Correlation between Cusp Field-Aligned Currents and Interplanetary Magnetic Field

Ryoichi FUJII* and Takesi IIJIMA**

ポーラカスプの沿磁力線電流と惑星間空間磁場の関係

藤井良一*・飯島　健**

要旨： 最近，カスプ領域の field-aligned current の研究が行われだした．しかし，何をもってカスプ field-aligned current と呼ぶのか，また，経度方向にどういう分布をしているのか等の諸特性はまだ分かっていない．この論文では，カスプ field-aligned current の分布および惑星間空間磁場 B_y による分布のシフトおよび B_z とカスプ field-aligned current の強度との相関を調べた．その結果，

1) カスプ型 field-aligned current は，午前側と午後側の region 1 の境目が午前側や午後側に移動することでは説明できない

2) カスプ型 field-aligned current の午前側と午後側タイプの境目は，IMF B_y にコントロールされる．

3) カスプ型 field-aligned current 強度と IMF B_z とは，B_z が負の値のとき負でかつ線型の相関がある

Abstract: From the analysis of vector magnetometer data of more than 200 passes of TRIAD that were recorded at McMurdo, Antarctica, during the winter season, 1974, the principal characteristics of the cusp field-aligned currents (FAC) in the midday south polar region are determined:

1) Cusp type FAC's exist in the midday polar region that is separate from the region 1 (and 2) FAC regimes. No satisfactory explanation is obtained by attributing the cusp type FAC's to dislocation in latitude and or shift in longitude of the general distribution of the region 1 and 2 FAC's.

2) The demarcation line between the pre-noon type and the post-noon type cusp FAC's is controlled well by the polarity of IMF B_y

3) There is a linear correlation between the intensity of the cusp FAC and the negative IMF B_z component. No clear relation was found between the cusp FAC intensity and the positive IMF B_z component.

* 国立極地研究所．National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173.

** 東京大学理学部地球物理研究施設 Geophysics Research Laboratory, University of Tokyo, 11-16, Yayoi 2-chome, Bunkyo-ku, Tokyo 113

1. Introduction

In recent years, characteristics of field-aligned currents (FAC) at low altitudes in the dayside cusp region have been determined from the magnetic field observation data acquired with polar-orbiting satellites (*e.g.* IIJIMA and POTEMRA, 1976a; MCDIARMID *et al.*, 1978; IIJIMA *et al.*, 1978). IIJIMA and POTEMRA (1976a) proposed that the cusp region FAC represents different regime of FAC from those of region 1 and 2 FAC's. IIJIMA *et al.* (1978) and MCDIARMID *et al.* (1978) have found a close correlation between the cusp FAC and the interplanetary magnetic field (IMF), especially its B_y component. Simultaneous observations of particles and magnetic field perturbations in the dayside polar region including the cusp region were also presented by BURROW *et al.* (1976) and POTEMRA *et al.* (1977). Furthermore, characteristics of plasma convection (electric field) in the cusp region were demonstrated by HEELIS *et al.* (1976) with the AE-D satellite experiments.

Questions, however, remain as to what is the cusp FAC, how is the cusp FAC different from region 1 or 2 FAC's, how does the cusp FAC distribution change depending on IMF B_z or B_y, what is the source of the cusp FAC, and how is the closure of the cusp FAC.

In this paper, magnetometer data acquired with the TRIAD satellite in southern high latitudes are analyzed. First, we show the local time distribution of FAC in the dayside region 1, and region 2 FAC's. Then we discuss the correlation between intensities of the cusp and region 1 FAC's and the interplanetary magnetic field.

2. Data

In our analysis we use the TRIAD satellite magnetometer data obtained during the period from the end of March to the end of August, 1974, that were recorded at McMurdo, Antarctica. The orbiting parameters and instrumental information are given in Table 1 and the coordinates for the three orthogonal components

Table 1. TRIAD satellite flying condition and instrumental information.

Altitude	800 km
Speed	5 km/s
Sampling rate	2.25/axes/s
Resolution of magnetometer	12 nT

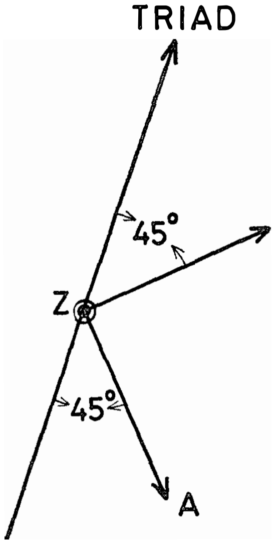


Fig. 1. Definition of coordinates of three orthogonal components of measured magnetic field by TRIAD's fluxagte magnetometer.

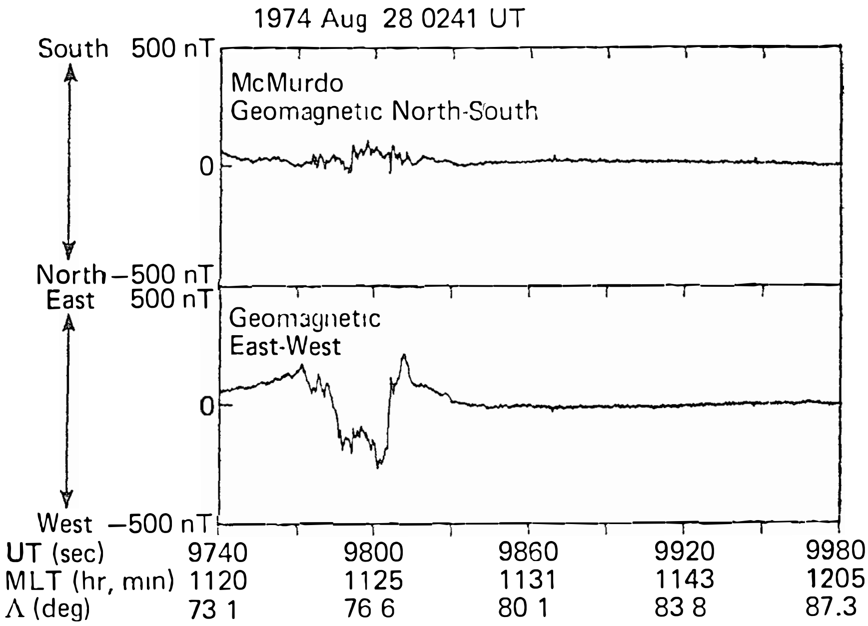


Fig. 2. Dayside magnetic field perturbations in which long period perturbations of each component were removed through a digital filter. Decrease of variation in east-west component corresponds to downward FAC (into the ionosphere) and increase corresponds to upward FAC (away from the ionosphere).

of measured magnetic field vector $\boldsymbol{B}$(A, B, Z) are displayed in Fig. 1

Magnetic field perturbations observed by TRIAD usually include two kinds of variations. One is short-lived (~60 s) perturbation and the other is slow and regular variation. It has been thought that the former shows an existence of field-aligned currents while the latter would be ascribable to TRIAD's attitude changes and self-magnetization effects (SUGIURA and POTEMRA, 1976).

The TRIAD data were recorded on the real time telemetry. Since McMurdo in the southern hemisphere is located at a higher latitude (geomagnetic latitude= 79.7°) than College (64.9°), the northern tracking station of TRIAD, the TRIAD data received at McMurdo are more useful for studying the characteristics of cusp region and polar cap field-aligned currents compared with those recorded at College.

An example of the dayside region FAC is shown in Fig. 2 in which long period variations of each magnetometer component were removed by passing the data through a digital filter.

In the following, we determine the FAC intensity and density from the magnetometer data under the following approximations:

1) Field-aligned current is represented by a current sheet with infinite length and uniform density.

2) Its longitudinal extent is much longer than latitudinal width.

3) The motion of the field-aligned current sheet is small during the observation as compared to the satellite velocity ($V_{sat} \gg V_{fac}$).

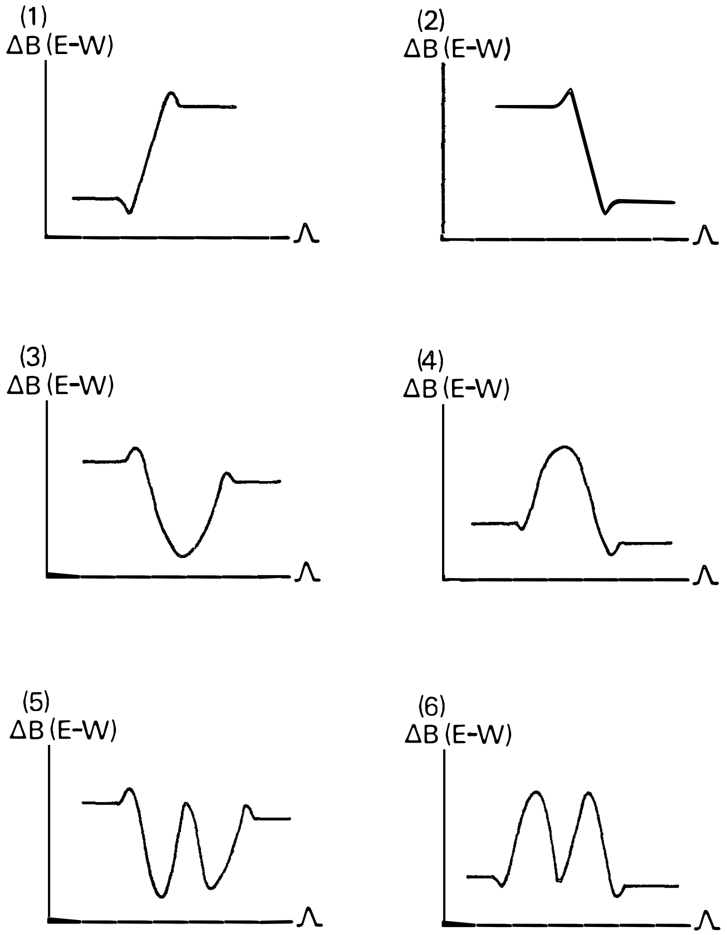
3. Signification of Distinction between the Cusp FAC and the Region 1 (or Region 2) FAC

From the magnetometer data obtained from 220 passes of TRIAD in the sector from 0600 MLT to 1800 MLT, only magnetic field perturbations with amplitude larger than 100 nT were examined. When two kinds of magnetic field perturbations are observed in close vicinity of each other and one of them is two tenth smaller than the dominant one, the smaller one is neglected.

Magnetic perturbations can be classified into 7 types (Fig. 3). In this paper we studied FAC's of types (1) through (4), because they occupy 93% of all events.

First we study FAC without considering IMF B_y's sign. Distribution of the single structure FAC's (types (1) and (2)) is displayed in Fig. 4a. On the vertical axis the word "occurrence" means the ratio of FAC observation number of a certain type for one hour magnetic local time interval (for example, from 1400 to 1500 MLT) to the total number of satellite coverage (type (1)–type (7)) for the same magnetic local time interval.

The number of the single FAC's flowing into the ionosphere has a peak (45%)

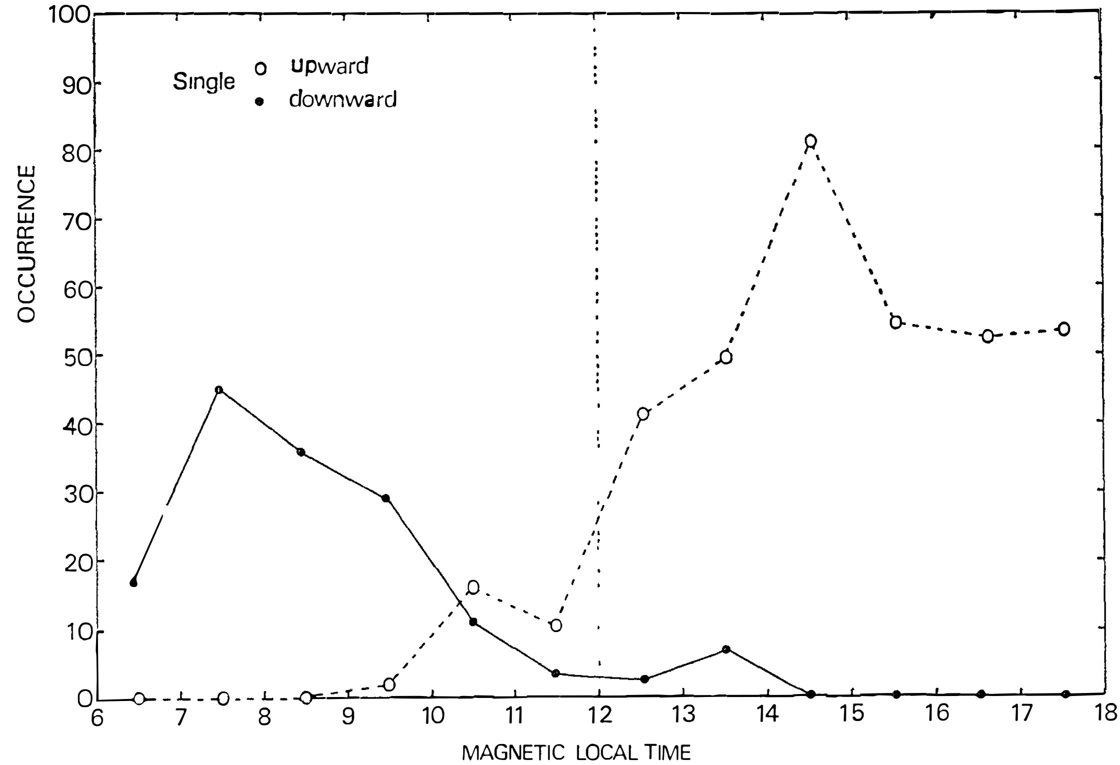


(7) MORE IRREGULAR TYPE

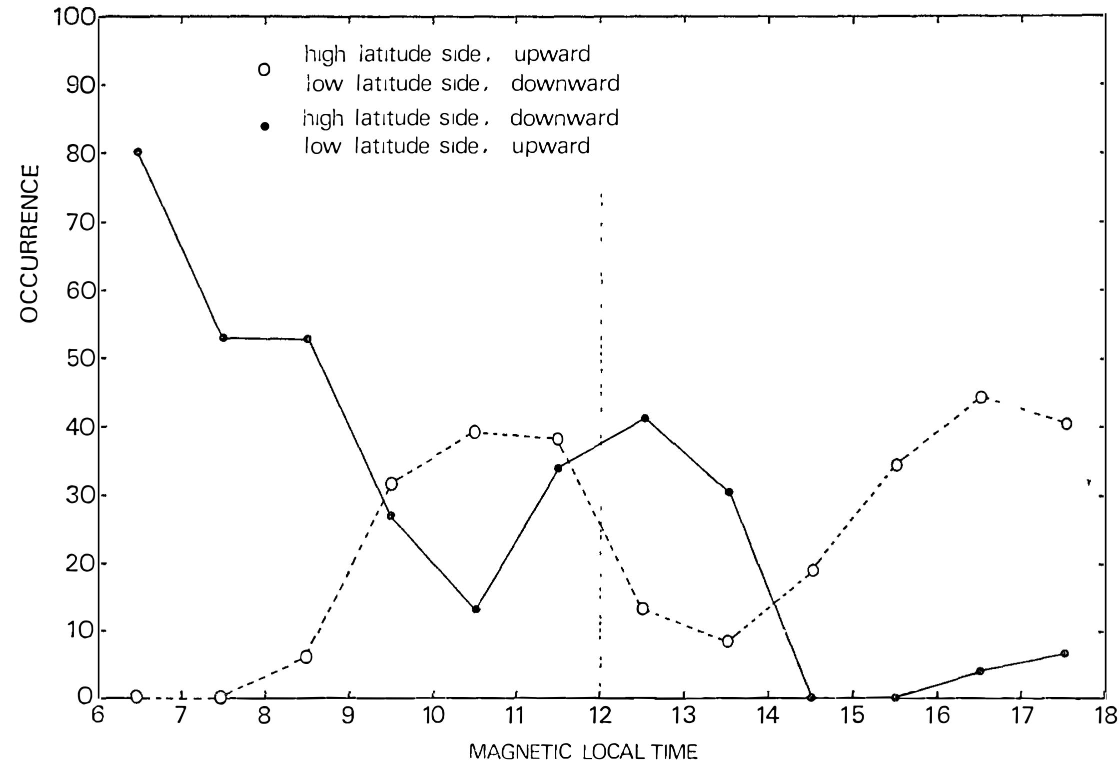
Fig. 3. Classification of magnetic field perturbations measured by TRIAD's magnetometer. Types (1) and (2) are referred to as 'single layer' FAC and types (3) and (4) are called 'double layer' FAC.

at 0700–0800 MLT and decreases when we approach the magnetic local noon. A small peak (7%) can be seen at 1300–1400 MLT. It is, however, doubtful that this peak is statistically significant, since the occurrence probability is much lower than that of the peak at 0700–0800 MLT. The number of the single FAC's flowing out of the ionosphere has a peak (81%) at 1400–1500 MLT and decreases when we approach the magnetic local noon. A small peak (16%) can be also seen at 1000–1100 MLT, similar to the case of downward FAC As for the distribution of the single FAC's the following points are noteworthy:

1) The demarcation MLT which divides the pre-noon type and the post-noon type FAC distributions is not exactly 1200 MLT, but 1000–1100 MLT. This fact is also noted in other observations (*e.g.* S_q^p current pattern).



(*a*) *Distribution of the single layer FAC.*



(*b*) *Distribution of the double layer FAC.*

Fig. 4. 'Occurrence' means the ratio of the number of FAC observations of a certain type for one hour local time interval to the total number of observations for the same interval.

2) The peak occurrence probability of upward FAC is greater than that of downward one. In the morning (0300–1000 MLT) and evening (1400–2100 MLT) regions this tendency has been also found (IIJIMA and POTEMRA, 1976b).

3) In each case there is a subpeak, but it is doubtful whether it is significant by itself.

Next, the distribution of double sheet-like FAC's (types (3) and (4)) is shown in Fig. 4b. A circle means that on the higher latitude side upward FAC is observed and on the lower latitude side downward FAC is observed. These current directions are the same to region 1 and 2 FAC's usually observed in the evening side (1400–2100 MLT). We refer this kind of FAC as the 'evening type FAC' The profile has a peak (44%) at 1600–1700 MLT and the occurrence decreases with decreasing MLT and has a minimum value at 1300–1400 MLT. Then the occurrence increases with decreasing MLT into the pre-noon sector and has a subpeak (41%) at 1000–1100 MLT. This subpeak is considered to be remarkable, because the preceding minimum probability is 9% at 1300–1400 MLT and this peak probability is more than 40%. A dot in Fig. 4b represents the case that on the higher latitude side downward and on the lower one upward FAC are observed. These current directions are the same to region 1 and 2 FAC's usually observed in the morning side (0300–1000 MLT). We refer this kind of FAC as the 'morning type FAC'. The occurrence decreases with increasing MLT until 1000 MLT and has a minimum value (13%) at 1000–1100 MLT and has a maximum value (41%) at 1200–1300 MLT, and then decreases toward late evening

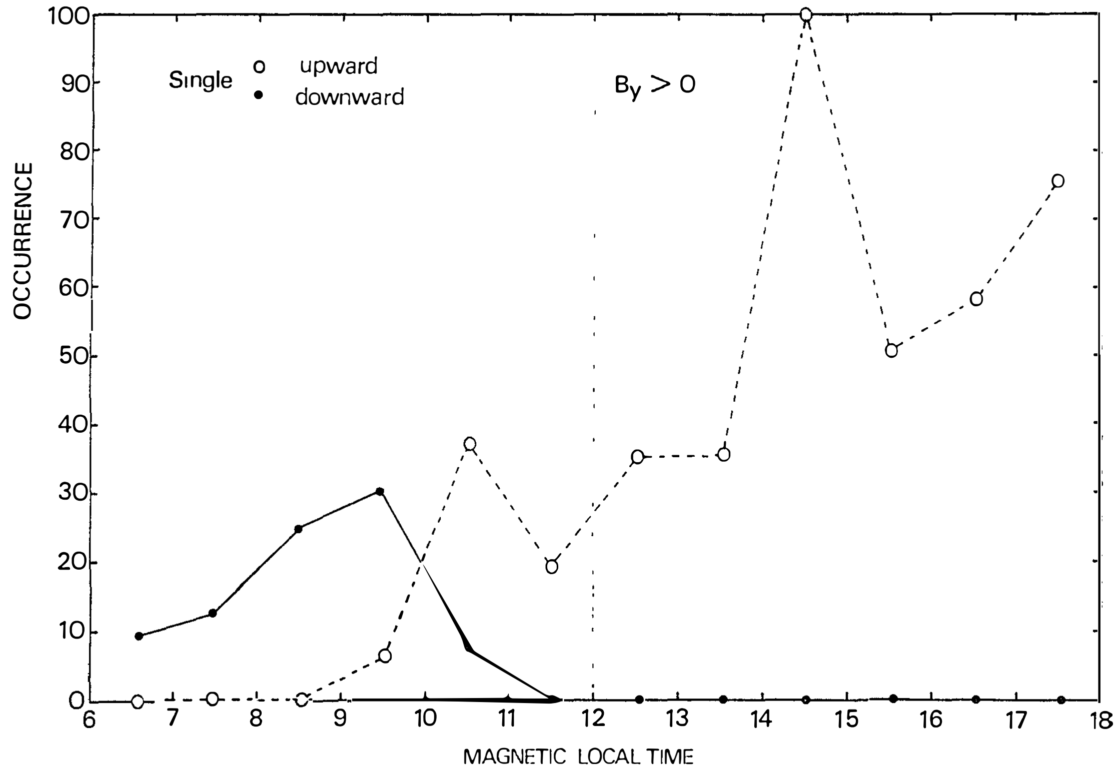
As for these double structured FAC's, the following points are noteworthy·

1) The morning (evening) type FAC has a peak at local time earlier (later) than the single layer FAC in the morning (evening).

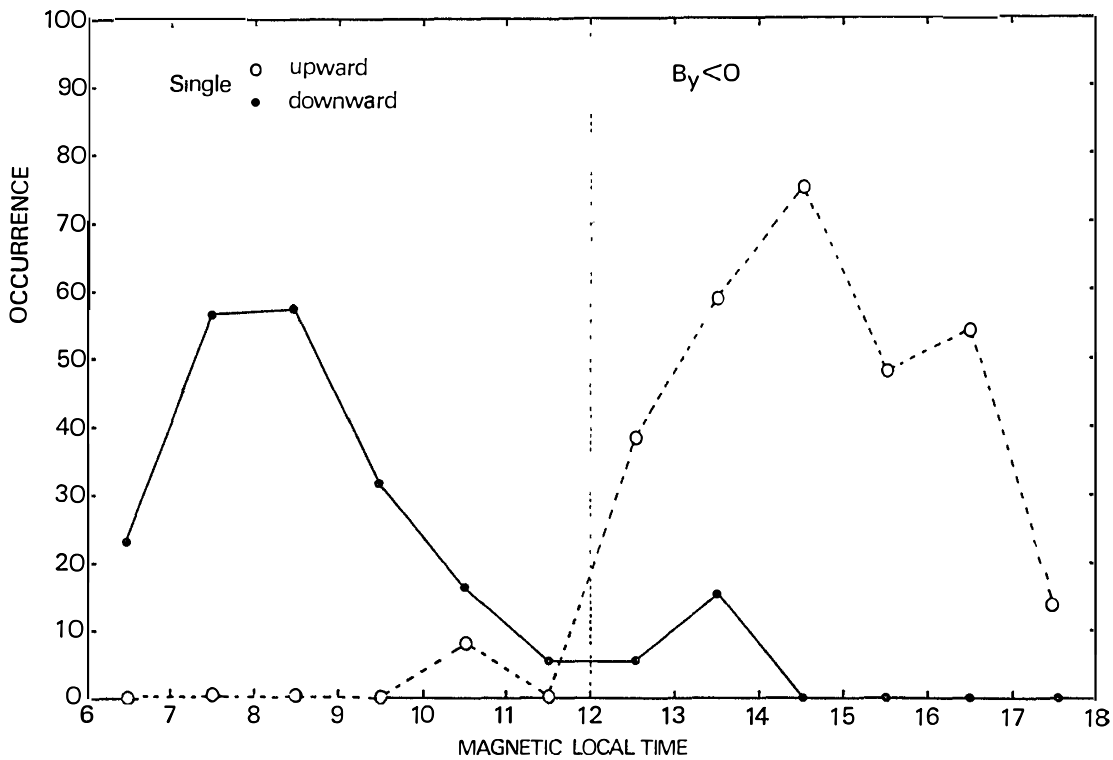
2) The morning (evening) type FAC has a peak in the evening (morning). This peak is statistically remarkable. The morning (evening) type FAC near the peak is thought to be different from a couple of region 1 and 2 FAC's in the morning (evening) side, because at 1000–1100 MLT (1300–1400 MLT) occurrence has a minimum value. We refer this FAC as the 'cusp FAC' in this paper

3) Demarcation magnetic local time between the two kinds of cusp FAC's leans to morning side (1100–1200 MLT), which is similar to the case of the single FAC.

The occurrence distribution of each type of FAC is displayed in Figs. 5 and 6 and is sorted according to the polarity of the IMF B_y component. On the vertical axis "occurrence" means the ratio of the occurrence number of a certain type of



(*a*)

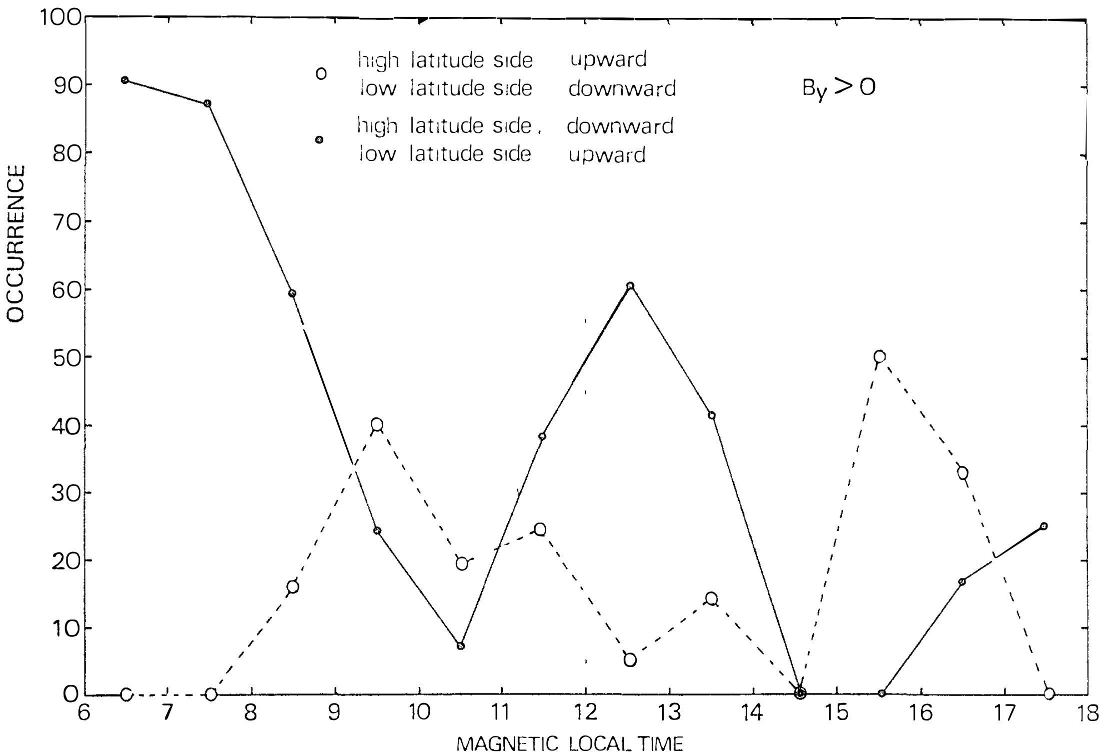


(*b*)

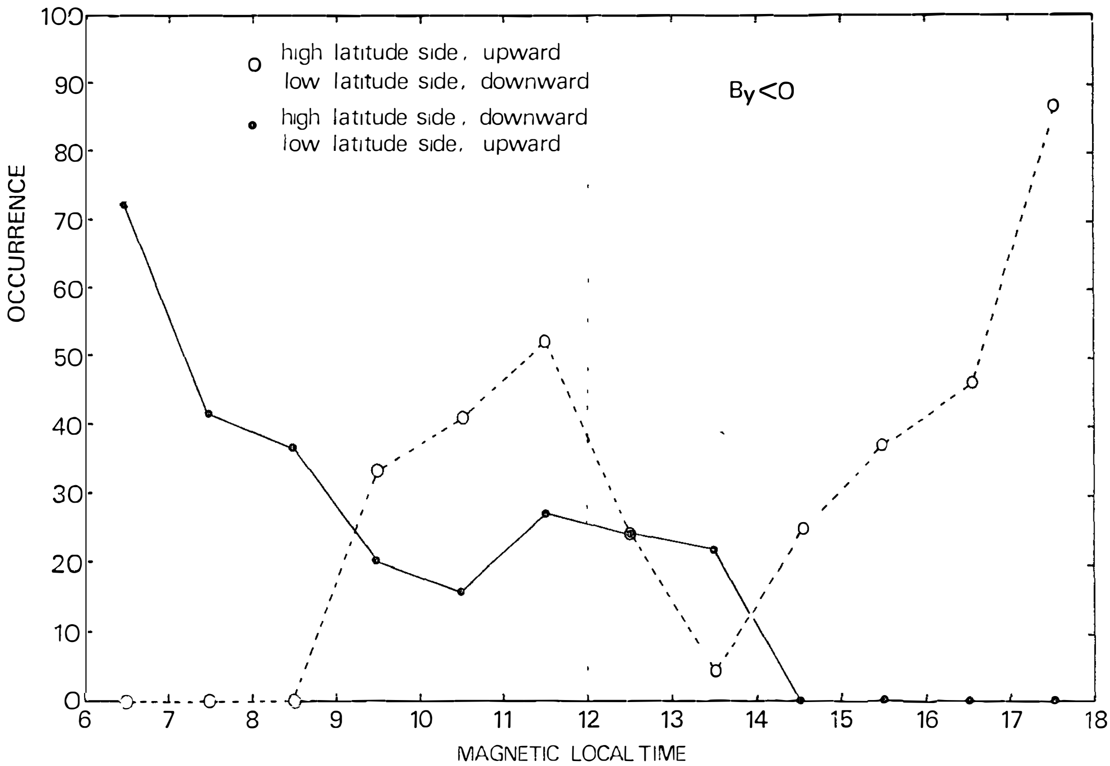
Fig. 5. Distribution of the single layer FAC when (a) IMF B_y is positive and (b) IMF B_y is negative.

FAC to the total number of satellite coverage for certain one hour magnetic local-time interval for positive or negative IMF B_y value. The total number for positive B_y is smaller (75 examples) than that for negative B_y (110 examples) (average $B_y=-0.5$ nT). First, distributions of the single layer type FAC's are given in Figs. 5a and 5b. Essentially, profiles for positive and negative B_y are similar to the overall profile given in Fig. 4a. The demarcation line which separates downward and upward FAC's, however, shifts to earlier MLT for positive B_y than for negative B_y. Namely, B_y is one of the controlling factors which shift the general distribution pattern of FAC's eastward or westward. Next, distributions of double-sheet structured FAC are shown in Figs. 6a and 6b. These are essentially the same as the distributions in Fig. 5. The isolated peaks in the midday sector demonstrate the existence of another regime of FAC, namely, cusp FAC. The B_y control is also examined. It is remarkable that demarcation line across which the distribution of cusp FAC changes from the pre-noon type to post-noon type is at 1200–1300 MLT when B_y is negative.

The important conclusion that can be drawn from the results shown in Figs. 4 through 6 is that the cusp FAC's display the spatial distributions that are distinct from the region 1 (and 2) FAC's, and their distributions are controlled by the polarity of the IMF B_y component.



(a)



(*b*)

Fig. 6. Distribution of the double layer FAC when (a) IMF B_y is positive and (b) IMF B_y is negative.

4. Relationships of IMF B_z with the Cusp FAC and Region 1 FAC

In the previous section we have shown that it is meaningful to classify the cusp FAC as of a distinct type from region 1 and 2 FAC's. Although our results may include some ambiguity that we may possibly have mistaken the region 1 FAC for the cusp FAC, its probability would be less than 10%. In this section we examine the correlation between the cusp FAC and IMF B_z. This correlation is very important for understanding the mechanism of the cusp FAC.

We selected the events by the following criteria:

1) We choose FAC's observed in the MLT sectors of 0900–1130 MLT and 1230–1500 MLT.

2) As for the double sheet type, upward (downward) FAC on the higher latitude side in the dawn (dusk) sector is examined.

3) Only events for which simultaneous IMF data are available are used. We used the hourly-averaged IMF B_z values in solar magnetospheric co-

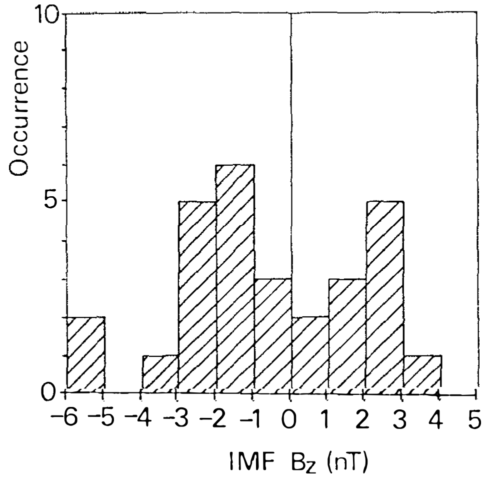
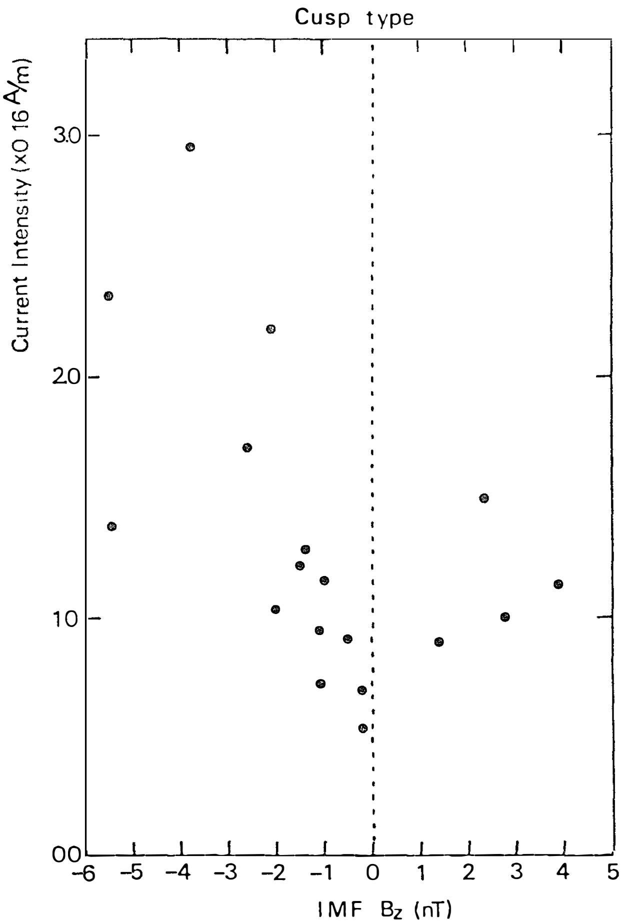
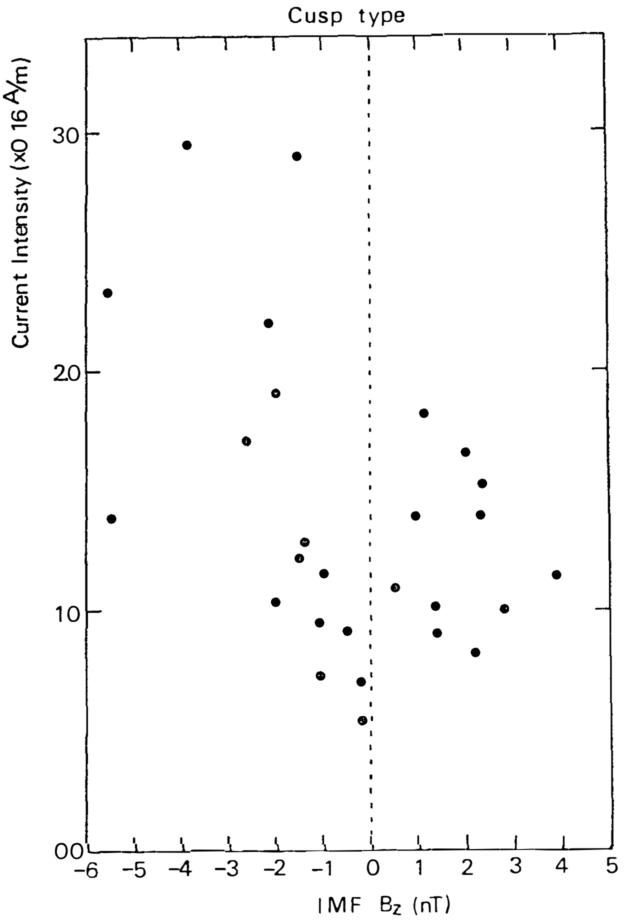


Fig 7 Occurrence number of the cusp FAC from 0900–1500 MLT plotted against the hourly averaged B_z



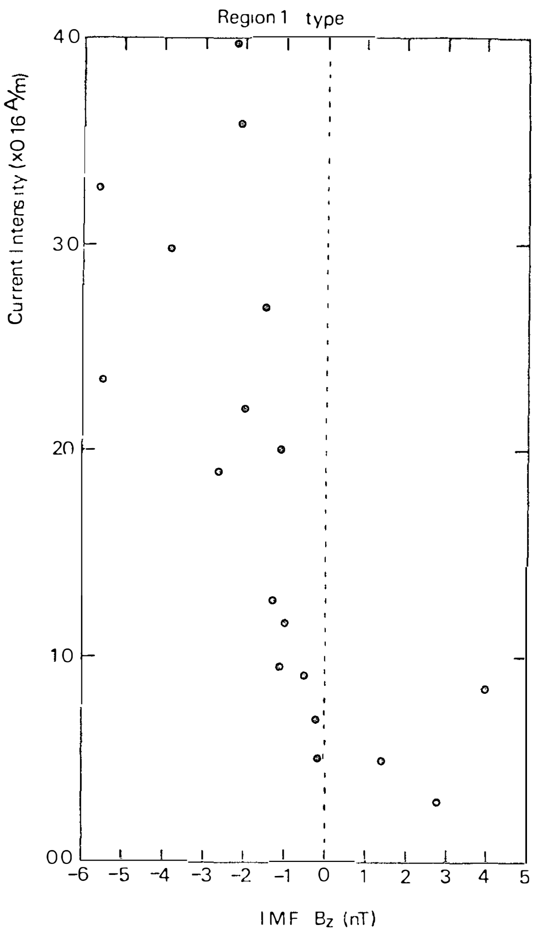
(*a*) *Case of relatively stable IMF B_z conditions. 'Stable' means that sign of B_z component does not change over three hours preceding the TRIAD observation.*



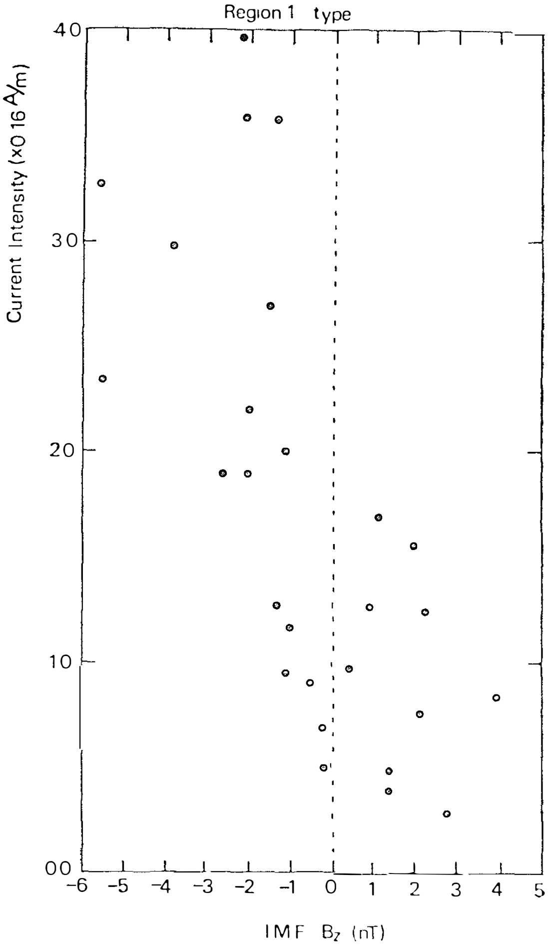
(*b*) *Case of all IMF B_z conditions.*

Fig. 8. Correlation between the cusp FAC intensity and IMF B_z.

ordinates (KING, 1977). It is well-known that the sign of IMF B_z is frequently changing even within one hour. Fig. 7 shows the occurrence number of the cusp FAC acquired in the local time sector 0900–1500 MLT plotted against the hourly-averaged B_z preceding the TRIAD observation. We used 28 passes. The correlation between the intensity of the cusp FAC and the region 1 FAC and B_z are examined only for those cases which are obtained under relatively stable IMF B_z conditions, *i.e.*, for such cases that the sign of B_z component did not change for more than three hours preceding the TRIAD observation. The result is shown in Fig. 8a for the cusp FAC. When B_z is negative, there is a linear correlation between B_z and the intensity of the cusp FAC (I_c). For the cases of positive B_z any clear relation could not be found although some large values of I_c also occur during periods of large positive B_z. The samples are satistically very few, but it should not be overlooked that the cusp type FAC exists even when B_z is positive. Relation between I_c and B_z for all IMF conditions is shown in Fig. 8b. Essentially



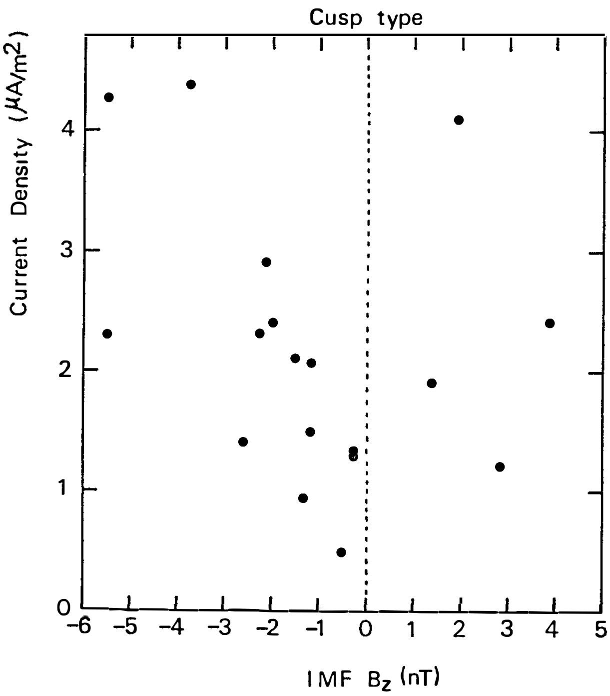
(*a*) *Case of relatively stable IMF B_z conditions.*



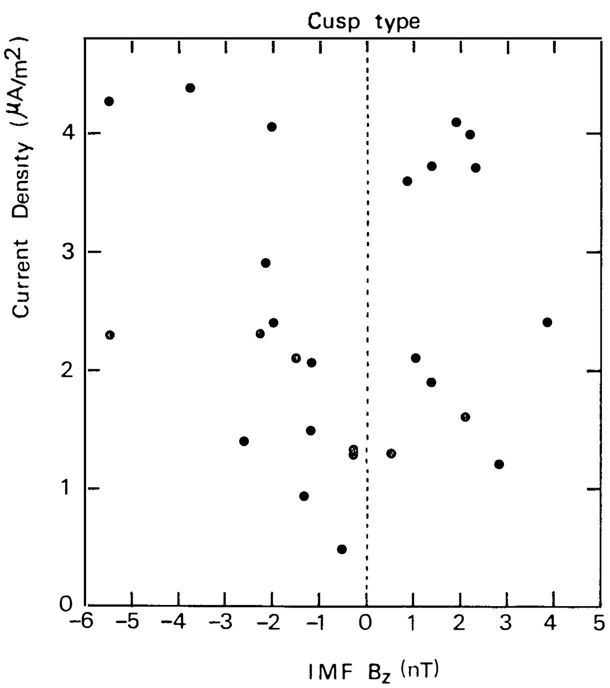
(*b*) *Case of all IMF B_z conditions.*

Fig. 9 Correlation between the region 1 FAC intensity and IMF B_z

it is not different from the relation shown in Fig. 8a, but is more scattered. Fig. 9a gives the relation between B_z and the region 1 FAC intensity during the IMF stable conditions. There is also a linear correlation between B_z and I_{R1} when B_z value is negative, which seems to extend toward the positive B_z domain. Relation between B_z and I_{R1} during all IMF conditions is shown in Fig. 9b. There is no essential difference from correlation shown in Fig. 9a, but the distribution is more broadened. On the average the intensity of the region 1 FAC is 1.2 times greater than that of the cusp FAC in the range of negative B_z, while the average intensity of the cusp FAC is somewhat larger than that of the region 1 FAC in the positive B_z range. The intensity of the region 1 FAC between 0900–1500 MLT for all IMF conditions amounts to about 0.27 A/m, which is comparable to the intensity of the region 1 FAC in the morning (0300–1000 MLT) and evening (1400–2100 MLT) sectors The relation between the cusp FAC density and IMF B_z is shown



(*a*) *Case of relatively stable IMF B_z conditions.*



(*b*) *Case of all IMF B_z conditions.*

Fig 10 Correlation between the cusp FAC density and IMF B_z

in Fig. 10a for stable IMF conditions and in Fig. 10b for all IMF conditions. These relations are more scattered than those obtained for the FAC intensity. This broadening may be caused by ambiguities in determination of the latitudinal width and intensity of FAC.

5. Discussion

The classification and interpretation of magnetic disturbances in the midday polar region in the winter season include the following important points:

1) Is the cusp FAC distinct from region 1 and 2 FAC's in the morning and evening regions?

It is impossible to explain the cusp FAC by the east-west shift of the demarcation line between the morning type region 1 (downward) FAC and evening type region 1 (upward) FAC as illustrated in Fig. 11, because the morning

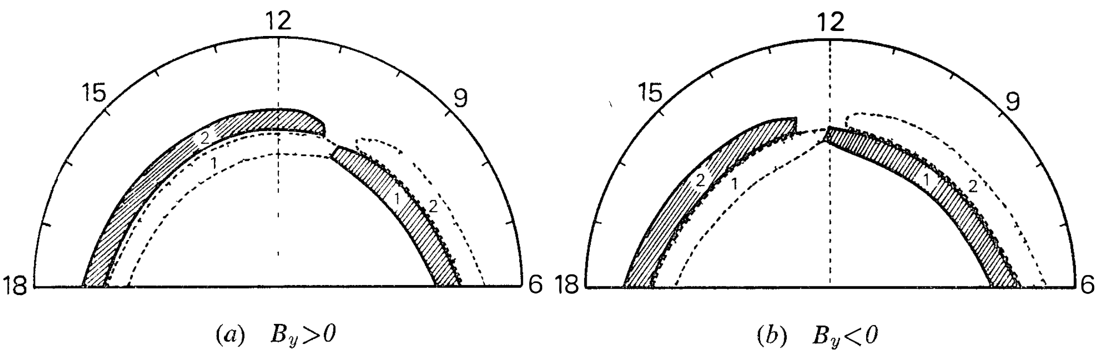


Fig. 11 Illustration of the east-west shift of the demarcation line between the morning type region 1 FAC and the evening type region 1 FAC.

(evening) type region 1 and 2 FAC's has a minimum occurrence at 1000–1100 MLT (1300–1400 MLT) as we mentioned in the previous section. Fig. 12 shows the relationship between the cusp FAC and the region 1, 2 FAC's by IIJIMA and POTEMRA (1976a) in which the cusp FAC is represented distinct from region 1 and 2 FAC's. The FAC distribution including the IMF B_y effects that has been obtained by our analysis is shown in Fig. 13. Demarcation line between the morning type FAC and the evening type FAC shifts eastward or westward systematically depending on the IMF B_y component as elucidated by the present analysis of the TRIAD data. Fig. 14 illustrates another case in which the morning type region 1 FAC and the evening type region 1 FAC are dislocated in latitude. In this case the cusp FAC (as we have defined) does not form an independent regime but it is interpreted as part of the region 1 and 2 regimes which extend eastward or westward significantly. The same type of overlapped and complex current structure is seen in the midnight Harang discontinuity sector (IIJIMA and POTEMRA, 1976b). In this case we have to explain why the morning type region 1 FAC is dislocated toward higher (lower) latitudes in comparison to the

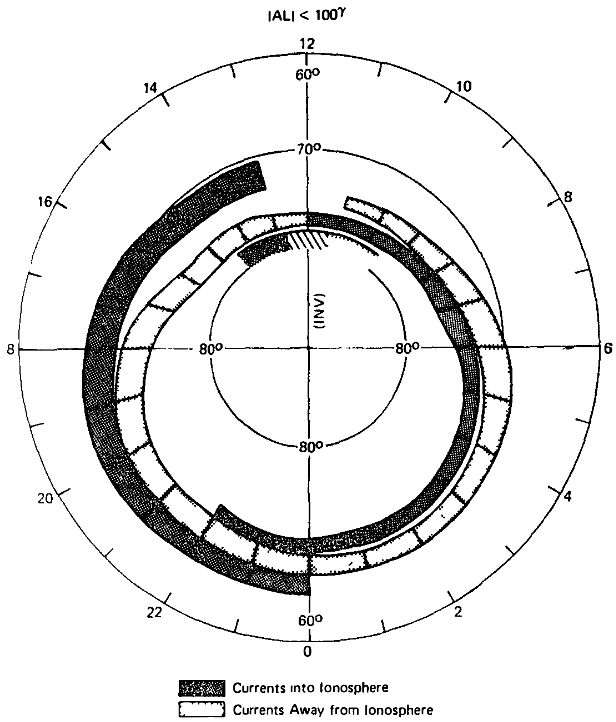


Fig. 12. Model of the cusp, regions 1, and region 2 FAC's proposed by IIJIMA *and* POTEMRA *(1976a).*

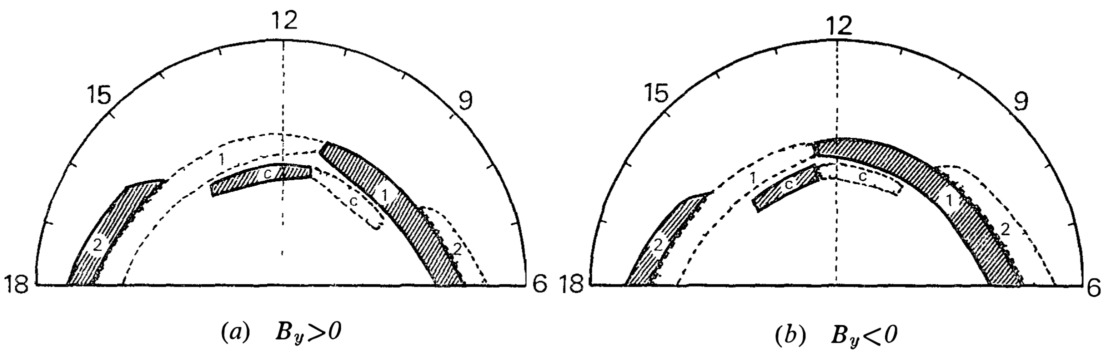
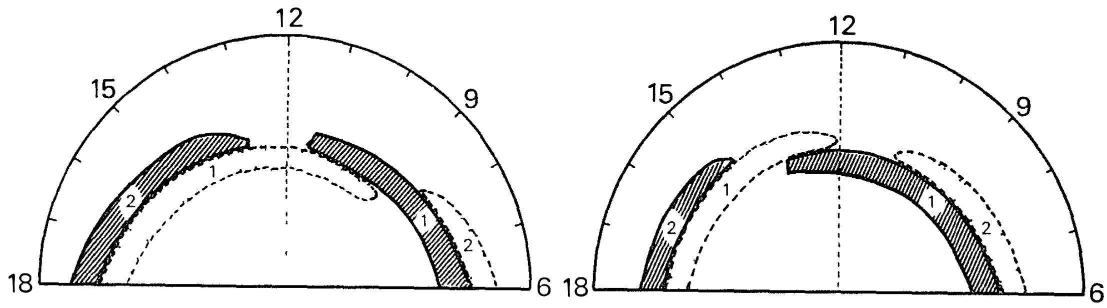


Fig 13. Illustration of our model of the dayside FAC distribution including the IMF B_y effects.



(*a*) $B_y>0$ (*b*) $B_y<0$

Fig. 14 Illustration of another possible model of the dayside FAC distribution, in which the morning type region 1 FAC and the evening type region 1 FAC are dislocated in latitude.

evening type for positive (negative) B_y. This control has not yet been observed in the midnight region FAC. If the subpeak of morning (evening) type FAC at 1100–1300 MLT is significant, this model would be invalid. At present we cannot decide which of the above two models is better to explain the cusp FAC Or is there any other better explanation for FAC distribution as mentioned before? In order to solve this problem simultaneous particle and field data are essential which would suggest the location of FAC current flow in trapping region, auroral region, cusp region, and polar cap.

2) How is the relation between FAC's observed above the ionosphere (800 km) and magnetic field perturbations recorded on the ground?

Equivalent current system in the polar cap near the dayside region was studied by MAEZAWA (1976). When IMF B_z is positive, an inverse S_q^p current system appears in the polar cap centered on the dayside. This current system was explained to be driven by the magnetic field reconnection between northward IMF and magnetospheric magnetic field. Equivalent current directions of this two-cell pattern are consistent with ionospheric real current that is expected from the cusp FAC demonstrated by IIJIMA and POTEMRA (1976a), though the equivalent current pattern is in general different from real ionospheric current as discussed by FUKUSHIMA (1969). If northward B_z reconnection drives the cusp FAC, the cusp FAC intensity should increase with an increase in positive B_z. Since our samples of the TRIAD data is few when B_z is positive, we cannot judge whether northward B_z reconnection process is related to the generation of cusp FAC In our analysis, however, it is obvious that the cusp FAC exists when B_z is negative and the cusp FAC intensity increases with an increase in the negative B_z. Therefore, the northward B_z reconnection is not considered as the principal cause for the generation of cusp FAC.

3) Future work

At present little is known for the origin and mechanism of the cusp FAC, which will be studied in more detail using the TRIAD data which began to be recorded at Resolute (83°), Canada since the end of July 1976.

6. Summary

In the midday polar region, various kinds of complex magnetic field variations were observed with the TRIAD magnetometer experiment. Most of them (93%) can be classified into four types of magnetic field perturbations. Without adherence to the previous study we have studied general distributions of FAC and found that a separate regime of FAC exists in the midday sector, poleward of, and adjacent to the region 1 FAC which is well established in the morning and evening sectors. We referred them as the cusp FAC. In this brief paper, the followings points are determined:

1) Existence of the cusp FAC cannot be explained only by the fact that the region 1 and 2 FAC's in the morning and evening sectors shift toward dawn or dusk by the polarity of IMF B_y.

2) Demarcation line between the pre-noon type and post-noon type cusp FAC's shifts eastward or westward, being controlled by IMF B_y. When B_y is positive the demarcation line moves towards morning side (1000–1100 MLT) and when B_y is negative it moves towards evening side (1200–1300 MLT). On the average, the demarcation line is placed at 1100–1200 MLT. This tendancy is also seen for the region 1 FAC.

3) Maximum occurrence of the pre-noon type cusp FAC is seen around 0900–1000 MLT (41%) and that of the post-noon type cusp FAC is placed at 1200–1300 MLT (61%) when B_y is positive. When B_y is negative the maximum occurrence position of the pre-noon type events shifts toward 1100–1200 MLT (53%) and that of the post-noon type FAC is located around 1100–1400 MLT (27%). It is doubtful whether the peak of the post-noon type FAC is statistically significant. On the average maximum occurrence of the pre-noon type cusp FAC is seen at 1000–1100 MLT (40%) and that of the post-noon type is observed at 1200–1300 MLT (41%). With regard to the region 1 and 2 FAC's the occurrence of the single type FAC (region 1) in the evening sector is more frequent

than that in the morning sector.

4) Average intensity of the cusp FAC is eight-tenths of that of the region 1 FAC (0.23 A/m) in the daytime sector. Intensity of the cusp FAC seems, however, to be larger than that of the region 1 FAC when IMF B_z is positive.

5) There is a linear correlation between B_z and the intensity of the cusp region FAC (I_c) for negative B_z while no clear relation between B_z and I_c was found for positive B_z. It should be noted that the cusp type FAC definitely and frequently exists even when B_z is negative, as well as when B_z is positive. Especially during the stable IMF condition preceding the TRIAD observation of FAC this tendency for the negative B_z is more clear.

Acknowledgments

The authors wish to thank Dr. K. MAEZAWA for his valuable discussions.

References

BURROWS, J. R., WILSON, M. D. and McDIARMID, I. B. (1976): Simultaneous field-aligned current and charged particle measurements in the cleft. Magnetospheric Particles and Fields, ed. by B. M. McCORMAC. Dordrecht, D. Reidel, 111–124 (Astrophys Space Sci Lib., Vol. 58).

FUKUSHIMA, N. (1969). Equivalence in ground geomagnetic effect of Chapman-Vestine's and Birkeland-Alfven's electric current systems for polar magnetic storms. Rep. Ionos. Space Res. Jpn., **23**, 219–227.

HEELIS, R A, HANSEN, W. B. and BURCH, J. L. (1976) Ion convection velocity reversals in the dayside cleft. J. Geophys. Res., **81**, 3803–3809.

IIJIMA, T. and POTEMRA, T. A. (1976a) Field-aligned currents in the dayside cusp observed by Triad. J Geophys. Res., **81**, 5971–5979

IIJIMA, T. and POTEMRA, T. A. (1976b)· The amplitude distribution of field-aligned currents at northern high latitudes observed by Triad. J. Geophys. Res, **81**, 2165–2174.

IIJIMA, T., FUJII, R., POTEMRA, T. A. and SAFLEKOS, N. A. (1978): Field-aligned currents in the south polar cusp and their relationship to the interplanetary magnetic field J. Geophys. Res, **83**, 5595–5603.

KING, J. H. (1977) Interplanetary medium data book-appendix. NSSDC/WDC-A-R&S, 77-04a.

MAEZAWA, K. (1976). Magnetospheric convection induced by the positive and negative Z component of the interplanetary magnetic field. Quantitative analysis using polar cap magnetic records. J. Geophys. Res., **81**, 2289–2303.

McDIARMID, I. B., BURROWS, J. R. and WILSON, M. D. (1978)· Comparison of magnetic field perturbations at high latitudes with charged particle and IMF measurements J. Geophys. Res, **83**, 681–690.

POTEMRA, T. A., PETERSON, W. K., DOERING, J. P., BOSTROM, C. O., MCENTIRE, R. W. and HOFFMAN, R. A. (1977): Low-energy particle observations in the quiet dayside cusp from AE-C and AE-D. J. Geophys. Res., **82**, 4765–4776.

SUGIURA, M. and POTEMRA, T. A. (1976): A net field-aligned current observed by Triad. J. Geophys. Res., **81**, 2155–2164.

(*Received June 10, 1978*)