

## **Investigation on High Velocity Plasmas and Field Aligned Currents at High Latitudes**

**J. C. K. Akhila<sup>1</sup> and C. P. Anil Kumar<sup>2\*</sup>**

<sup>1</sup>*School of Pure and Applied Physics, M. G. University, Kottayam, Kerala, 686 560, India.*

<sup>2</sup>*Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Krishnapuram, Tirunelveli, Tamil Nadu, 627 011, India.*

### **Authors' contributions**

*This work was carried out in collaboration between both authors. Author CPAK designed the study and performed the data analysis. Author JCKA managed the literature searches and assisted the analysis. Both authors read and approved the final manuscript.*

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### **ABSTRACT**

The interaction of high velocity plasma with Earth's magnetic field is fundamental and offer many questions on high latitude electrodynamics. The problems associated with influence of electric field and Field Aligned Current (FAC) generation is investigated with the aid of spherical cap harmonic analysis at 83<sup>o</sup> Mag. Lat. in southern hemispheres. The investigation is done on the cases with different Interplanetary Magnetic Field (IMF) conditions after the earth directed solar events. The helio-plasma parameters viz., density, velocity, energy, electron temperature are also noted during the field aligned current studies. It seems that, due to external magnetic field influence polarization of plasma electric field take place (reorientation of the convective cells). It happens with different orientation as per the magnitude and direction of B<sub>y</sub> and B<sub>z</sub> component and the horizontal currents. It is noted that the FAC value also depends on kinetic energy of the plasma streams and conductivity of external loading. As the plasma decelerates by force  $J_{sw} \times E_{sw}$ , the resultant current may extend along the field lines. Increases in the FAC density are seemed to be proportional to the transmission function.

**Keywords:** *Helio-plasma parameters; high latitude electrodynamics; plasma polarization; field aligned currents.*

## 1. INTRODUCTION

Magnetosphere is an open geospace system driven by the turbulent solar wind. Most of the magnetospheric processes are essentially nonlinear in nature. The current understanding of the coupled solar wind-magnetosphere system has been based largely on the processes involving the plasma in the geospace. Most of these processes are electro-dynamic in nature and the interaction between different parts of magnetosphere leads to a global coherence in its dynamics. The field-aligned currents (FAC) are manifestation of magnetosphere-ionosphere coupling mainly in the auroral ionosphere. Since ionosphere and magnetosphere regions are connected by the same field lines a strong coupling occurs between them. The first suggestion of Field Aligned Currents (FAC) was done by K. Birkeland in 1908, hence it is also known as Birkeland currents. The space measurement of the intensity and distribution of FAC is a difficult task.

Large-scale FAC currents which flow into and away from the polar ionosphere have been observed by virtue of the associated transverse magnetic disturbances they produce at low-altitude. Various important characteristics of these FACs have been determined [1,2]. Iijima and Potemra suggested that large scale field-aligned current system plays an important role in the coupling processes between interplanetary plasma and the auroral ionosphere. Their spatial distribution of flow direction pattern can be specified by three dominant regions: The Region 1 current dominates in the pole ward part of the auroral Birkland current belt, the Region 2 currents exist in the equator ward part of the FAC belt and Region 0 currents in the local noon time very near to cusp region [3].

Empirical models of high-latitude ionospheric electrodynamics have an important role in understanding of the solar wind-magnetosphere-ionosphere coupling system and FAC [4,5-8]. Most of these statistical models usually show how the interplanetary magnetic field (IMF) and solar wind (SW) control the electric and magnetic potentials of high latitude ionosphere. Later, Weimer in 2005 [9] used least error fit of spherical harmonics coefficients with data from multiple satellite passes and incorporated night

side processes and contribution due to sub-storm activity.

This paper accurately provides output, ordered according to IMF activity indices since the model is based on spherical cap coefficients that were derived with least error fit satellite measurements. The data base of this investigation consists of solar wind/IMF measurements from Advance Composition Explorer (ACE) Satellite from 2001 and 2002. FAC are computed over this specified period.

## 2. METHODOLOGY

A new technique for yielding FAC with satellite magnetometer data has been used by Weimer [8,9]. This model quantifies the currents above the desired high-latitude ionosphere. This technique uses scalar magnetic Euler potential, derived from integrating the measured magnetic deviations in as much the same way as electric potentials are derived from integrating electric fields. The FAC produced with this new technique are more quantitative and they yield much insight into how the currents vary as IMF changes; further we studied how the FAC pattern changes with IMF clock angle and how the field-aligned current maps overlaps the associated electric potential patterns. The most of the notable aspects of FAC are during geomagnetic storms of April 06-08, 2001, September 23-25, 2001 and March 23-25, 2002 and are detailed in this paper.

It seems that the ionospheric reconfiguration starts everywhere almost immediately after the arrival of the signal from the IMF and it is calculated to be 12.6 minutes [10] and adding another 10 minutes for the propagation to the ionosphere considered in the analysis. Since the IMF and solar observations are based on onboard instrument they are accordingly time shifted during our investigation. The interplanetary magnetic field components have been measured from the ACE satellite [www.srl.caltech.edu/ACE/ASE/level2\\_](http://www.srl.caltech.edu/ACE/ASE/level2_). High resolution data has been selected for this study. The investigation has been carried out during the active period of solar cycle 23 from January, 2001 to December, 2002 period. During this time span 21 geomagnetic storms occurred

out of which three were selected for presentation in this paper.

### 2.1 Spherical Cap Harmonic Method

Spherical cap harmonic analysis (SCHA) is a regional modelling technique based on the functions appropriate for such a region subject to boundary conditions. The region pole ward of the highest ring is modeled using spherical harmonics so that the potentials are given by is the associated Legendre polynomial. After the Fourier coefficients are determined for exactly equal to that of each latitude rings; the potential is constructed from a Fourier series as a function of angular position around the ring, for details Weimer, 2005 [9] and references there in.

On each ring the potential is constructed from a Fourier series as a function of angular position around the ring:

$$\psi(\varphi) = \sum_{m=0}^4 A_m f_m(\varphi) \tag{1}$$

Where  $\varphi$  is the angle and  $f_m(\varphi)$  is given by

$$f_0(\varphi) = 1$$

$$f_1(\varphi) = \cos(\varphi)$$

$$f_2(\varphi) = \sin(\varphi)$$

$$f_3(\varphi) = \cos(2\varphi)$$

$$f_4(\varphi) = \sin(2\varphi)$$

Every Fourier coefficient  $A_m$  has its own independent response function to the IMF, solar wind velocity, density, dipole tilt angle.

$$\psi(\lambda, \varphi) = \sum_{l=0}^2 \sum_{m=0}^2 D_{lm} P_l^m(\cos\lambda) (g_n^m \cos m\varphi + h_n^m \sin m\varphi) \tag{2}$$

$P_l^m$  is the associated Legendre polynomial and  $\lambda$  is a function of colatitudes varying from zero at the pole to  $\frac{\pi}{2}$  at the most pole ward ring. Large degree  $l$  and order  $m$  are not required in this region as the purpose is to smoothly bridge the

polar gap with a continuous function. After the Fourier coefficients are determined for the most pole ward ring, then the spherical harmonic coefficients  $D_{lm}$  can be set so that the potential from (2) is exactly equal to that of (1) where the two regions are joined. This matching of the potentials are accomplished by making all  $\sin(m\varphi)$  and  $\cos(m\varphi)$  terms equivalent for all  $m$ . Using finite differences to calculate the derivative of these Fourier components are the boundary; the slope of the potentials are also matched.

### 3. RESULTS AND DISCUSSION

The results of FAC during the period of the selected geomagnetic storms are summarized in Figs. 1 to 3 in bottom panel. The top row of figures shows the solar wind number density ( $N_{sw}$ ), second indicate the solar wind speed ( $V_{sw}$ ) and third and fourth provide IMF directions. The times for each pattern are marked in the X-axis in UT. The contour scales are the same for Fig. 4 and Fig. 5. It is obtained from the Weimer model [9] from the values of all pseudo-clock angle index indicated with magnetic local time.

Fig. 1 for 1100UT, April 06 2001 to 1100UT April 08, 2001, the peaks in the FAC have been marked with short bars, the corresponding variations in  $B_z$  trace also been marked. The slope of the lines illustrate to positive progression of the FAC, for the time interval from 1100 to 2200 UT, within which the IMF- $B_z$  component is consistently negative with values ranging from 0 to -10nT, very good agreement is found between the IMF- $B_z$  trace and the trace for the FAC. When IMF-  $B_z$  trace from 2300UT, 6 April to 0500UT, 7 April corresponding FAC variation is found negative. In this case solar streams are 700km/s. Slander lines indicates IMF- $B_y$  traces and the time series values at the window show no clear correlation with the observed FAC. A narrow window width of  $N_{sw}$  however, introduces apparent increase in FAC. It is indicating that FAC depends on the direct conductivity of external loading.

Fig. 2 displays the data for 1700UT, 23 September 2001 to 1100UT, 25 September 2001. In this case some correspondence is found between the IMF-  $B_y$  variations and the related FAC traces. In this case a few of the related peaks and valleys have been marked and annotated at FAC trace.

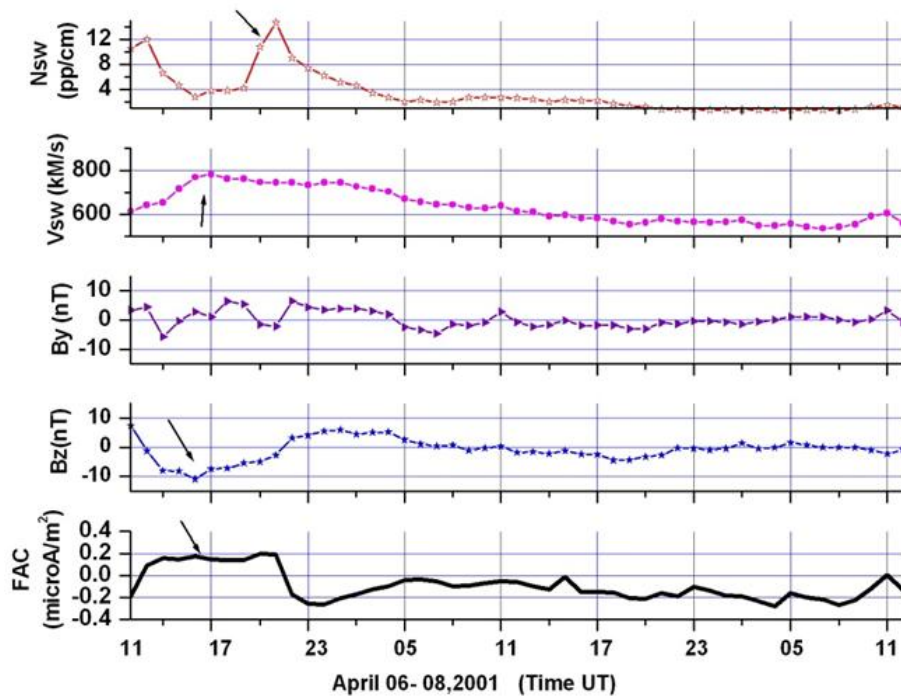


Fig. 1. Macroscopic motion of the high latitude ionospheric plasma is in the plane perpendicular to geomagnetic field lines. Upper panel illustrate particle density. Second from the top give the solar wind velocity. Third panel IMF- $B_y$  and four panel IMF- $B_z$ . A current flowing in a direction parallel to the Earth's magnetic field will produce a magnetic perturbation  $\delta B$  in a direction perpendicular to the field ( $\mu_0 J_{||} = \nabla \times \delta B$ )

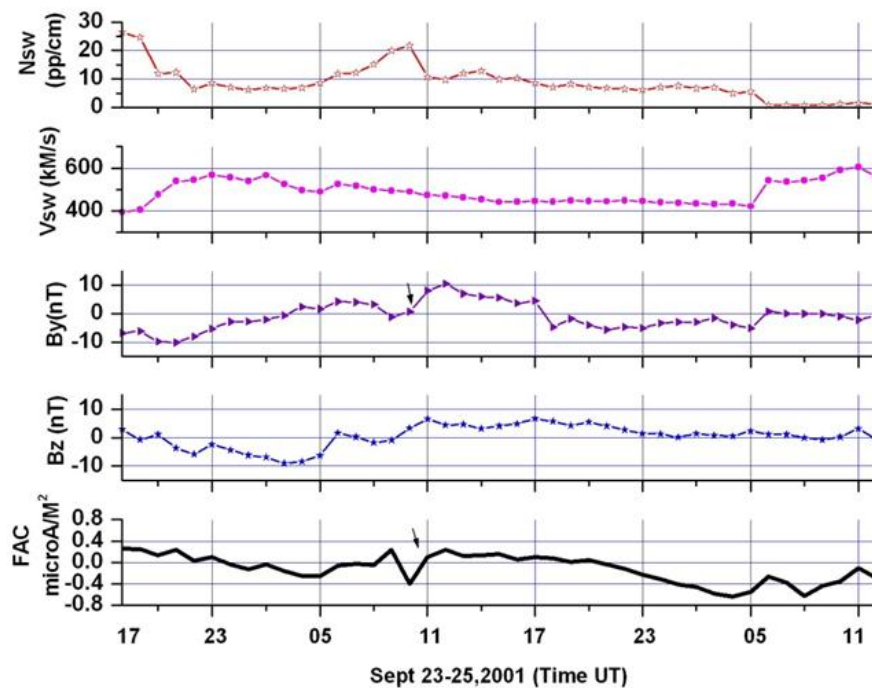


Fig. 2. Coupling of IMF- $B_y$  variations into the polar ionosphere. Upper panel illustrate particle density. Second from the top give the solar wind velocity. Third panel IMF- $B_y$  and fourth panel MF- $B_z$ . FAC trace in bottom panel

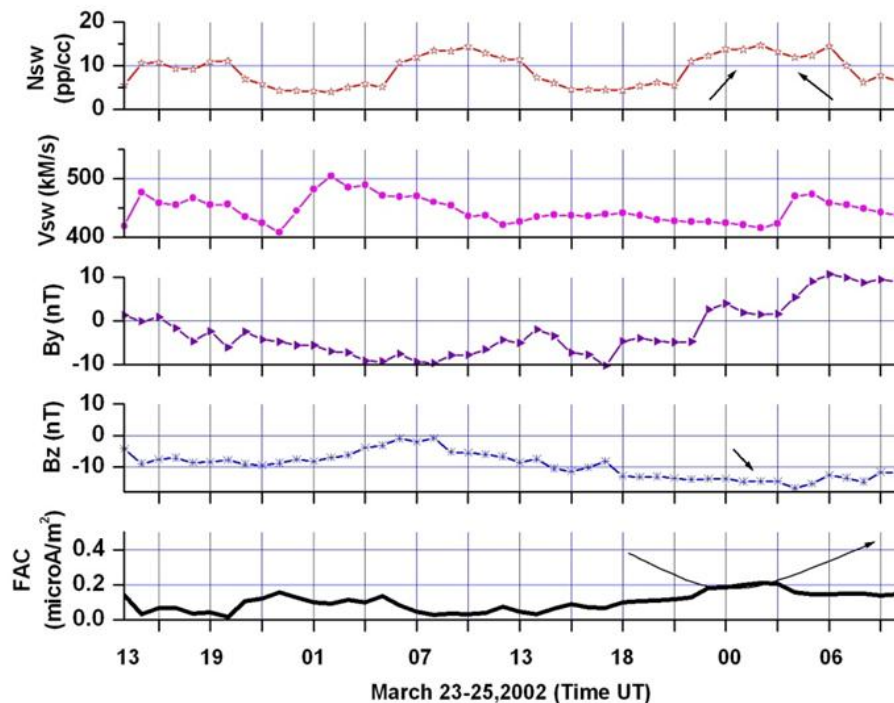
Magnetic reconnection may play an important role in determining the strength of Region 1 currents. Persistent FAC current may seem to be related to the associated electric fields which prevail during the periods of IMF- $B_Y$ . Remember in general cases the flow of Region 1 current is into the ionosphere on the morning side and away on the afternoon side. The progressing FAC variations are interpreted as the foot prints of the variable IMF  $B_Y$  component present in the solar wind volume which is magnetically connected to the polar cap ionosphere. The open magnetosphere topology resulting from the merging of the geomagnetic field and the interplanetary field during southward conditions too allows these currents to flow along the merged field lines to the polar cap ionosphere.

However, it is noted that the basic spatial distribution of flow direction pattern of Region 1 and Region 2 current is not affected by the interplanetary magnetic field (IMF) Iijima and Potemra, [3], but larger current intensities occur on the dawn side of the north pole as noted by Mc Diarmid et al.[11] and on the dusk side of the south pole, Saffekos and Potemra, [12] during periods of positive IMF ( $B_Y$ ) and it is reverse for negative IMF ( $B_Y$ ).

The Region 1 current shows relatively stable behaviour, they persist during periods of geomagnetic quiet conditions. The dominance of the morning upward current and the dominance of the afternoon downward current occur in the southern polar region during positive IMF-  $B_Y$  and reverse during the negative IMF- $B_Y$ .

In this paper we only examine the amplitudes of the Region 1 currents and solar wind parameters in an attempt to identify the controlling mechanisms and modulating influence viz., occurrence and the flow direction and special distribution patterns during disturbed conditions for the 3 selected geomagnetic storms.

The more negative level of IMF  $B_Y$  have been observed 1700UT to 0100UT 24 September, 2001, during the southward progression of IMF  $B_Z$ , hence variations are larger due to  $B_Z$  than  $B_Y$ . However 1900UT 24 Sept. to 0600UT 25 Sept., 2001, the more negative level of IMF  $B_Y$  has caused the FAC to downward direction in the corresponding window. Fig. 2 results as a compromise between  $B_Y$  and  $B_Z$  values conflicting conditions consequently result needs a verification in the 3<sup>rd</sup> case.



**Fig. 3.** The investigation is done on the cases where external magnetic field turned southward. It seems that, due to magnetic field influence polarization of plasma electric field appears (contours features of Fig. 4) and FAC enhanced. Panel parameters are depicted same as in Figs. 1 & 2



Fig. 3 displays the data during geomagnetic storm from 23 March 2002 to 25 March 2002, with close correspondence is observed the data throughout interval from 1300UT 23 March to 0800UT 25 March, 2002 in records of IMF  $B_z$  component in addition to IMF  $B_y$  related negative progressing trends. One case of positive enhancement in  $B_y$  has been marked up 1900UT 24 March to 0080UT ,25 March, 2002 an addition feature to note is the smaller variability in FAC compared with  $B_z$  components.

We have to look into the lower boundary of the electrical potential pattern since it is now variable according to the conditions rather than fixed at an arbitrary location, ( $83^\circ$  Mag. Lat.). The low-latitude boundary can also move southward better in response to large southward IMF values. Since Weimer model can provide minute changes in the patterns as the IMF rotates in the GSM Y-Z plane it is very useful for scientific studies, Fig. 4. As the satellite was located at

$X_{GST}(R_E)$  and the solar wind velocity was  $V_{sw}$  (km/S), the estimated delay time is  $X_{GST}/V_{sw}$  minutes. The precise timing is inconsequential in this case since the model parameters that are used for the example would have simply occurred at an earlier or later time.

IMF has a profound influence on the convection intensities (electric field) and convection patterns. The north-south component IMF  $B_z$  appears to be particularly important. The influence of the IMF  $B_y$  component on the ionospheric convection patterns has attracted considerable attention. East-West directed convective currents occur in response to the  $Y_{GSM}$  component of the IMF [13]. Following the satellite exploration of the field aligned currents to the noon sector of the dayside ionosphere at high latitudes were found to be closely related to the sign and magnitude of the IMF  $B_y$  component, by Taguchi [14] but it differs in perturbed time as in Fig. 5.

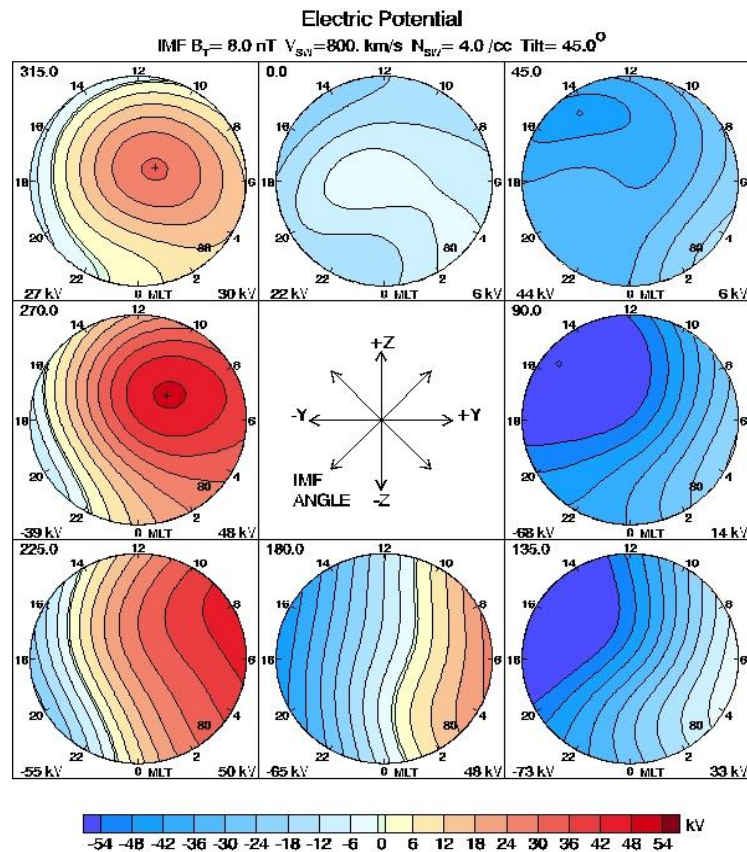
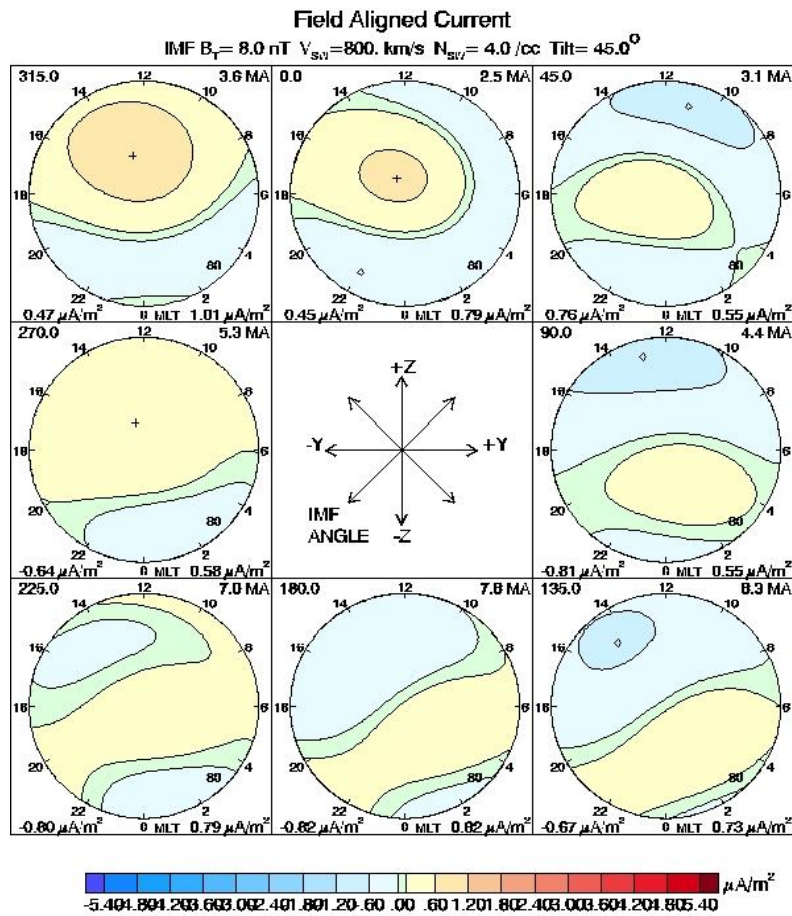


Fig. 4. The contours showing the features of convection pattern under different IMF  $B_y$  and  $B_z$  orientation when Tilt is 45 in the southern hemisphere. The IMF influence polarization of ionospheric convection since the magnetosphere is magnetically connected to the ionosphere; a corresponding circulation of plasma is also set up in the high-latitude ionosphere. The convection can be described in terms of potentials i.e.,  $E = -\nabla\Phi$



**Fig. 5.** Shows colour-coded FAC pattern organized according to IMF-orientation in the form of eight clock angle sectors of  $45^\circ$  widths. The dominant two cell pattern corresponds to dipolar term of the associated Legendre polynomial series which represent more power

IMF  $B_Y$  dependent FAC are most often observed in the form of oppositely directed pairs of east-west oriented current sheets. As suggested by Wilhjelm et al. [15] these IMF  $B_Y$  related sheets of oppositely directed FAC to the cusp region close in the ionosphere via horizontal Pederson currents. The electric field generated by these imposed Pederson currents drive transverse plasma convection which in turn generate Hall currents.

#### 4. CONCLUSION

We have investigated the FAC values with ACE satellite data. Studies were done after earth directed solar events traced the signals for morning and afternoon FAC densities. The current densities show good influence with negative values of  $B_z$  and relatively poorly with positive magnitude. The dominant factor appears to the magnitude of IMF in the Y-Z plane  $(B_T = B_y^2 + B_z^2)^{1/2}$  and its orientation with respect to the geomagnetic field  $\sin(\theta/2)$ .

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#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

#### REFERENCES

1. Iijima T, Potemra TA. The amplitude distribution of field-aligned currents at northern high latitudes observed by TRIAD, J. Geophys. Res. 1976;81:2165-2174.
2. Sugiura M, Potemra TA. A net field-aligned current observed by Triad, J. Geophys. Res. 1976;81:2155-2164.

3. Iijima T, Potemra TA. The relationship between interplanetary quantities and Birkeland current densities, *Geophys. Res. Lett.* 1982;9(4):442-445.
4. Papitashvili VO, Belov BA, Faermark DS, Ya I Feldstein, Golyshev SA, Gromova LI, Levitin AE. Electric potential patterns in the northern and southern polar regions parameterized by the interplanetary magnetic field, *J. Geophys. Res.* 1994; 99:13251-13262.
5. Weimer DR. Models of high-latitude electric potential derived with a least error fit of spherical harmonic coefficient, *J. Geophys. Res.* 1995;100(19):595-19602.
6. Weimer DR. A flexible IMF dependence model of high-latitude electric potential having space weather applications, *Geophys. Res. Lett.* 1996;23:2549-2553.
7. Weimer DR. Substorm influence on the ionospheric electric potential and currents, *J. Geophys. Res.* 1999;104:1099-2007.
8. Weimer DR. Maps of ionospheric field-aligned currents as a function of the interplanetary magnetic field derived from Dynamics Explorer 2 data, *J. Geophys. Res.* 2001;106:12889-12,902.
9. Weimer DR. Predicting surface geomagnetic variations using ionospheric electrodynamics models, *J. Geophys. Res.* 2005;110:A12307.  
DOI:10.1029/2005JA011270
10. Ridley AJ, Lu G, Clauer CR, Papitashvili. A statistical study of the ionospheric convection response to changing interplanetary magnetic field condition using the assimilation mapping of ionospheric electrodynamics technique, *J. Geophys. Res.* 1998;103:4023-4030.
11. Mc Diarmid, Burrows IBB, Wilson MD. Magnetic field perturbations in the dayside cleft and their relationship to the IMF, *J. Geophys. Res.* 1978;83:5753-5760.
12. Saflekos NA, Potemra TA,. The orientation of Birkeland current sheets in the dayside polar region and its relationship to the IMF, *J. Geophys. Res.* 1980;85:1987-1994.
13. Fris-Christensen E, Kamide Y, Richmond AD, Matsushita S. Interplanetary magnetic field control of high-latitude electric fields and currents determined from Greenland magnetometer data, *J. Geophys. Res.* 1985;90:1325-1331.
14. Taguchi S, Sugiura M, Winningham JD, Slavin JA. Characterization of the IMF BY dependent field aligned currents in the cleft region based on DE 2 observation, *J. Geophys. Res.* 1993;83:5586-5591.
15. Wilhelm J, Friis-Christensen E, Potemra TA. The relationship between ionospheric and field aligned currents in the dayside cusp, *J. Geophys. Res.* 1978;83:5586-5592.

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