4	353.7	03.51
PB	Point Barrow	68.4	240.7	33.5	10.45	Ot	Ottawa	57.0	351.5	2.4	05.04
GWR	Great Whale River	66.8	347.2	4.5	05.18	Vi	Victoria	54.3	292.7	16.4	08.23
CC	Chelyuskin Is.	66.1	176.5	356.6	17.05	Ya	Yakutsk	50.8	193.8	5.9	15.35
						T3	Ice Island T3	79.2	209.6	84.6	09.02

Note that ψ_E, the angle between the geographic and geomagnetic meridians at a station, is measured eastward from the geographic meridian.

Calculations of ΔX, ΔY, from ΔH, ΔD, and of ΔX′, ΔY′, ΔZ, and the equivalent line current plots were programmed on the Hewlett-Packard desk calculator and plotter. In calculating the line currents, it was assumed arbitrarily that 25 per cent of the observed magnetic effect could be attributed to induction within the earth. The equivalent currents were calculated using both the horizontal and vertical components of the perturbation vector, whereas the usual practice has been to derive an overhead current density from the horizontal components only. The vertical component was included in the calculations for the sake of completeness, and to give some estimate of the position of the equivalent current north or south of the station. In a few cases, for stations near the centre of a current circulation, when very large Z effects were associated with small perturbations in the horizontal components, the current intensity and distance from the station are obviously unrealistic (e.g. Baker Lake at 0830, Figure 3). It is evident that the equivalent line currents have only limited physical validity, and precise contours of current flow were not attempted. The current plots are used as illustrations only of the development and changes in time and space of the currents flowing in and near the auroral oval.

KP indices for December 5 for the eight three-hour U.T. intervals were

3– 3o 5+ 5o 4o 3– 3+ 3–

The Dst indices had a small positive maximum of three gammas at 08 U.T. and a minimum of −48 gammas at 01 U.T. on December 6.

Auroral data for December 5, 1968

Auroral information available from the National Research Council of Canada, was unfortunately limited, as all-sky camera data were missing from the Churchill, Great Whale River and Ottawa sites owing to cloud cover.

The auroral radar at Thompson (Φ65N; Λ317.5E) recorded very intense echoes between 0330 and 0400 and around 0800 U.T. Echoes of comparable intensity were recorded at Ottawa between 0830 and 0900 and at Churchill at 0500. Slightly less intense echoes were observed at Churchill in the interval 08 – 09.

The visual observations of aurora reported for the night are as follows:

A bright rayed arc 30° above the horizon north of Saskatoon at 08 U.T.

Weak homogeneous arc (WHA) 30° above the horizon north of Cape Parry (70.2N, 124.7W) at 09 U.T. (7/10 cloud).

Series of glows and rays to SW and SE of British Arctic Expedition Ice Island (geographic co-ordinates 85N; 149.2W) at 10 U.T. No cloud, but a bright full moon was reported.

WHA 30° above the horizon north of Saskatoon at 1145.

WHA 10° above the horizon north of Regina Airport (50.4N, 104.7W) at 1200.

WHA 25° above the horizon NE of Saskatoon at 1245 U.T.

Sequence of magnetic events, December 5

The sequence of magnetic events in the night sector began with negative impulsive bays in H at Leir and Na shortly after 02 U.T. The maximum for this disturbance was recorded at BL at 0342 U.T. (-505 gammas in X).

The next magnetic event of interest was the SSC at 0633, clearly visible on all the magnetograms examined except for Ch and BL. Initial movements as high as 100 to 200 gammas were observed at Na, Leir, PB and Ab. For several hours after the SSC, Leir, Ab and Na in the early and mid-morning sector recorded strong micropulsations with periods of three to five minutes.

At 0810 very large micropulsation activity was observed on the dY/dt recording at Byrd, Antarctica (private communication, Rostoker). At about this time an intense substorm developed in the midnight sector in mid-Canada. The maximum magnetic effect was recorded at MLB (-ΔH approximately 2,000 gammas). This was followed by three less intense substorms with maxima at 1207 (Co), 1435 (Di) and 1915 (Di) U.T. respectively. The maximum perturbation in H for each of these storms was just under -800 gammas.

Polar substorm 08 – 10 U.T.

This substorm is particularly interesting because of the very intense negative bay at MLB (dp. lat. 79.1). The bay began suddenly in X and Y at 0905 U.T. with maximum deflection at 0909, suggesting the close approach to MLB of the northern edge of the oval at that time. The negative bay, which lasted about 37 minutes, followed a small negative indentation at 0836. The bay was impulsive and belongs to the class of indented positive bays discussed by Meng and Akasofu (1967). Maximum deflections from the quiet level were -1893γ in X, -1259γ in Y and 453γ in Z. It is known that the geomagnetic anomaly at Mould Bay may enhance the hourly ranges in X and Y by as much as 20 per cent and 50 per cent respectively (Whitham, 1965). An anomalous effect of this magnitude would reduce the maximum perturbations at Mould Bay to -1578γ in X and -893γ in Y. However, this amplitude is still almost twice as large as that recorded at any other observatory during the storm, and is the largest perturbation recorded at Mould Bay since observations began there in 1962.

The limited number and unequal distribution of observatories available for the analysis of polar substorms makes it impossible to accurately determine the extent in longitude and latitude of the auroral electrojet. In an attempt to estimate these parameters the stations were grouped into six sectors, as follows:

Sector	*Stations*	*Mean geomagnetic longitude*
1	Th Go Na St. J	22.3° E
2	Th BL Ch GW Ot	338.7
3	RB BL Ch Me Vi	303.7
4	RB MLB PB Co We	255.3
5	Al T3 CC Ti Ya	182.9
6	Al HI Ab Nu	138.7

Latitude profiles in ΔX′ and ΔZ were drawn during the storm for each of the six sectors.

The development of the substorm is reflected in the changing distribution of areas of maximum ΔZ, since it is only near the storm centre that the vertical component of magnetic perturbation is appreciable (Bostrom, 1967). The three stations with maximum positive and negative ΔZ for a number of instances during the storm are listed in Table II. An examination of the latitude profiles and Table II suggests that the storm can be described in three phases: an initial phase, an expansive phase, and a recovery phase. Akasofu (1968) lists an expansive and recovery phase as the two characteristic phases of the auroral substorm.

It must be emphasized that any interpretation based on the distribution of areas of maximum ΔZ may be affected by the poor distribution of observatories.

Initial phase (0800 – 0824)

The storm apparently developed in the midnight sector shortly after 0800 U.T. The bright rayed arc observed north of Saskatoon at 0800 was located immediately east and about 2° north of Me. Z bays and negative H bays were recorded around this time at all stations in and south of the auroral zone in the midnight and pre-dawn sectors (Figure 2). Times of commencement of the Z bays were often indefinite. Positive H bays were observed at Vi and Si in the return current system south of the oval in the midnight sector and at RB and MLB in the polar cap. About five minutes after the start of the bay at Me (0806), a negative bay was recorded at Co in the evening sector, when Co came under the influence of the primary electrojet. Welen recorded a slow negative H bay beginning about 0809. These bays are typical for stations in the return current regime south of the auroral oval in the evening sector (Rostoker, 1966). In the afternoon sector, positive H bays began at Ti and Di at 0820.

At 0812 the largest values of ΔZ were measured at Ch, BL and GWR in the early morning secor. The largest -ΔZ was at HI at 71.1°N in the noon sector. The current vector plot (Figure 3) indicates a strong eastward current along the auroral zone latitudes in this sector at 0812, contrary to the findings of Kamide *et al.*, 1969. At 0821 maximum positive and negative values of ΔZ were measured at GWR and Me respectively. These values were about three times larger than for 0812.

The latitude profiles (Figure 4) indicate that the electrojet was limited to the first three sectors in the initial phase of the storm, with well pronounced maxima in -ΔX′ at Na, GWR and Me at 0812. The maximum value of -ΔX′ was observed at GWR. The primary westward current flow was north of Na and Me and to the south of GWR (Figure 5).

Expansive phase (0824 – 0918)

At 0824 there is a sharp negative movement in the Z component at Co. At this time Z at PB shows a sharp positive rise followed by a negative bay which begins at 0830. A negative bay in H begins suddenly at PB at 0824, at which time a positive indentation of the -H bay is observed on the Co record (Figure 2). These magnetic effects indicate passage of a westward flowing surge north of Co at 0824 (Akasofu, 1968). The H variation at Vi and Si is typical of stations south of the oval in the midnight sector: a small positive bay beginning at 0810 followed by a negative bay. The time of beginning of the negative movements corresponds closely to the time assumed for the passage of the westward surge north of Co. At We the slow negative movement in

Table II

	Maximum +ΔZ	Maximum −ΔZ	Maximum −ΔX′	Maximum equivalent current vector x10⁵ amps.
Initial phase				
0812	CH 103γ	HI −143		
	BL 99	Me −104	GWR	Ch 2.12
	GWR, Go 70	Na −101		
	(Di 60)			
0821	GWR 239	Me −286		
	BL 158	HI −151	Co	
	Ch 146	Na −105		
Expansion phase				
0830	GWR 414	Me −527		
	Ch 361	Co −222	PB	Me 8.75
	BL 191	HI −151		
0839	Ch 456	Me −358		
	GWR 379	Co −254	PB	
	BL 250	PB −206		
0848	Ch 507	Me −475		
	GWR 450	PB −296	Co	Me 8.75
	BL 407	Co −235		
0900	BL 512	Me −495		
	GWR 492	Co −209	Co	Me 11.9
	CL 404	Si −176		
0909	GWR 548	Me −515		
	CH 490	Co −266	MLB	RB 11.9
	MLB 453	Si −187		
0918	RB 496	Me −436		
	BL 407	Co −362	MLB	
	Ch 344	PB −329		
Recovery phase				
0927	RB 540	Co −273		
	MLB 348	Me −248	MLB	
	Ch 327	Si −220		
0936	RB 420	Me −183	Na −530γ	
	MLB 371	Si −176		MLB 5.88
	BL 276	Co,PB −165	Co −472γ	
0945	MLB 470	Co −222		
	RB 452	PB −185	GWR	
	BL 236	We,Si −138		
0954	MLB 470	PB −226		
	BL 341	CC −197	GWR	
	RB 300	Co −184		
1003	MLB 395	CC −222		
	BL 341	Na −189	GWR	RB 4.38
	RB 245	PB −152		
1021	BL 394	GWR −365		
	MLB 371	PB −309	GWR	GWR 6.25
	Ch 318	CC −159		

Table II (cont'd)

	Maximum $+\Delta Z$		Maximum $-\Delta Z$		Maximum $-\Delta X'$	Maximum equivalent current vector $x10^5$ amps.	
1057	Ch	211	CC	−203			
	BL	210	HI	−166	Ch	Ch	3.94
	MLB	151	PB	−103			
	(Ti	121)					
1106	BL	171	CC	−190			
	MLB	133	HI	−163	Ch	GWR	4.00
	Ch	129	GWR	−141			
	(Ti	111)					
New substorm begins about 1120 U.T.							
1209	Co	368	We	−495			
	PB	226	Ti	−194	Co	Co	5.31
	Ch	189	Si	−193			
1245	CC	260	We	−306			
	MLB	215	Co	−273	PB	Co	4.14
	Ch	181	Ti	−226			

H beginning 0809 changes abruptly at about 0823 with the development of a positive bay. From comparisons with all-sky photographs, Akasofu and Meng (1967) have shown that such positive bays to the south of the oval are associated with westward travelling surges. The bay at We appears to be an example of a class of H transition bays studied by Rostoker, 1966, who attributes the change in form to the effect of the rotation of the earth in moving a station south of the oval from the return current regime into the regime of the primary electrojet.

In the early morning sector BL moved out of the eastward return current in the polar cap into the regime of the primary electrojet at 0835, as shown by the transition in X and Y from gradual positive bays to negative bays at this time. At Ch a brief indentation of the positive Z bay reaches its maximum value at 0847, at the time of the maximum of the negative H bay. At 0857 at BL an abrupt negative movement in H is simultaneous with a negative indentation of the positive Z bay. These effects at BL and Ch are interpreted as resulting from the expansion to the north and east of the auroral oval.

An expansion to the north and west in sector 4 is indicated by the small negative indentation of the positive X bay at MLB at 0836.

Following the westward surge at 0824 the maximum amplitude of ΔZ increases by a factor of two but remains centred in the GWR, Ch and BL area until 0909. The $-\Delta Z$ maximum is strongly intensified at Me, and the Alaskan observatories, with amplitudes comparable to the postive maximum.

During the expansive phase the electrojet appeared to spread into sectors 4, 5 and 6, with the main current at 0830 flowing south of GWR, north of Me, Na, PB and HI and between T3 and CC (Figure 5). The approximate geomagnetic latitude of the main westward current (equivalent) was 72° in sector 1, 65° in sector 2, 64° in sector 3, 68° in sector 4, and 73° in the daylight sector as given by the current vector for HI. At 0835 ΔZ became positive at Na as the electrojet moved to the south about $1\frac{1}{2}°$ in sector 1. By 0900 there is a significant shift (about $1\frac{1}{2}°$) to the south in sector 6 as well. A pronounced poleward movement is evident on the 0900 plots, which show the current vector for BL at $\Phi \sim 72°$. $-\Delta X'$ was maximum at PB until 0909 when the unusually large maximum in $-\Delta H$ was recorded at MLB, indicating the near approach of the northern edge of the oval to MLB at that time. This marked the extreme northward expansion of the electrojet. The current vectors for RB and MLB at 0909 were at $\Phi \sim 78°$.

Evidence for a double substorm

The intense perturbation at MLB about one hour after the beginning of the storm, suggests that a second substorm may have developed south of MLB at this time. (See the latitude profile for 0909 in Figure 4.) A number of observations support this interpretation.

The weak homogeneous auroral arc observed under poor conditions from Cape Parry was centred about 430 km geomagnetic southeast of MLB at 09 U.T.

The double nature of the negative H bay at Meanook could result from the conjunction of two negative bays or from a positive indentation lasting from 0831 to 0918. Such a positive indentation could be explained by the rapid northward movement of the electrojet in the midnight sector during the expansive phase (Rostoker, 1966). Assuming two negative bays, it is evident that the effects of the 0806 storm started to decay in this sector after 0831, and a second disturbance began around 0855, reaching maximum intensity at 0918.

As discussed later in this study, the rate of expansion of the 0806 storm in the direction of MLB strongly supports the argument for a double substorm.

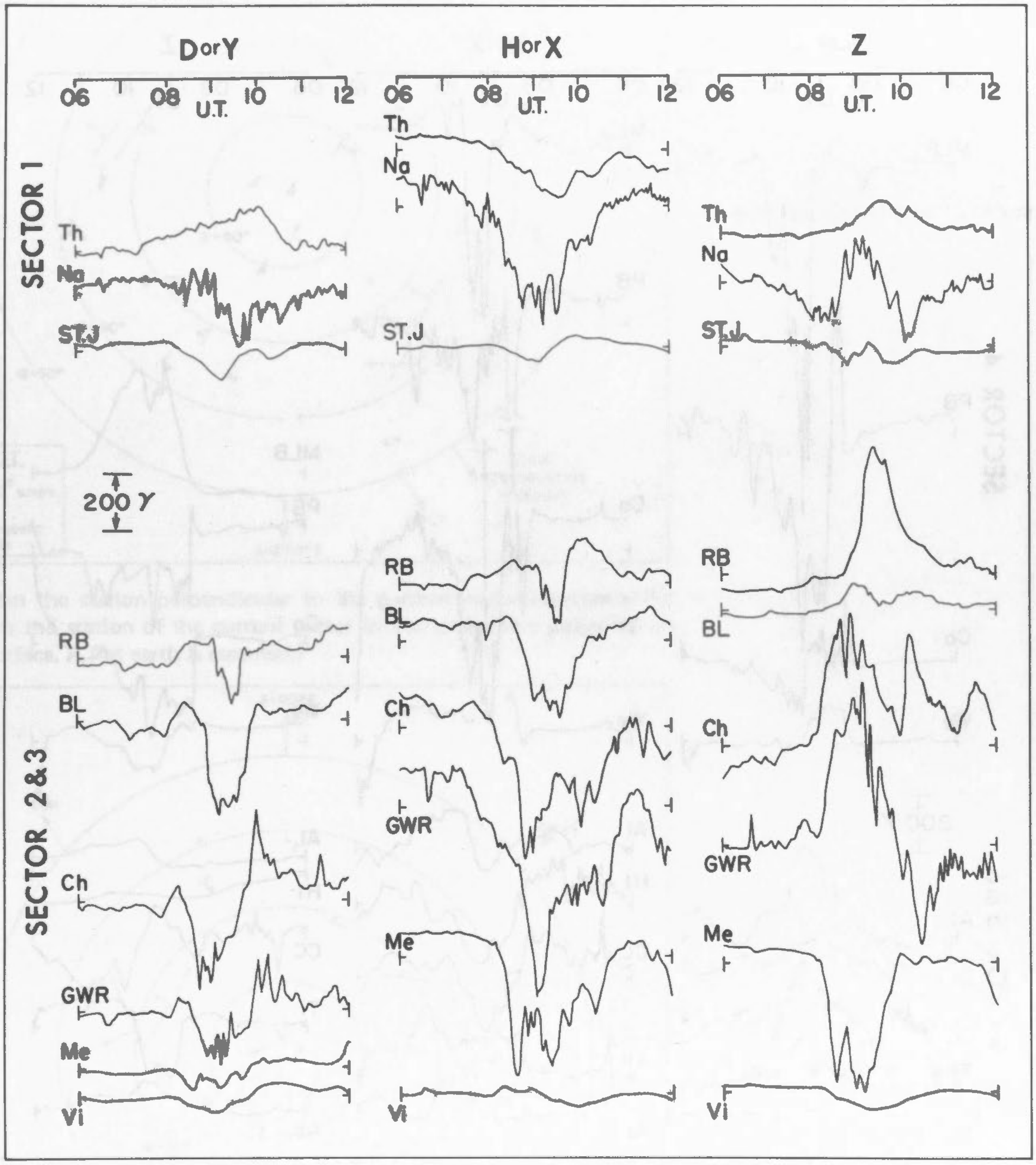

Figure 2a. H(X), D(Y), Z magnetogram traces drawn from 75 sec digitized data, for Th, Na, St. J. (section 1) RB, BL, Ch, GWR, Me, Vi (sectors 2 and 3).

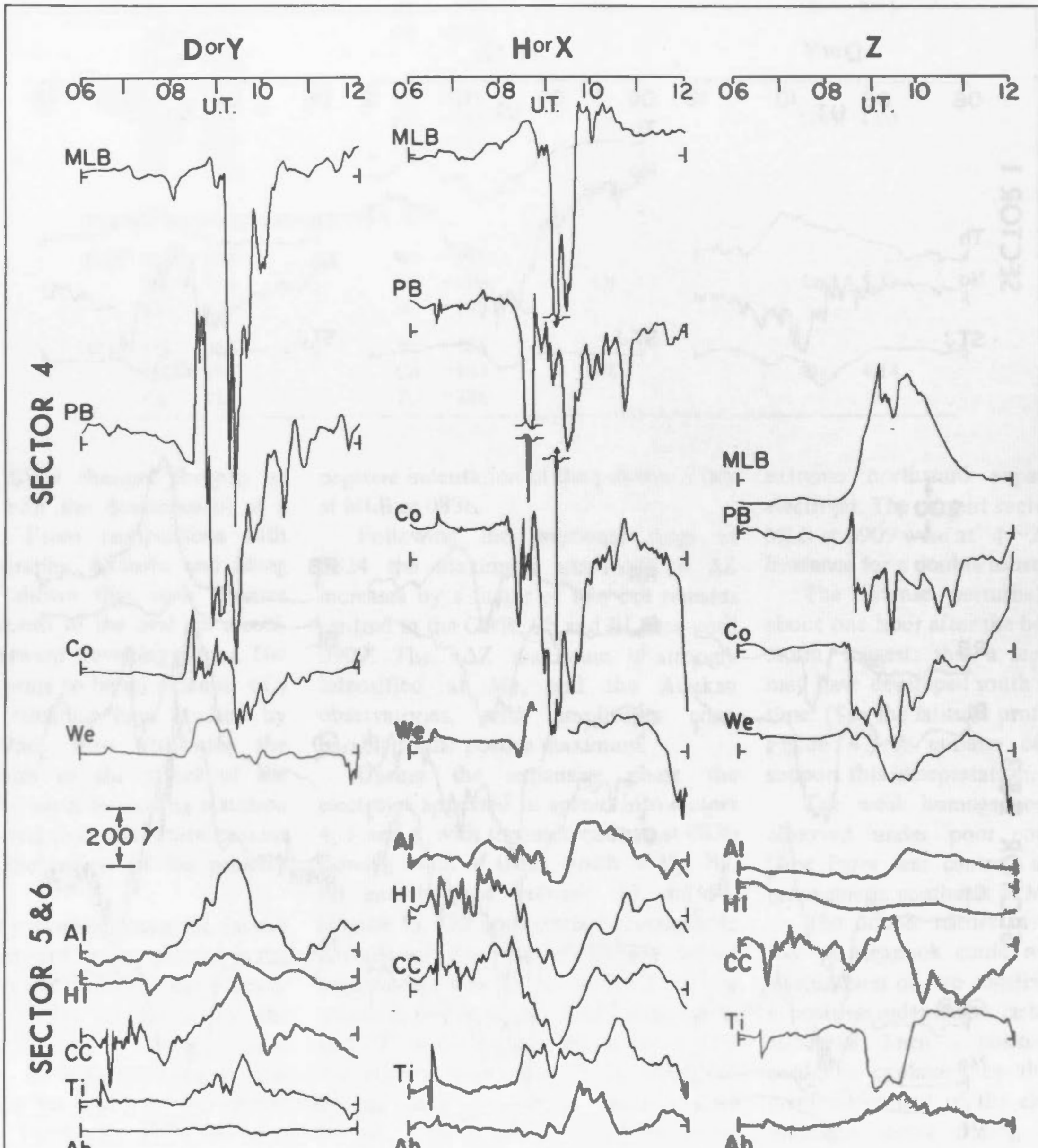

Figure 2b. H(X), D(Y), Z magnetogram traces drawn from 75 sec digitized data, for MLB, PB, Co, We (sector 4) Al, Hl, CC, Ti, Ab (sectors 5 and 6).

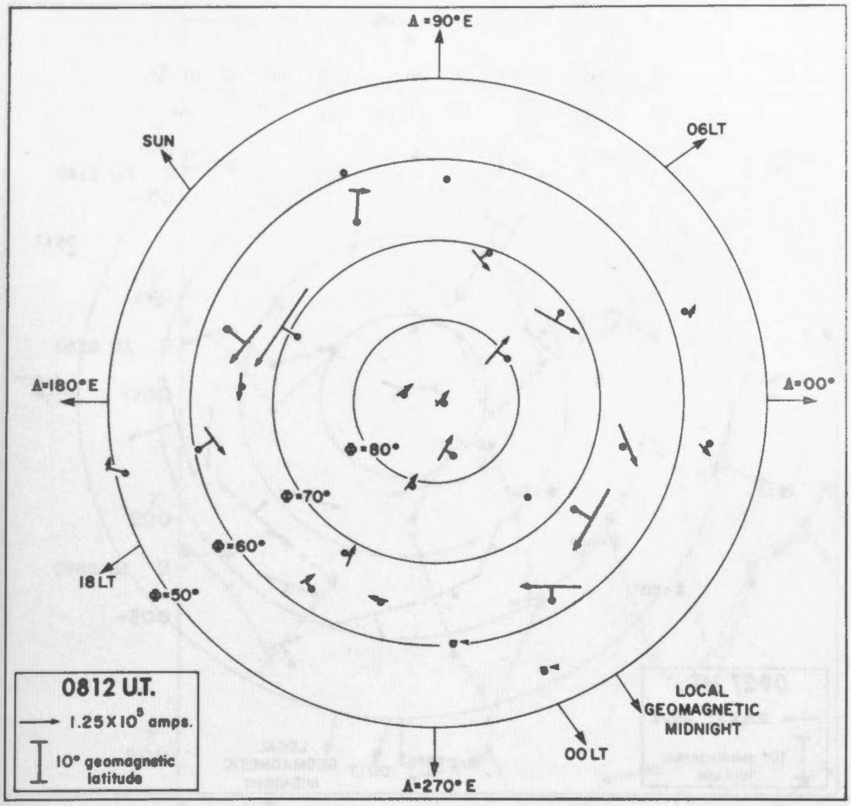

Figure 3a. Current vector plots for 0812 U.T.

(The line from the station perpendicular to the current vector represents the distance from the station of the current vector in the ionosphere projected on the earth's surface. A flat earth is assumed.)

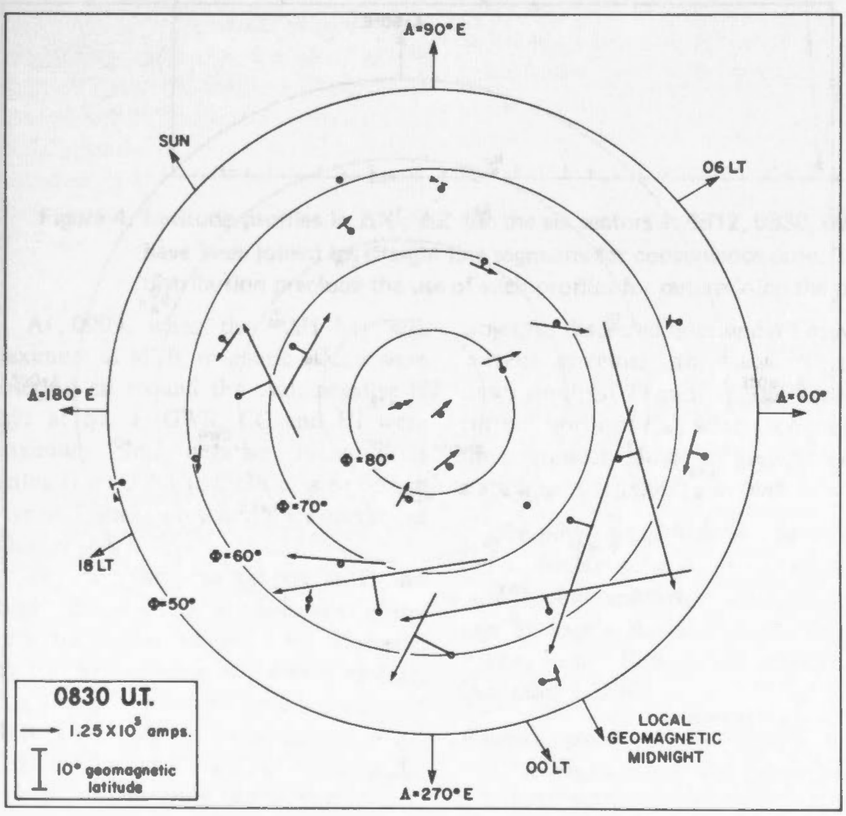

Figure 3b. Current vector plots for 0830 U.T.

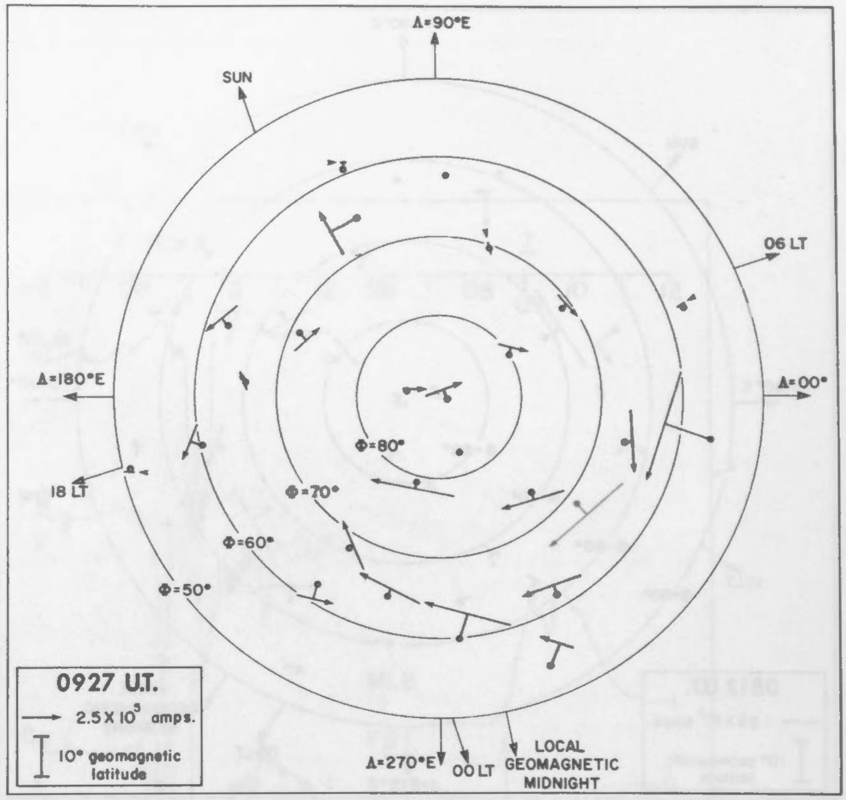

Figure 3c. Current vector plots for 0927 U.T.

(The line from the station perpendicular to the current vector represents the distance from the station of the current vector in the ionosphere projected on the earth's surface. A flat earth is assumed.)

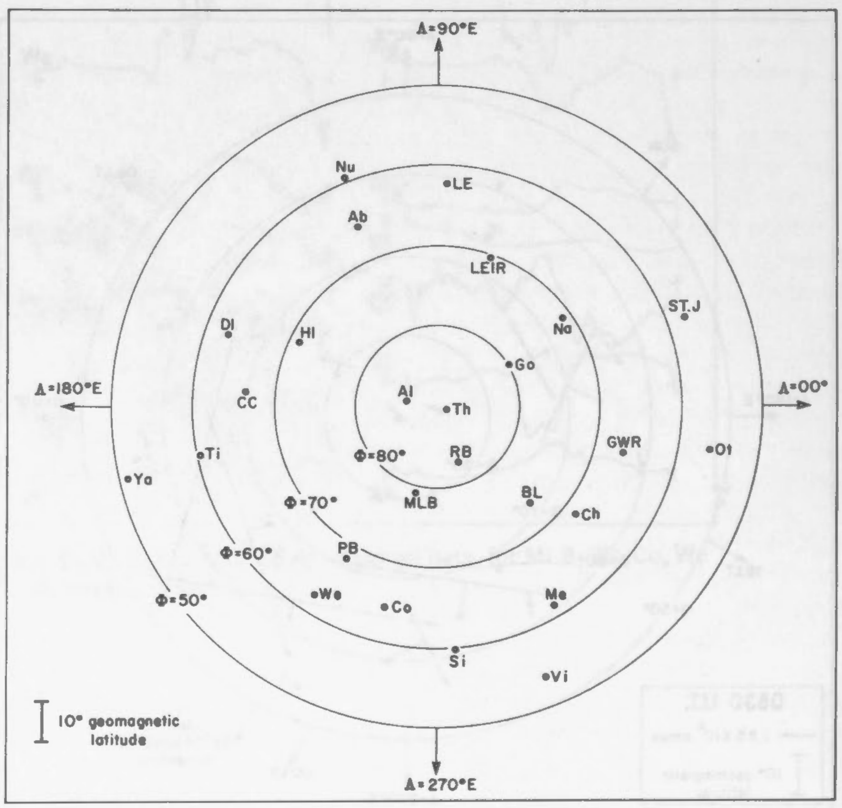

Figure 3d. Key to location of stations.

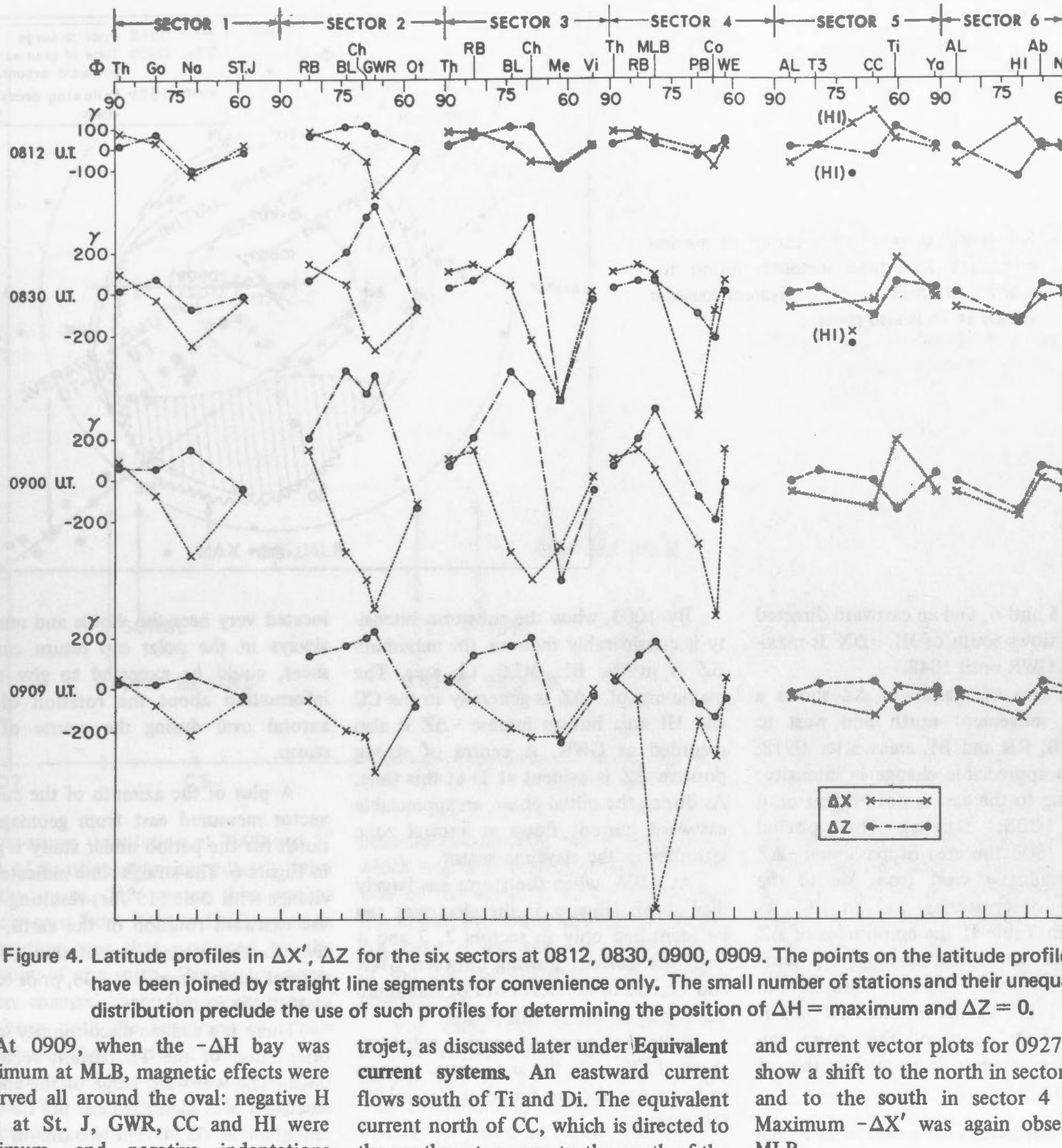

Figure 4. Latitude profiles in ΔX′, ΔZ for the six sectors at 0812, 0830, 0900, 0909. The points on the latitude profiles have been joined by straight line segments for convenience only. The small number of stations and their unequal distribution preclude the use of such profiles for determining the position of ΔH = maximum and ΔZ = 0.

At 0909, when the −ΔH bay was maximum at MLB, magnetic effects were observed all around the oval: negative H bays at St. J, GWR, CC and HI were maximum, and negative indentations lasting from 0905 to 0930 of the positive bays at Ti and Di reached their maximum value, at 0909.

The negative indentations at Ti and Di reflect the sudden enhancement of the westward electrojet and its associated return currents south of the oval resulting from the new substorm activity south of MLB around 09 U.T. During the period 0905 to 0930 Ti, Di and CC remain in the leakage current from the westward electrojet, as discussed later under Equivalent current systems. An eastward current flows south of Ti and Di. The equivalent current north of CC, which is directed to the southwest, moves to the south of the station between 0900 and 0909.

Recently Akasofu *et al.* (1970) observed a double substorm from the all-sky camera photographs and magnetic recordings at Sach's Harbour in the Canadian Arctic, and College, at 0858 U.T., December 6, 1969.

Recovery phase (0927 – 1106)

The beginning of the recovery phase is already evident on the latitude profiles and current vector plots for 0927, which show a shift to the north in sector 1 (Na) and to the south in sector 4 (MLB). Maximum −ΔX′ was again observed at MLB.

Following 0927 the oval contracted rapidly, with significant shifts of the current flow to the north in sectors 1, 2 and 6. The electrojet moved north of Na at about 0935 and north of GWR at 0954, as shown by the reversal in sign of the Z perturbations at these stations. A much smaller poleward motion was seen in sector 4 between 0945 and 0954. Little change was seen in sector 3. At 0954 the electrojet is no longer evident in

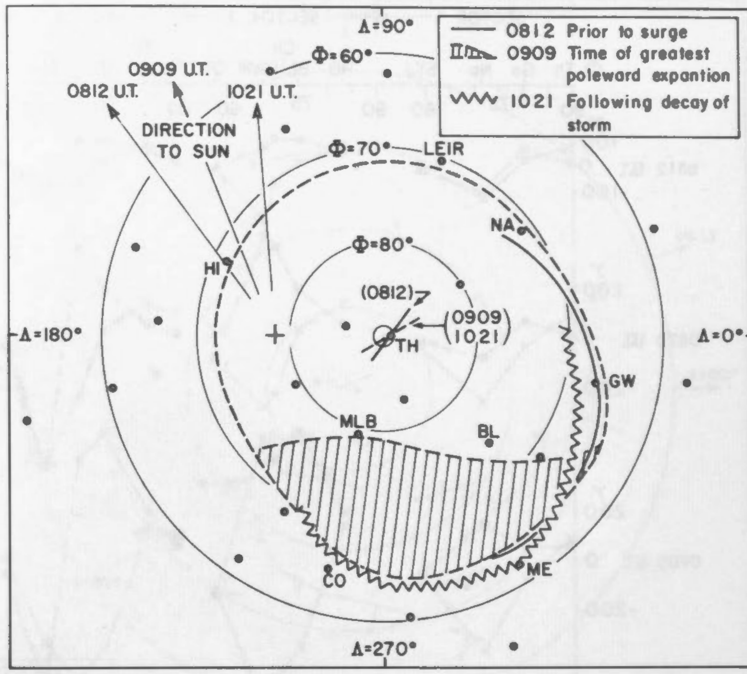

Figure 5. Schematic diagram of location of auroral electrojet for three instants during the storm. Orientation of equivalent current vector at Th is also shown.

sectors 5 and 6, and an eastward directed current flows south of HI. $-\Delta X'$ is maximum at GWR until 1048.

The area of maximum ΔZ shows a marked movement north and west to the MLB, RB and BL areas after 0918, with no appreciable change in intensity: the swing to the east is not evident until after 1003. During the period 0927 – 1003 the area of maximum $-\Delta Z$ drifts gradually west from Me to the Alaskan observatories and to CC. As shown in Table II the amplitudes of ΔZ and $-\Delta Z$ are approximately the same from 0812 – 0918 and from 1021 – 1106, but during the first part of the recovery phase of the storm the negative maximum drops to half that of the positive.

The apparent drift to the west of the area of maximum $-\Delta Z$ and its marked reduction in amplitude in the interval 0927 – 1003 must result from the lack of magnetic data around latitude $\Phi \sim 70°$ between the longitudes of Ch and PB. After the storm centre returns to its most easterly position, the amplitudes of $-\Delta Z$ and $+\Delta Z$ are again comparable. This strongly suggests that during the recovery phase the southern edge of the oval moved poleward in the early morning sector (sector 3) to about $\Phi=70°$.

By 1003, when the substorm intensity is considerably reduced, the maximum ΔZ is in the BL, MLB, Ch area. The maximum of $-\Delta Z$ is generally in the CC and HI area but an intense $-\Delta Z$ is also recorded at GWR. A centre of strong positive ΔZ is evident at Ti at this time. As during the initial phase, an appreciable eastward current flows at auroral zone latitudes in the daytime sector.

At 1106, when the storm has largely died down (Figure 5) the electrojet can be identified only in sectors 2, 3 and 4 with the current flowing between GWR and Ch and to the north of PB. Maximum $-\Delta X'$ is at Ch during this period.

Following onset of another substorm about 1120 U.T. the maximum positive and negative ΔZ are found at Co and We respectively.

Polar cap

It has been suggested by a number of authors (e.g. Rostoker, 1966; Kamide *et al.*, 1969) that the auroral oval is fixed in space with respect to the sun-earth line. In all models of equivalent current flow, the change in orientation of the polar cap return current is related to the rotation of an idealized eccentric auroral oval about the dipole. An examination of the change with time of the geomagnetic azimuth of the current vector at Thule, which is located very near the dipole and remains always in the polar cap return current sheet, could be expected to give some information about the rotation of the auroral oval during the course of the storm.

A plot of the azimuth of the current vector measured east from geomagnetic north for the period under study is given in Figure 6. The straight line indicates the change with time (15°/hr) resulting from the eastward rotation of the earth, relative to the average orientation of the current vector from 07 – 08, prior to the start of the storm.

There is a sudden discontinuity in the orientation of the Th current vector at 0821. The westward surge of the auroral electrojet was identified on the Co magnetogram at 0824. The maximum west orientation of the Th current vector was reached at 0927. The maximum northward expansion of the double substorm, as inferred from the MLB records, was at 0909. The latitude profiles show the electrojet flowing in sector 6, at its farthest west extension, from 0830 to 0927. Following 0945 the electrojet is no longer evident in sectors 5 and 6. During the recovery phase of the storm, the Th current vector swung rapidly eastward until 1003, when it was only 16° west of

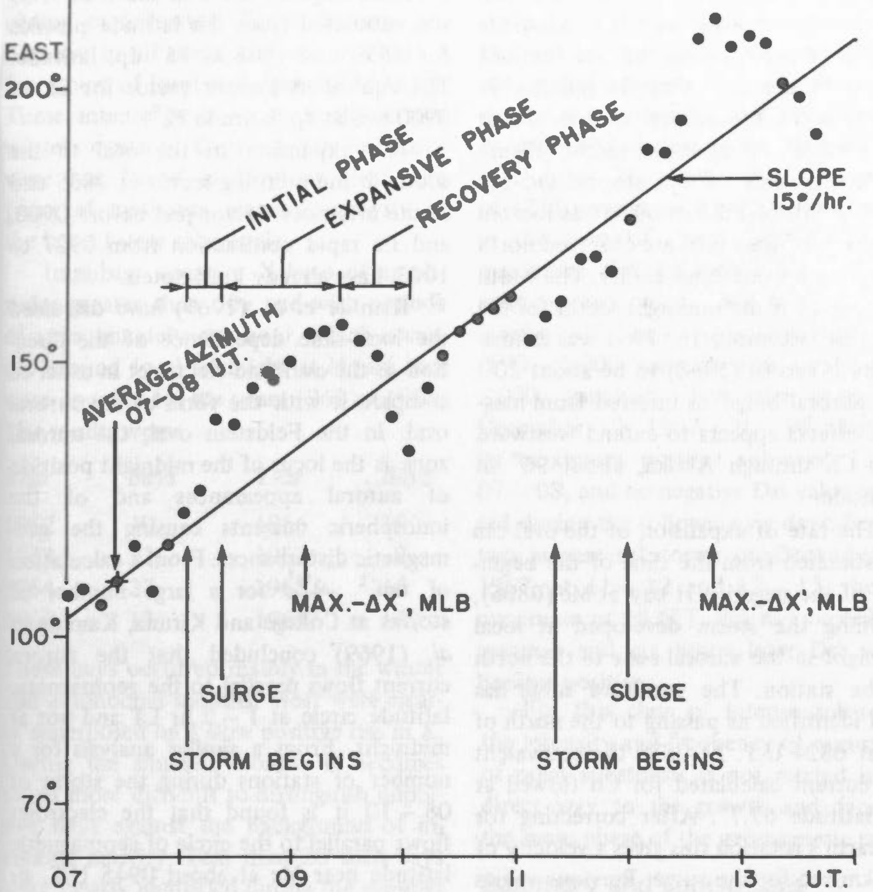

Figure 6. Graph of change with time of geomagnetic azimuth of Th current vector.

its pre-storm orientation at 0800 and 5° west of its orientation immediately prior to the surge. The vector then moved rapidly west from 1003 to 1030, when its orientation was that predicted by the rotation of the earth. The vector orientation changed thereafter at the rate of 15°/hour until the beginning of a new disturbance shortly after 1100.

A negative bay begins as early as 1107 on the We magnetogram. The magnetic effects associated with a westward surge are observed on the PB magnetogram at 1202. A negative bay begins at MLB at 1220 and $-\Delta X'$ is maximum there at 1245. It may be assumed that this marks the peak of the northward expansion (and intensity) of the 11 – 14 U.T. storm. These magnetic effects are reflected in the graph of the Th current vector, which again shows a very rapid swing to the east in the recovery phase of the storm. At 1339, the last point used in this analysis, the current vector is already oriented considerably east of the position which would be predicted from the rotation of the earth. It would appear that this effect, previously implied by the ΔZ, $\Delta X'$ data, is real and not a consequence of the unequal distribution of magnetic observatories.

For these two substorms the Th current vector swings westward at an average rate of 25° – 30°/hour to the time of maximum storm intensity, and then about twice as rapidly back to the east in the recovery phase.

Equivalent line current systems and the auroral oval

Akasofu and Meng (1969) have pointed out that it is not possible to determine an accurate equivalent current system from the present network of observatories. There is no doubt that the polar electrojet flows along the auroral oval rather than the auroral zone; however the nature of the eastward current in the afternoon and evening hours is not definitely established (Akasofu, 1967, Afonina and Feldstein, 1969). It has been suggested that such a current could be produced by an asymmetric ring current configuration (Akasofu and Meng, 1968).

Afonina and Feldstein have suggested a test to discriminate between a two-celled equivalent current system of the modified SD type, and the Feldstein-Akasofu model in which the polar electrojet flows westward at all longitudes during the substorm. The test consists essentially in determining the direction of the equivalent current at $\Phi \sim 70°$ at 20 – 22 h LT and at $\Phi \sim 75°$ at 09 – 10 LT, since at these times and locations the current directions predicted by the two models differ significantly.

Although it is difficult to apply this test rigorously to the storm of 08 – 10 U.T. owing to the unequal distribution of observatories, the equivalent current vectors for the expansion of the storm strongly support the Akasofu model. However, at 0803 and 0812, in the pre-breakup phase of the storm, the current directions can be interpreted as belonging to a two-celled system (Figure 3).

On the latitude profiles for sectors 5 and 6 (Figure 4) at 0812, a pronounced positive maximum in $\Delta X'$ ($+170\gamma$) is seen at CC ($\Phi \sim 66°$). The $\Delta X'$ value for HI was 110γ and for Ti 40γ. The corresponding ΔZ values for HI, CC, and TI were -140γ, -40γ, and 100γ respectively. These profiles are very nearly mirror images of the profiles in sector 2 at this time where $\Delta X'$, ΔZ are both maximum at GWR ($\Phi \sim 67°$) with amplitudes of -235γ and 105γ respectively. This indicates that in addition to the primary westward electrojet flowing in the dark sector, a current only slightly less intense flows eastward in the afternoon sector at $\Phi \sim 65°$. It is not possible to determine if this eastward current completes its circuit by a return current westward across the polar cap. The orientation of the current vector at Ti suggests that this may be the case.

During the expansion phase and early part of the recovery phase, the eastward currents flowing in the afternoon (Figure 3) are most readily interpreted as return currents from the westward electrojet, in agreement with the model suggested by Akasofu. As early as 0830, a strong westward current is observed just north of HI. It is likely that the electrojet flows westward all around the oval at this time.

In the latter part of the recovery phase, after 0945, the latitude profiles are similar in sectors 5, 6 to the profiles discussed for 0812: $\Delta X'$ has become positive at HI and CC. Its maximum is now at TI. The current flow at 08.5 and 09.5 LT at Leir ($\Phi \sim 70°$) is north of the station and directed to the northeast. Again, it is possible that an SD-type current exists at these times. In their study of the substorm of July 18, 1964, Kamide *et al.* (1969) found evidence for an SD-type current system only toward the end of the recovery phase of the substorm.

The current vector plot at 0927 when the storm intensity is maximum shows large equivalent line currents south of MLB, RB and BL and north of Me and Alaskan stations. Although the line currents are obviously not an adequate physical representation of the current flowing in the oval, they do indicate an expansion of the auroral oval of about 15° north in the midnight sector (Figure 5). The latitude of the auroral arc observed south of MLB at 0900 was located 12° north of the rayed arc observed north of Saskatoon one hour earlier. The width of the oval in the midnight sector for the storm of December 16, 1964 was estimated by Akasofu (1968) to be about 20°. The 'auroral bulge' as inferred from magnetic effects appears to extend westward from Ch through Alaska, about 90° in longitude.

The rate of expansion of the oval can be estimated from the time of the beginning of the negative H bay at Me (0806), assuming the storm developed at local midnight in the auroral zone to the north of the station. The westward surge has been identified as passing to the north of Co at 0824 U.T. At 0830 the equivalent line current calculated for Co flowed at dp. latitude 67.7°. After correcting for the earth's rotation this gives a velocity of 1.1 km/sec for the surge. Previous values given in the literature are 1 km/sec measured by Akasofu (1968) and 0.9 km/sec inferred by Rostoker (1970) from magnetic effects. The rate of expansion of the oval to the northwest, as given by the negative indentation of the MLB X trace at 0836, was 0.7 km/sec. The rate of expansion to the northeast indicated by the abrupt movement at BL at 0857 was 0.65 km/sec. The position of the northern edge of the oval south of MLB was estimated from the latitude profiles for 1839 and 1848 as 75° dp. latitude. The equivalent current vector for BL at 0900 was at dp. latitude 72°.

The expansion of the oval to the south in the morning sector at 0835 and in the afternoon sector just before 0900, and its rapid contraction from 0927 to 1003, have already been noted.

Kamide *et al.* (1969) have discussed the local-time dependence of the direction of the overhead electrojet in order to compare it with the form of the auroral oval. In the Feldstein oval, the auroral zone is the locus of the midnight position of auroral appearances and of the ionospheric currents causing the geomagnetic disturbances. From a calculation of $\tan^{-1} \frac{\Delta Y'}{\Delta X'}$, for a large number of storms at College and Kiruna, Kamide *et al.* (1969) concluded that the auroral current flows parallel to the geomagnetic latitude circle at 1 – 2 hr LT and not at midnight. From a similar analysis for a number of stations during the storm of 08 – 10 it is found that the electrojet flows parallel to the circle of geomagnetic latitude near Me at about 0945 U.T. or 1.5 hr geomagnetic time (2.2 LT), in good agreement with Kamide's result.

Time of occurrence of substorms

The hourly range is a convenient index for identifying large bays with periods less than one hour. The following is a list of times when the hourly range in a horizontal component exceeded 1,000 gammas at MLB.

Date			*U.T.*	*Hourly range in gammas*	*Element*
Nov.	24,	1962	8 – 9	1,580	Y
Dec.	19,	1962	8 – 9	1,090	Y
Jan.	1,	1963	9 – 10	1,430	Y
Feb.	12,	1963	8 – 9	1,400	Y
	14,	1963	8 – 9	1,140	Y
Dec.	3,	1963	7 – 8	1,050	Y
Jan.	22,	1966	6 – 7	1,010	X
Dec.	10,	1967	9 – 10	1,020	X
	20,	1967	11 – 12	1,080	Y
	20,	1967	12 – 13	1,070	Y
Oct.	31,	1968	11 – 12	1,280	Y
Dec.	5,	1968	9 – 10	2,170	X
Sep.	28,	1969	11 – 12	1,044	Y
	29,	1969	9 – 10	1,000	Y

These ranges are many times greater than the range for the hour immediately preceding or following. The deflections are negative in all cases, and occur within a few hours of local midnight (0758 U.T.). These intense bays occur usually in the winter months. Bays of this intensity were not found in 1964 or 1965, the years of minimum magnetic activity in the last 11-year solar cycle.

Impulsive negative X bays of amplitudes greater than 50γ and with periods of approximately one hour, which occurred around local midnight at Mould Bay were counted for the years 1962 to 1969. The results were:

Year	*Bays*	*Year*	*Bays*
1962	30	1966	19
1963	32	1967	9
1964	27	1968	16
1965	13	1969	18

These bays occurred mainly in the winter and equinoctial months. Most were clearly superposed on a slow positive rise in X. During the summer months it becomes much more difficult to distinguish impulsive bays against the background of increased activity. Less than 20 such bays were clearly identified during the summer months of these years.

The intensity of substorms, as measured by the poleward extension of the auroral oval in the midnight sector of Mould Bay, is greatest in the years preceding the minimum of the 11-year cycle, and not at the minimum as Meng and Akasofu (1967) had inferred from the occurrence of negative bays in the evening at Godhavn for the first three months of 1958 and 1964. The distribution of implusive negative H bays around local midnight at Baker Lake and Resolute Bay confirm the Mould Bay results. In a study of the solar cycle effect on magnetic activity, Loomer and Jansen van Beek (1969) found that magnetic activity around midnight at BL and Ch, which is clearly associated with polar substorms, was greatest about two years before sunspot minimum.

Polar substorms and Dst

Of the 26 substorms recorded at Mould Bay with amplitudes in H greater than 500 gammas, 19 were associated with the main phase of a geomagnetic storm. For the remaining seven storms, Dst was positive. The maximum Dst for the period following these intense substorms was generally small, and did not exceed −88 gammas, except for the storm of October 31, 1969, when a maximum of −211 gammas was reported. Dst values at the time of the substorm, and the maximum Dst following the substorm were approximately the same for two levels of bay intensity at MLB (500 – 1,000 gammas and greater than 1,000 gammas). For the storm of December 10, 1967 (09 – 10), Dst had its maximum positive value of 11γ at 07 – 08, and no negative Dst value occurred during the following six days. For the two intense substorms on December 20, 1967, at 11 – 12 and 12 – 13, the Dst maximum at 18 U.T. did not exceed −25 gammas and six hours later Dst values became positive.

For this class of intense substorms, the intensity and frequency of occurrence of polar substorms is not related in any direct way to the growth and decay of the main phase of the geomagnetic storm.

Summary and conclusions

Four well-defined polar substorms occurred on December 5, 1968. The second of these, at 08 – 10 U.T., believed to be a double substorm, was analyzed in some detail. Both December 4 and 5 were moderately disturbed days, with Ap's of 21 and 25. The ssc at 0633 on December 5 could be expected to enhance the conductivity in the polar region (Obayashi and Jacobs, 1957). The main phase of the geomagnetic storm which followed the ssc was small, and Dst did not exceed −48 gammas.

The storm developed around 08 U.T. with a rayed auroral arc in the midnight sector at $\Phi \sim 64°$, and negative H bays at stations in and near the auroral zone in the midnight and early morning sectors. At Byrd, Antarctica, conjugate to Great Whale River, large micropulsational activity began in dY/dt at 0810. The westward surge was identified on the Co and PB magnetograms at 0824. In the initial phase (0800 – 0824) a westward electrojet flowed in the dark sector north of Na, south of GWR and north of Me. In the daylight sector a less intense eastward current flowed at the auroral zone latitude.

In the expansive phase of the storm (0824 – 0918) a westward current apparently flowed at all longitudes, as the auroral oval expanded rapidly to the west, north and east. In the early morning sector (at Na) the oval expanded to the south at 0835. The expansion of the oval to the north and east was noted at BL at 0857. The expansion to the north in the midnight sector produced a small negative indentation on the X trace at MLB at 0836. The sharp negative H bay of 2,000 gammas recorded at MLB at 0905 is attributed to a second burst of substorm activity a few hundred km to the southeast around 09 U.T. The observed maximum of the northern expansion was at 0909, when the equivalent line currents for RB and MLB were at 78° dp. latitude. The equivalent current plots for this phase of the storm are in good agreement with the Akasofu model with the polar electrojet flowing westward all around the oval and the eastward currents in the daylight and evening sector apparently resulting from return or leakage currents from the west electrojet. Values deduced from the magnetic effects for the velocity of the westward surge (1.1 km/sec) and for the maximum width of the oval in the midnight sector of an intense substorm (15°) agree fairly closely with those found in the literature. The direction of current flow in the oval was found to be parallel to the auroral zone a few hours after local midnight, as noted previously by Kamide *et al.* (1969).

In the recovery phase of the storm the poleward contraction of the oval is very rapid (about twice the rate of the previous expansion) until 1003. All data for the recovery phase indicate that the centre of the storm had returned by 1003 to the BL-GWR area near the pre-breakup position, considerably east of the local midnight meridian. By 1030 the position of the oval relative to its position prior to the storm is that predicted by the effect of the earth's rotation.

The intensification of the storm and the movement to the west and north of the storm centre during the expansion phase are clearly reflected in the table of maximum ΔZ. The ambiguity in the maximum ΔZ data for the recovery phase of the storm is a result of the lack of magnetic data, and emphasizes the impossiblity of carrying out a precise analysis of the development of polar substorms with the existing network of magnetic observatories.

The changing orientation of the equivalent current vector at Th which was always well inside the polar cap, represents very closely the time development of the storm. The time of maximum storm intensity, and the expansion and recovery phases of both the 08 U.T. and 11 U.T. substorms, as indicated by the Th vector, are in close agreement with deductions from other data. It is concluded that the average position of the auroral oval changes with the rotation of the earth from one substorm to the next, if the substorms are separated by a few hours in time.

The Afonina-Feldstein (1969) test was not sufficient to distinguish between the two models of equivalent current flow, owing to the lack of stations in the 09 – 10 and 18 – 20 LT sectors. However, there is some indication the SD-type current systems exist prior to the westward surge and following the end of the substorm.

A class of intense substorms for the years 1962 – 1969 was identified from the occurrence on the Mould Bay ($\Phi \sim 79^\circ$) magnetograms of indented positive bays in the horizontal component during the midnight hours. As the bays have periods of 1 – 2 hours typically, the hourly range is a convenient index for identifying such magnetic substorms. These substorms occurred mainly in the winter and equinox, and were significantly most numerous in the years immediately preceding sunspot minimum. Maximum occurrence as indicated by the MLB, BL, and RB records, was in 1963.

No clear relationship was found between the Dst index and the class of substorms for which −ΔH was greater than 500 gammas at MLB. Most of these substorms were associated with the main phase of small geomagnetic storms. However the Dst index for these storms did not exceed −88 gammas except for one storm which occurred five hours after local midnight. No increase in Dst was evident in the case of two substorms which occurred within less than one hour of each other. In one case no negative value of Dst was listed for a period of six days following the substorm. These results were unexpected, and suggest an inverse relationship between the occurrence of intense polar substorms and the development of a ring-current.

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