Equatorward expansion of the westward electrojet during magnetically disturbed periods

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[1] The auroral electrojet (*AE*) indices have widely been used in various fields of solar terrestrial physics since their introduction to the community. Recently, it has been reported that the *AE* indices do not, at times, properly monitor the auroral electrojets because as magnetic activity increases, they expand equatorward beyond the standard *AE* network, resulting in a serious underestimation of the auroral electrojet intensity. It is particularly the case during severe geomagnetic storms. To determine quantitatively the equatorial expansion of the auroral electrojets, we examined an extensive database obtained from the Alaska, International Monitor for Auroral Geomagnetic Effects (IMAGE), and Canadian Auroral Network for the OPEN Program Unified Study chain of magnetometers. These chains of magnetometers enable us to determine the latitude where the maximum current density of the auroral electrojet flows. It is generally understood that the center of the auroral electrojet tends to migrate equatorward with an increase in magnetic activity. We note, however, that there seems to be a lower limit particularly of the westward electrojet, $\sim 60°$ in corrected geomagnetic latitude, regardless of magnetic activity levels. The relative location of the westward electrojet with respect to the global auroral image taken from the Polar satellite is also examined. Contrary to the generally accepted notion, the auroral electrojets are found to be most intense not in the region of bright auroral luminosity but slightly poleward of it in less luminous region. The current center seems to be the region where both ionospheric conductivity and electric field become significantly high.

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1. Introduction

[2] It has been widely recognized that the auroral electrojets expand equatorward during magnetically disturbed periods [e.g., *Feldstein et al.*, 1997; *Ahn et al.*, 2000]. It is believed that particularly during geomagnetic storm periods, due to the equatorward expansion of the auroral electrojet beyond the standard *AE* stations, the *AE* indices are seriously underestimated. *Akasofu* [1981] examined the relationship between the *AE* and *Dst* indices, finding that *AE* tends to saturate for large values of *Dst*. As one of several possible causes of the saturation, he suggested that the equatorward shift of the auroral electrojet prevents the *AE* stations from monitoring the electrojets properly.

[3] Recently, *Ahn et al.* [2000] also reported that the *AE* indices, particularly the *AL* index, do not properly monitor the auroral electrojets because they expand equatorward beyond the standard *AE* network. They further reported that the equatorward expansion is more serious than the longitudinal *AE* station gaps. Thus the latitudinal standardization of the *AE* indices as a function of magnetic activity is highly desirable. To assess the equatorward expansion of the westward electrojet, we analyze an extensive ground magnetic database obtained from the Alaska, Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS), and IMAGE chains of magnetometers. The relative location of the westward electrojet with respect to auroral imagery is also examined. For this purpose a case study is conducted by using auroral images taken from the Polar satellite on 22 October 1999, during which a major magnetic storm was in progress. By doing so, it is possible to locate the auroral electrojet with respect to the aurora that was

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Table 1. Coordinates of the Magnetic Observatories

Magnetic Chain	Code	Geographic Coordinates		Corrected Magnetic Coordinate	
		Latitude	Longitude	Latitude	Longitude
		Alaska			
Fort Yukon	FOT	66.56	214.78	67.21	264.45
Poker Flat	POK	65.11	212.56	65.35	263.75
Gakona	GAK	62.20	214.50	62.79	267.41
Talkeetna	TLK	62.30	209.90	61.99	263.42
Anchorage	AMU	61.24	210.13	60.95	264.24
Sitka	SIT	57.05	224.67	59.77	279.74
		CANOPUS			
Taloyoak	TAO	69.54	266.44	79.03	328.51
Rankin Inlet	RAO	62.82	267.89	74.98	334.38
Eskimo Point	ESO	61.11	265.95	71.27	331.50
Fort Churchill	FCC	58.76	265.91	69.06	331.97
Gillam	GIL	56.38	256.36	65.65	317.94
Island Lake	ISL	53.86	265.34	64.32	331.93
Pinawa	PIN	50.20	263.96	60.60	330.37
		IMAGE			
Hornsund	HOR	77.00	15.60	74.06	110.08
Bear Island	BJN	74.50	19.20	71.38	108.49
Soroya	SOR	70.54	22.22	67.29	106.49
Masi	MAS	69.46	23.70	66.12	106.71
Muonio	MUO	68.02	23.53	64.67	105.49
Pello	PEL	66.90	24.08	63.51	105.18
Lycksele	LYC	64.61	18.75	61.41	99.53
Hankasalmi	HAN	62.3	26.65	58.67	104.80
Nurmijarvi	NUR	60.5	24.65	56.85	102.35
		Others			
St. Johns	STJ	47.60	307.32	53.73	31.35
Ottawa	OTT	45.40	284.45	56.07	1.01
Newport	NEW	48.30	242.90	55.03	303.06
Meanook	MEA	54.6	246.7	62.61	302.90
Victoria	VIC	48.5	236.6	54.12	292.40

observed at as low a latitudinal region as the continental United States.

2. Center of the Auroral Electrojet

[4] The center of the auroral electrojet in the latitudinal direction is determined from magnetic disturbance data obtained from the Alaska, CANOPUS, and IMAGE chains of magnetometers during 1998. Table 1 lists the locations of the magnetic stations of the three-magnetometer chains and several other stations. We assume that the magnetic stations belonging to one magnetic chain lie along the same magnetic meridian. Since we are interested in the location of the auroral electrojet during disturbed periods, a data day is selected when at least one of the stations along each chain of magnetometers recorded horizontal component, ΔH, <-1000 nT. The number of data days that satisfied this selection criterion was 38, 40, and 72 for the Alaska, CANOPUS, and IMAGE chains, respectively, during 1998. Although the IMAGE chain operates 23 magnetic stations, for the purpose of comparing with the other chains, we utilized only nine stations as indicated in Table 1. They are located within about ±5° from 104° meridian of corrected geomagnetic longitude and cover a wide latitudinal range from 74.06° to 56.85° in corrected geomagnetic latitude. Since the IMAGE chain consists of more stations than the other chains, it has a higher probability of recording more disturbed days.

[5] Each data day is subdivided into epochs of 5 min intervals. Although the highest disturbance during a given day under consideration always exceeds -1000 nT, due to the selection criterion, every epoch of 5 min intervals does not necessarily record such a highly disturbed level. The latitude of the station that recorded the highest disturbance along a meridian chain is used as a proxy for the location of the center of the westward electrojet at the given epoch. The disturbance level thus identified is further binned by every 100 nT level. According to previous studies [e.g., *Ahn et al.*, 1984, 1986; *Sun et al.*, 1993], the latitudinal profile of the auroral electrojet is approximated by a Gaussian distribution. Thus the region where the maximum magnetic disturbance is recorded can be assumed as the center of the auroral electrojet in the latitudinal direction. Figures 1, 2, and 3 are constructed by utilizing the information on the highest magnetic disturbance and the station that recorded it during each 5 min interval. For example, if Poker Flat recorded the highest disturbance, -850 nT, among the Alaska meridian chain stations during a given epoch and that happened to occur at 0100 magnetic local time (MLT), we would mark a circle on the location of 65.35° (corrected geomagnetic latitude of Poker Flat; all positions are expressed in terms of corrected geomagnetic coordinate unless otherwise specified) and 0100 MLT in Figure 1b. Since we are interested in the westward electrojet, the magnetic disturbances recorded only between 2000 and 0900 MLT through the midnight sector are considered in this study. Although we examined every 100 nT level, only eight activity levels, $0 < |\Delta H| < 200$, $200 < |\Delta H| < 400$, $400 < |\Delta H| < 600$, $600 < |\Delta H| < 800$, $800 < |\Delta H| < 1000$, $1000 < |\Delta H| < 1200$, $1200 < |\Delta H| < 1400$, and $1400 < |\Delta H| < 1600$ nT, are shown here. The circles show the latitudinal and magnetic local time distribution of the largest negative disturbance of the horizontal component for a given level of magnetic activity. Each time-latitude grid point can have several hits since each panel presents an accumulation of days. To give an indication of the number of data points, we used open circles with increasing area for an increasing number of hits. It is a kind of probability distribution about the center of westward auroral electrojet for a given level of magnetic activity in terms of corrected geomagnetic latitude and MLT.

[6] The Alaska magnetometer chain consists of six stations, thus six rows of circles appearing in Figure 1. For the magnetic activity level of $0 < |\Delta H| < 200$ nT, one can note that the six rows of the circles corresponding to the six stations are distributed continuously without showing any significant change in the size of the circles, indicating that the probability of observing this level of magnetic activity is almost the same regardless of either latitude or magnetic local time. In other words, during a very quiet period such a level of magnetic disturbance can be observed at any latitude and any MLT sector. The large circles indicate that every grid point has several hits. Although it does not carry any meaningful message at this particular activity level, the thick plus sign denotes the average location of the westward electrojet with plus or minus one standard deviation both of the latitudinal and MLT directions. The latitudinal center of the westward electrojet, 62.33° ± 2.39°, slightly lower than the average latitude of the Alaska meridian chain, suggests

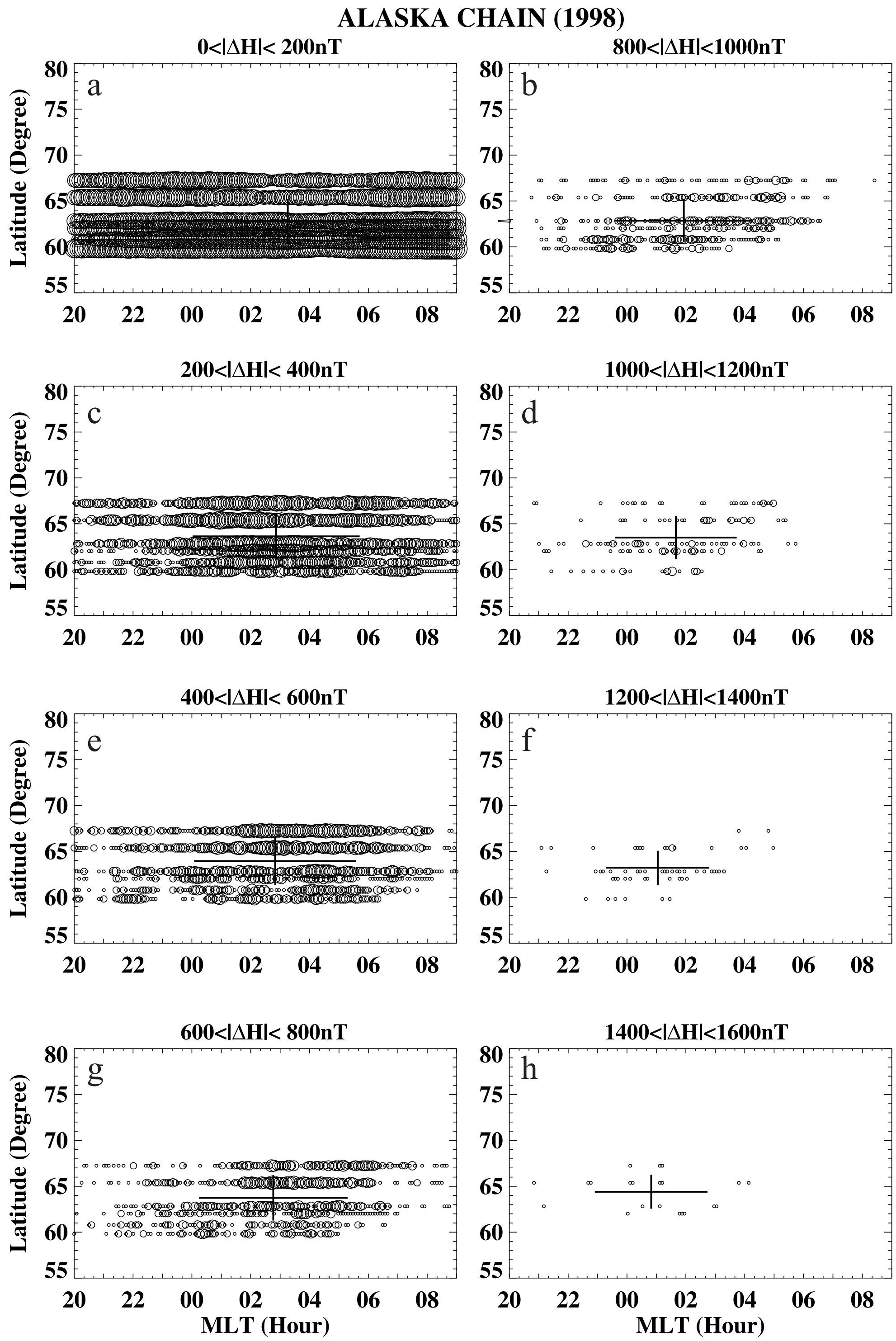

Figure 1. Distribution of the center of the westward electrojet for (a–h) eight different levels of magnetic activity. Circles represent the latitude and magnetic local time of the center of the westward electrojet for a given level of magnetic activity. Area of the circle is proportional to the number of hits at each grid point. A total of 38 days is examined for the case of the Alaska meridian chain stations. Thick plus sign is used to indicate the average latitude and MLT of the center of the westward electrojet during a given level of magnetic activity. Total length of the error bars (length of the thick plus sign) represents two standard deviations in the latitudinal and local time directions.

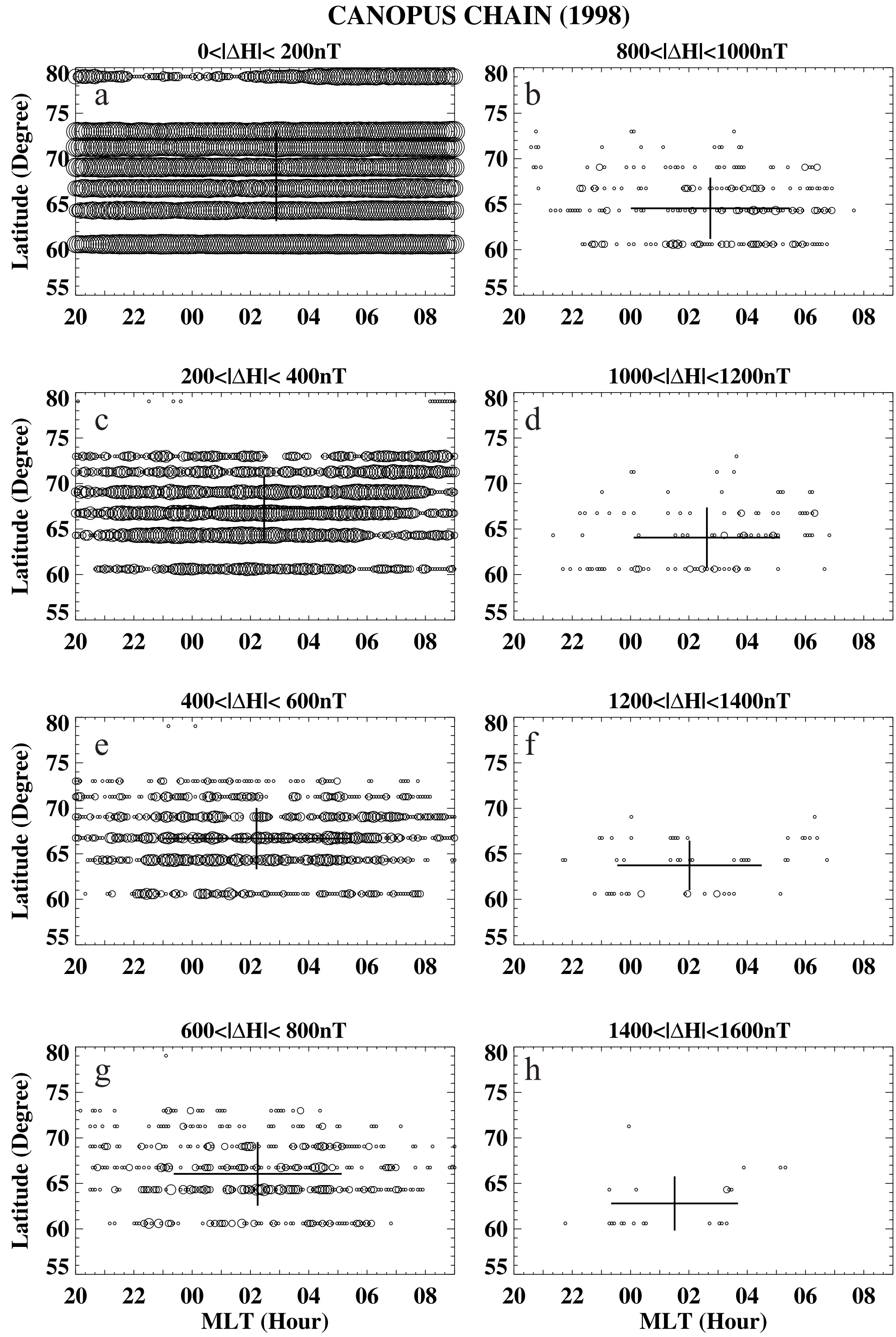

Figure 2. (a–h) Same as Figure 1 but for the CANOPUS chain of magnetometers.

that there are more data points in the lower latitude stations. On the other hand, the longitudinal center, 3.32 ± 3.99 MLT, is located at slightly later hours than 2.5 MLT, the halfway point between 2000 and 0900 MLT. It is simply because there were more data points beyond 2.5 MLT than earlier local time.

[7] As the magnetic activity increases, changes are noted in the distribution pattern of the circles. Figure 1c shows the distribution of the auroral electrojet center for the activity level of $200 < |\Delta H| < 400$ nT. Although the location of the electrojet center in terms of either latitude or MLT does not show any noticeable change compared to the lowest activity level, $0 < |\Delta H| < 200$ nT, a couple of interesting changes are worth mentioning. First, the number of data points in earlier local time has decreased significantly. Second, the probability of observing this level of activity at the lower latitude

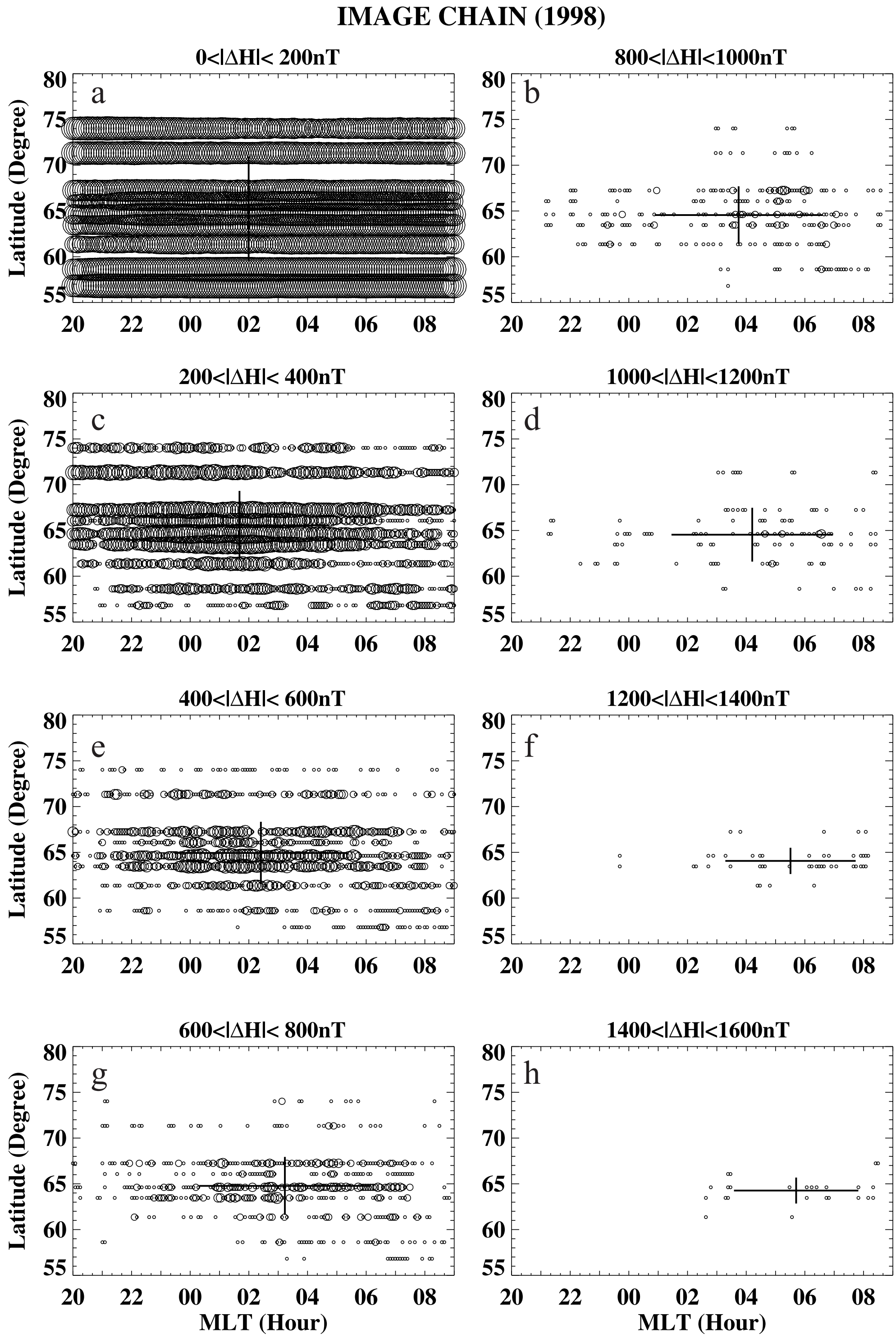

Figure 3. (a–h) Same as Figure 1 but for the IMAGE chain of magnetometers.

stations tends to decrease. As magnetic activity further intensifies, such a tendency becomes more apparent.

[8] It is also interesting to note that there is a significant decrease of data points in the late morning hours particularly in the lower latitudinal region. Even if the magnetic activity exceeds −1000 nT, as shown in Figure 1d, the same trend persists. The average center of the auroral electrojet is found to be at 63.42° ± 2.32° and 1.75 ± 2.15 MLT. The westward electrojet does not seem to expand equatorward considerably with magnetic activity, but it shifts to earlier local times, more than 1.5 hours, compared to the lowest activity level. We also examined the location of the center during very disturbed periods, $1400 < |\Delta H| < 1600$ nT, finding similar characteristics at the lower activity levels.

[9] It is important to note that although no station lower than Sitka in latitude is utilized in this study, it is unlikely that the center of the westward electrojet is located beyond Sitka during very disturbed periods: see Figure 1. If the

center shifts equatorward considerably during severely disturbed periods, the distribution pattern of the circles would reflect such a trend with fewer data points in the higher-latitude regions. In other words, most of the circles would distribute around the latitude of Sitka or its equatorward side if there were other magnetic stations located lower than Sitka in latitude. However, no hint of such a trend is noted even during very disturbed periods; see Figure 1h. Although it is not shown here, the same trend persists even during the magnetic activity level of 1800 < $|\Delta H|$ < 1900 nT, the most active period ever recorded over the Alaska meridian chain during 1998. By examining magnetic records from College (65.1°) and Sitka (59.8°) during the International Geophysical Year (one of the most disturbed periods ever recorded during the last century), *Weimer et al.* [1990] found that perturbation in the Z-component from Sitka almost always shows negative values, indicating that the westward electrojet was located poleward of Sitka. On the other hand, the center of the westward electrojet tends to shift to earlier local times. During severely disturbed periods, say $|\Delta H|$ > 1600 nT, the average center of the westward electrojet is found to be at 23.59 ± 1.57 MLT. Thus it is concluded that while the center of the westward electrojet tends to shift to earlier local times, its equatorward expansion is insignificant with an increase of geomagnetic activity as far as the Alaska meridian chain is concerned.

[10] Figure 2 shows the distribution of the centers of the westward electrojet over the CANOPUS meridian chain during 1998. As can be noted from Table 1, only the eastern meridian line, Churchill line, of the CANOPUS chain is utilized in this study. Since the magnetic stations of the CANOPUS cover a wide latitudinal region, from 79.03° to 60.60°, it is better than the Alaska chain in monitoring the westward electrojet for a wide range of magnetic activity. During very quiet periods, say $|\Delta H|$ < 200 nT, the probability of observing this level of activity is almost the same regardless of latitude and magnetic local time except for the highest station around 0000 MLT meridian. As magnetic activity increases, one can clearly see that the probability of recording the activity level of, say, 200 < $|\Delta H|$ < 400 nT, at the highest latitude station, Taloyoak (79.03°), becomes very low. The average center of the westward electrojet during this activity level is found to be at 67.31° ± 3.47° and 2.55 ± 3.36 MLT. This is higher in latitude than in the Alaska chain for the same activity level. It is simply because the CANOPUS chain is generally located at a higher-latitude region than the Alaska chain is.

[11] As magnetic activity further increases, the center of the westward electrojet migrates equatorward gradually without showing any significant local time shift. During the activity level of 800 < $|\Delta H|$ < 1000 nT, i.e., Figure 2b, the center is found to be at 64.55° ± 3.37° and 2.69 ± 2.71 MLT. During an extremely disturbed situation, 1400 < $|\Delta H|$ < 1600 nT, shown in Figure 2h, it expands as low as 63.39° ± 3.18°. From the distribution pattern of the circles, showing a finite latitudinal range, one may expect a possibility that the center of the westward electrojet is also found beyond Pinawa (60.60°), the lowest station of the CANOPUS chain. Although not shown here, however, even during activity level as high as 1700 < $|\Delta H|$ < 1800 nT, the center of the westward electrojet was properly monitored by several lower CANOPUS chain stations. Thus it is unlikely that the center of the westward electrojet expands well beyond 60° for the magnetic activity levels examined in this study.

[12] Similar to Figures 1 and 2, Figure 3 shows the locations of the center of the westward electrojet based on the data obtained from the IMAGE chain of magnetometers during 1998. It also shows the same characteristics noted from Figures 1 and 2. For example, the center of the westward electrojet during a quiet period, say $|\Delta H|$ < 200 nT, can be located at any latitude, while during a disturbed period, say 800 < $|\Delta H|$ < 1000 nT, Figure 3b, it shifts to 64.80° ± 3.23° and 3.68 ± 2.74 MLT, almost the same latitudinal region recorded from the CANOPUS chain for the same activity level. During the extremely disturbed situation, e.g., 1400 < $|\Delta H|$ < 1600 nT, the center is located at 64.33° ± 1.38° and 5.50 ± 2.08 MLT. The latitude of the center is comparable to that of the CANOPUS chain for the same activity level. However, it shifts toward late local time sector, about 3 or 4 hours, compared to the Alaska and CANOPUS chains. It is further interesting to note that the data points tend to shift to a later local time sector as magnetic activity increases. Thus it is likely that the longitudinal center would be found in a later local time sector than noted here particularly during highly disturbed periods if we expand the limitation in local time (2000–0900 MLT). It is an unexpected tendency and should be examined as a separate topic. Since the lowest station of the IMAGE chain is located as low as 56.85°, it provides us with an opportunity to check whether during extremely disturbed periods the westward electrojet flows equatorward of the latitudinal region covered either by the Alaska or CANOPUS chain. It is noted, however, that the center deduced from the IMAGE chain does not seem to expand steadily beyond the latitudinal range of either Alaska or CANOPUS chain covers but rather to approach 63°–64° ± ≈2.0° regardless of magnetic activity.

[13] For the CANOPUS chain we examine the location of the center of the westward electrojet by utilizing 4 years' data, 1990, 1991, 1997, and 1998. Although not shown here, the general trend is the same as that based on the 1 year's data, 1998. Since more data are employed, the scatter of the locations of the center in terms of standard deviation is more significant than the one based on the 1 year's data. For example, the centers for the activity level of 1000 < $|\Delta H|$ < 1200 nT are found at 65.37° ± 3.23°. The average local time sector where the electrojet center appears is located almost at the same MLT sector recorded during 1998 except for a larger standard deviation.

[14] Figure 4 summarizes the results of Figure 2, showing the latitude and the magnetic local time where the centers of westward electrojet are recorded during various activity levels. As an example, only the result of the CANOPUS chain is shown here. Figure 4a shows how the center of westward electrojet expands equatorward as magnetic activity increases. It clearly shows that the center of the westward electrojet tends to migrate equatorward steadily down to 63.22° (with the mean error of 0.97°) until magnetic activity reaches up to 1500 nT. After that the fluctuation is so erratic that it is not possible to determine any systematic behavior. It may be an intrinsic characteristic of the auroral electrojet during the maximum phase of

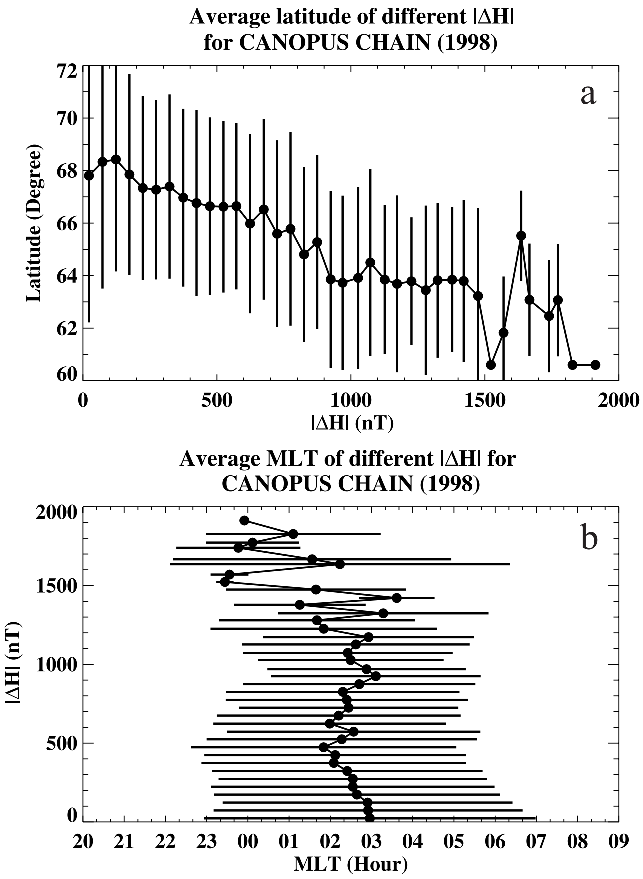

Figure 4. (a) Tendency of the center of the westward electrojet to expand equatorward with magnetic activity. Each vertical bar represents two standard deviations in the latitudinal direction. (b) Magnetic local time variation of the center of the westward electrojet with magnetic activity. As in Figure 4a, the horizontal bars correspond to two standard deviations in the MLT direction.

severe substorm. Although one cannot confirm such a systematic equatorward expansion over Alaska and IMAGE chains as noted in the CANOPUS chain in Figure 2, however, the two chains show that the center of the westward electrojet does not shift beyond 64°–65°. In any case, there seems to be a lower limit to the westward electrojet even during severely disturbed periods. Even if taking into account the standard deviation, it is unlikely that the center expands beyond 60°.

[15] Figure 4b shows how the center of the westward electrojet over the CANOPUS chain shifts longitudinally, as magnetic activity increases. Until the activity level reaches up to about $|\Delta H|$ = 1200 nT, the center is mildly fluctuating around 0300 MLT. Many years ago, *Allen and Kroehl* [1975] arrived at the same conclusion. According to them, the *AL* index is most often derived from the records of stations located around 0315 MLT. One can note that the center tends to migrate toward earlier local time sector as magnetic activity exceeds 1500 nT. As the activity exceeds 1500 nT in terms of $|\Delta H|$, however, such a trend becomes very erratic. It is partly because not enough data were available during very disturbed periods to determine any statistically significant trend. More importantly, it seems to be an intrinsic nature associated with dynamics of the auroral oval that expands poleward as well as in the westward direction during the expansion phase of substorms.

3. Relative Location of the Westward Electrojet With Respect to Auroral Image

[16] During severe geomagnetic storms, auroras can be seen at latitudes as low as Texas. It is an interesting question to ask: Where is the auroral electrojet located with respect to the aurora during such occasions? Does the westward electrojet belt also expand together with the bright auroral image to such a lower latitude? Figure 5 shows five consecutive Polar Visible Imaging System images, taken every 3 min from 0714 UT on 22 October 1999. It was during the maximum phase of a magnetic storm with the *Dst* index being −237 nT at 0700 UT. Overlapped with the images are seven geomagnetic stations to determine the center of the westward electrojet during the period: St. Johns, Ottawa, Pinawa, Meanook, New Port, Victoria, and Sitka. A map is also included to show the locations of those ground magnetic stations. Although a color code for the luminosity scale of aurora is adopted, one can identify approximately three kinds of color in the images. The low, intermediate, and bright regions are represented approximately by the colors of purple, deep blue, and green or brighter. The latitude circles of 80°, 70°, 60°, and 50° and the dawn-dusk and noon-midnight meridians are also indicated.

[17] At 0714 UT an extraordinary bright region was located along the southern border of the auroral oval in the midnight sector. The oval becomes narrower toward both afternoon and postmidnight sectors. It is interesting to note that magnetic stations New Port and Victoria, which were embedded in or close to the brightest auroral image, did not record the highest magnetic disturbance. They recorded merely −201 and −62 nT, respectively, less intense compared to the disturbances at the five other stations located poleward. Disturbed conditions were recorded rather away from the bright region. The strongest ΔH disturbance, −872 nT, was record at Ottawa. Pinawa and Meanook also recorded relatively higher ΔH disturbance, −660.0 and −662 nT, respectively.

[18] Figures 6a and 6b show the stack plots of ΔH and ΔZ components of the seven magnetic stations during the first half of 22 October 1999. The vertical dotted line indicates the epoch during which the first auroral image was taken. To determine the relative location of a magnetic station with respect to the center of the auroral electrojet, one can use Z component [*Rostoker and Hughes*, 1979]. Figure 6b shows that only two out of the seven stations, Pinawa and Meanook, recorded positive Z component during the entire period covered by the five images, indicating that the center of the westward electrojet was located equatorward of the two stations. In other words, the center of the auroral electrojet was located poleward of the rest of the five stations during the entire period. Thus the center of the electrojet seemed to be located somewhere between Meanook and New Port in the premidnight sector. Three minutes later at ~0717 UT, Pinawa, which was located at the border region between bright (green) and less bright (deep blue) auroral

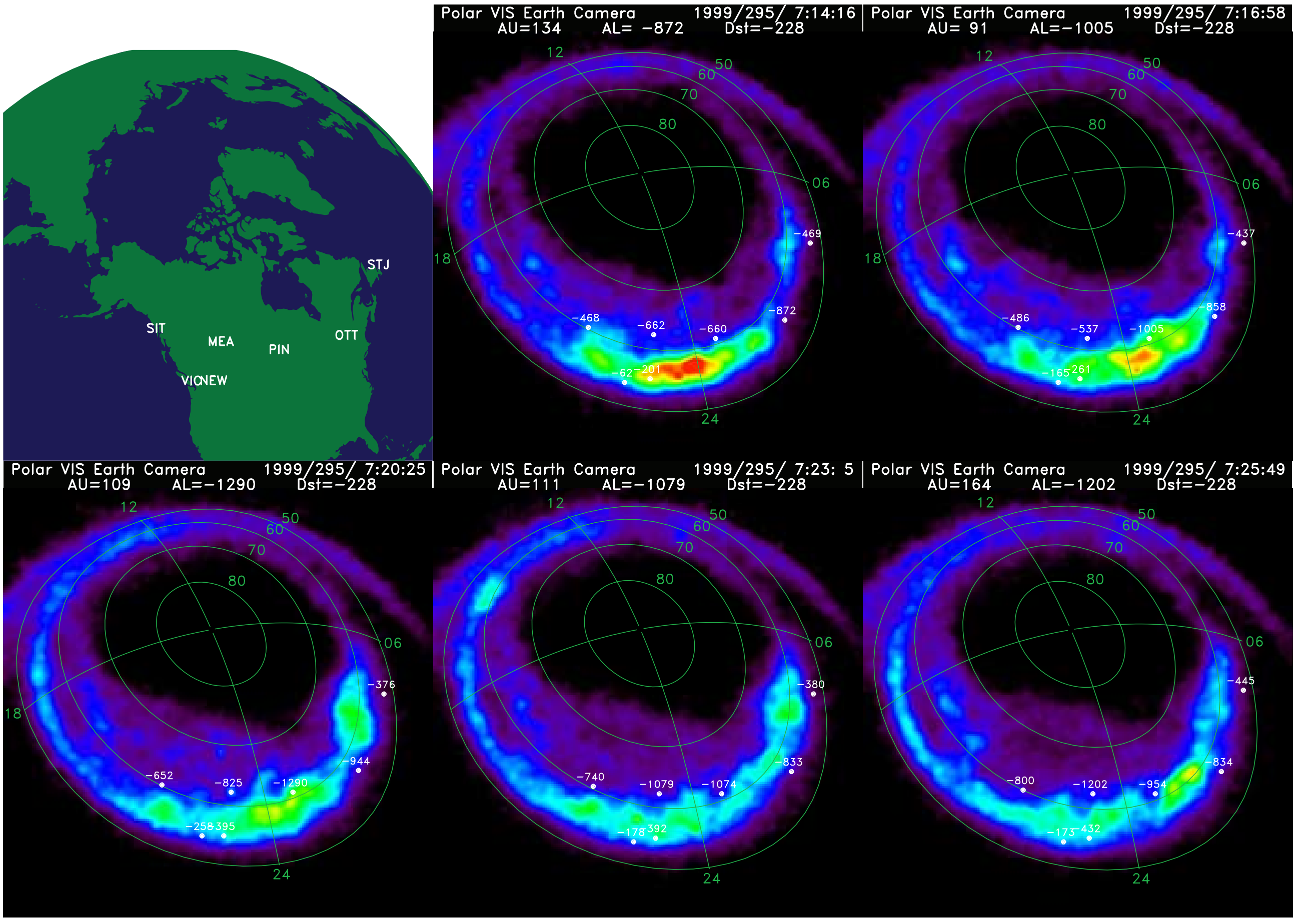

Figure 5. Five Polar Visible Imaging System auroral images, each taken ∼3 min apart from 0714 UT on 22 October 1999, shown with a map showing the locations of the seven ground magnetic stations. Superimposed with the images are ΔH variations observed at the seven magnetic stations (SIT, Sitka; VIC, Victoria; NEW, Newport; MEA, Meanook; PIN, Pinawa; OTT, Ottawa; STJ, St. Johns). Latitude circles of 80°, 70°, 60°, and 50° along with the dawn-dusk and noon-midnight meridians are marked. *AU*, *AL*, and *Dst* indices during each epoch are also indicated.

image, recorded significantly high magnetic disturbance, −1005 nT, while the other stations did not show any noticeable enhancement.

[19] At 0720 UT the bright region of the aurora shrank somewhat compared to the two previous epochs. However, one can note that most of the stations, except for St. Johns, recorded higher magnetic disturbances compared to the earlier epochs. It is a strong indication that the intensity of the auroral electrojet is not necessarily proportional to the auroral luminosity or ionospheric conductivity. At ∼0723 UT the overall brightness of the entire auroral image was reduced further while the level of overall magnetic disturbance persisted more or less the similar level of the previous epoch. A close examination of the auroral image at 0723 UT reveals that there seems to be a boundary dividing two regions in terms of brightness of aurora with a deep blue−colored zone occupying the equatorward side and a purple-colored zone in the poleward side. It is likely that the demarcation in the auroral brightness delineates the center of the westward auroral electrojet. Note that three stations, Pinawa, Meanook, and Sitka, located along the demarcation line recorded relatively higher magnetic disturbances.

[20] Admitting that high ionospheric conductivity would be expected over a bright auroral region but it is also the region of a rather weak electric field [*Kamide et al.*, 1986], the intense auroral electrojet would flow in the region where both the ionospheric conductivity and the electric field are considerably high. The center of the auroral electrojet seems to correspond to the boundary region that separates the brighter auroral region of the equatorward portion from the wide but less bright area of the poleward portion. Note that although they are under the brighter part of the auroral image, the magnetic disturbances recorded at New Port and Victoria during the epoch (0723 UT) were lower than those of the three stations Pinawa (−1074 nT), Meanook (−1079 nT), and Sitka (−740 nT), all located in the less bright auroral region. Note particularly that Pinawa recorded a significantly high ΔH and also a considerably high positive ΔZ, indicating that the center of the westward electrojet is at least a few degrees equatorward of it. Such a tendency persisted until the epoch of ∼0726 UT as well.

[21] Despite the fact that it is a lower latitude station and under less bright auroral image, Ottawa recorded a highly disturbed condition in early morning hours. At the same

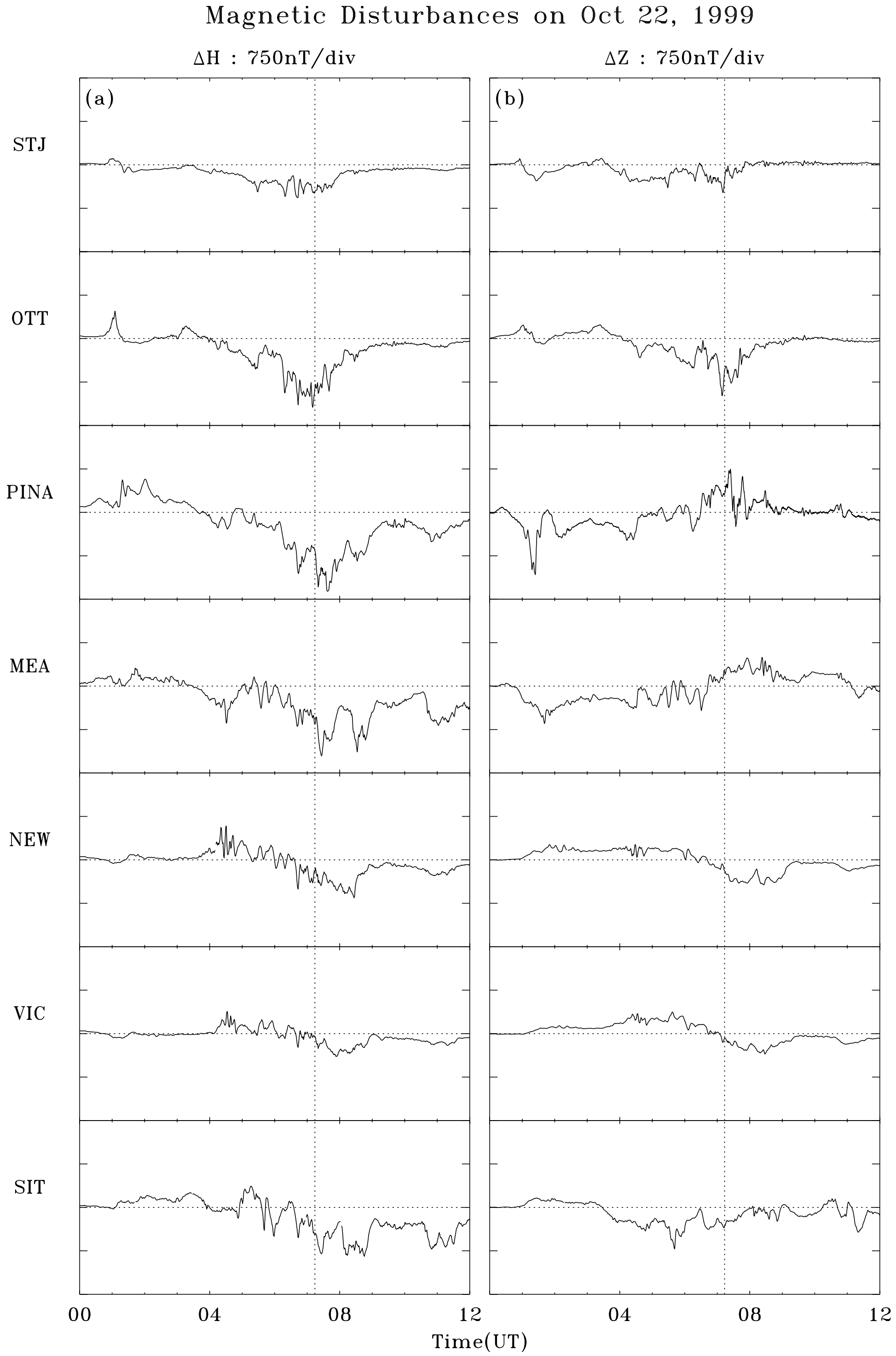

Figure 6. Magnetic variations of (a) ΔH and (b) ΔZ of the seven magnetic stations appearing in Figure 5 for the first half of 22 October 1999. Vertical dotted line corresponds to the epoch, 0714 UT, when the first auroral image shown in Figure 5 was taken. Horizontal dotted line denotes the baseline value of each station.

time it recorded a considerably large negative *Z* component, indicating that the center of the westward electrojet flows far poleward of the station. This can be accounted for by considering that the auroral oval over the region is rather narrow and less bright compared to the portion over the midnight sector. It can be interpreted that the electric field plays an important role in intensifying the auroral electrojet in the region. St. Jones, which was far east of Ottawa, showed the same tendency. On the other hand, Sitka, under less bright region (purple), also recorded a significantly high disturbance, indicating that electric field plays an important role. Enhancements in the electric field and ionospheric conductivity seem to be complementary of each other, implying that if the electric field is strong in a region, the ionospheric conductivity would be rather weak in that region and vice versa. However, the electric field appears to play a leading role in intensifying the westward electrojet, while the ionospheric conductivity enhancement is also essential but seems to play a secondary role. We have seen that large magnetic disturbance is associated not with bright but with less bright aurora region. It is an indirect indication that the electric field plays a major role in intensifying the auroral electrojet. In other words, an enhancement in the *AL* index is, in general, more closely associated with a sudden intensification of the electric field rather than an impulsive ionospheric conductivity enhancement.

[22] Throughout the five epochs, Pinawa and Meanook recorded positive *Z* component while the other five stations recorded negative *Z* component, indicating that the center of the auroral electrojet seems to flow equatorward of the two stations, Meanook and Pinawa, and poleward of the rest of the five stations. Considering the magnetic latitude of the seven stations, we can infer that the latitude of the westward electrojet center is at around 60° in the night hemisphere. It would be approximately the same lowest possible latitude of the westward electrojet center, determined statistically from the three-meridian chain data and shown in Figures 1, 2, and 3.

4. Discussion

[23] To estimate equatorward expansion of the auroral electrojet during very disturbed periods, the latitude of the station that recorded the highest disturbance along a meridian chain is used as a proxy for the location of the center of the westward electrojet at the given epoch. As expected, the auroral electrojet tends to expand equatorward with magnetic activity. However, the expansion does not seem to exceed a certain latitudinal range even during severely disturbed periods. The lowest possible latitude of the center of the westward electrojet seems to be at around 60° in corrected geomagnetic latitude. Such a tendency is also confirmed from an event study of a major magnetic storm during which a bright aurora was observed as low as the northern part of continental north America. Interestingly, the intense part of the westward electrojet during the storm period does not flow near the equatorward boundary of the auroral oval, where the aurora is brightest, but flows along the demarcation line which divides bright and less bright auroral regions or relatively dark region. The latitude of the demarcation was ~60° during a storm event analyzed in this study. In other words, an intense auroral electrojet is not necessarily collocated with a bright aurora image. Allowing that the auroral electrojet represents a combined manifestation of the ionospheric conductivity and the electric field, it is reasonable to mention that a bright aurora alone cannot activate an intense electrojet. Actually, the intense westward electrojet during the storm period seemed to flow along the demarcation line between the bright auroral region and a less bright one or along the poleward boundary of the bright auroral image. It is the region where both conductivity and electric field are expected to be considerably high. Since intense electrojets always flow in less luminous auroral region, however, the electric field seems to play a more important role in intensifying the auroral electrojet than the ionospheric conductivity does.

[24] Using a realistic conductivity distribution based on bremsstrahlung X-ray image data, *Ahn et al.* [1989] examined the spatial relationship between conductivity enhancement and auroral electrojet. They found that the poleward half of the westward electrojet in the postmidnight sector is dominated by the electric field, while its equatorward half is dominated by the ionospheric conductivity. The demarcation line seems to delineate the boundary between the bright and less bright aurora regions. They further confirmed that the intense westward electrojet flows along the demarcation line between the electric field- and conductivity-dominant regions. It was also noted that the enhanced conductivity region even at the nightside auroral latitude does not necessarily accompany an enhanced ionospheric current. Such a tendency is clearly demonstrated in the ionospheric conductivity model by *Ahn et al.* [1998]. According to them, the ionospheric conductivity in the equatorward half of the auroral electrojet is significantly higher than the poleward half for a given level of magnetic activity.

[25] Figure 7 shows the relationship between the colatitude of the maximum westward electrojet and the magnitude of its current density during the magnetic storm of 4–6 November 1993 [*Knipp et al.*, 1998]. The current density was estimated from the Kamide-Richmond-Matsushita (KRM) method [*Kamide et al.*, 1981] using the magnetic disturbance data simultaneously obtained from 87 ground magnetic stations of the Northern Hemisphere. As confirmed from the meridian chain data in Figures 1, 2, and 3, the center of the westward electrojet during relatively quiet periods with current density lower than ~0.5 A/m can be found from higher than 75° to as low as 60°. It tends to expand equatorward as the current density increases. Such a tendency, however, does not persist continuously. Even during very disturbed periods with the current density approaching ~1.5 A/m, the center of the westward electrojet does not expand beyond 60°.

[26] *Kamide and Brekke* [1975] showed that there is a simple relationship between the ionospheric current density (I) and geomagnetic disturbance (H): I (A/km) $\approx 2H$ (nT). In other words, when an ionospheric current with the density of 1500 A/km flows, magnetic disturbance of ~750 nT is expected on the ground. Figure 7 shows that during such an activity level the center of the westward electrojet is located within the latitudinal range of from around 60° to 66°, consistent with what Figures 1, 2, and 3 indicate. It is another piece of evidence that even during very disturbed periods the center of the westward electrojet does not seem to expand well beyond ~60°.

[27] It is interesting to note that while the bright aurora can march toward lower latitudes during severe magnetic storm, the center of the westward electrojet does not seem to expand accordingly but approaches to around 60°. Therefore the current *AE* network, which covers as low as ~62°, does not have any serious problems in monitoring the auroral electrojet even during intense geomagnetic storm as long as the lowest *AE* station is located in the dark hemisphere. *Weimer et al.* [1990] also confirmed that the electrojet appears to remain poleward of 60° during substorms. The only problem, as noted by *Ahn et al.* [2000], is

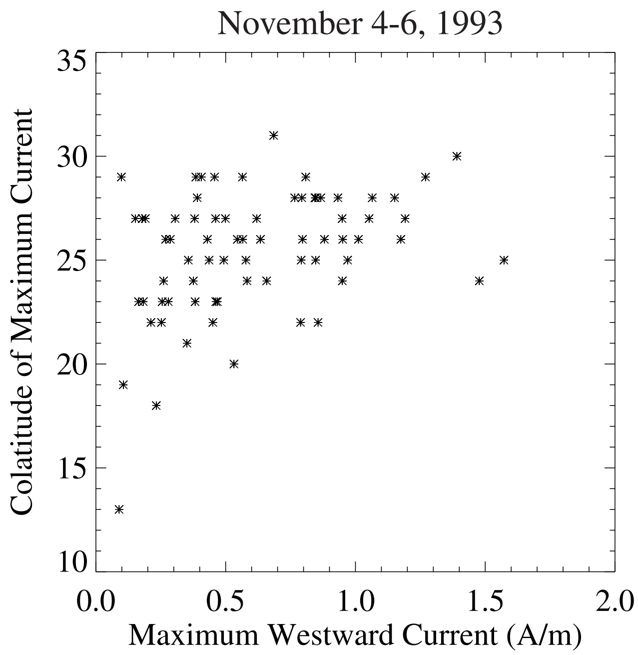

Figure 7. Relationship between the maximum westward current inferred from the Kamide-Richmond-Matsushita (KRM) method and the colatitude where the current was recorded during the magnetic storm that occurred on 4–6 November 1993.

that when the lowest *AE* station, previously Cape Wellen (62.2°), is located outside the night sector, the *AE* indices tend to be underestimated during severely disturbed periods. It is particularly the case when Narssarssuag (68.9°) and Leirvogur (66.8°) come to the midnight-early morning sector during early UT hours.

[28] Although bright auroras can be seen all the way down to the subauroral region, the intense auroral electrojet does not seem to flow in the bright auroral region but rather in the less bright region, or the poleward side of the brightest auroral oval as shown in Figure 5. It is partly because high ionospheric conductivity associated with bright aurora image can short-circuit the electric fields. As proposed by *Weimer et al.* [1990] and *Russell et al.* [2001], it is closely associated with the nonlinear response of the cross-polar cap potential to large magnetospheric potential imposed by enhanced reconnection on the dayside magnetopause during large southward B_z period, thus resulting in the saturation of the cross-polar cap potential. Actually, the saturation level of the potential is lowered as the auroral conductivity increases, because a bright aurora is associated with high ionospheric conductivity. This may be a reason why the center of westward electrojet does not expand equatorward continuously but expands to approach a certain limiting latitude, around 60°, even during periods when aurora can be seen at much lower latitudes.

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