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SUBSTORM TIME IONOSPHERIC FIELD-ALIGNED CURRENTS AS OBSERVED BY CHAMP

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Abstract Field-aligned currents (FACs) play an important role in the energy, momentum, and mass coupling between magnetosphere and ionosphere. This study investigates the statistical characteristics of polar ionospheric FACs during substorms by using high resolution magnetic field measurements on board CHAMP. Obvious day-night and dusk-dawn asymmetries emerge in both FACs density and location. It shows: (1) FACs densities are related to AL index, with larger AL for larger current density. FACs densities during substorm are 5 times of that during quiet period. The duskside and nightside FACs densities correlate well with AL , while the dawnside and dayside FACs densities are not well correlated with AL ; (2) the locations of peak FACs densities do not correlate with AL . The dusk FACs are located equatorward of the dawn, and the nightside FACs are located equatorward of the dayside.

Key words Substorm, Polar ionosphere, Field-aligned current, CHAMP

1 INTRODUCTION

Field-aligned currents (FACs) play an important role in the magnetosphere-ionosphere coupling processes, which are influenced directly by solar wind and interplanetary magnetic field (IMF). Since FACs, also called Birkland current, were disclosed by satellite measurements in situ for the first time in 1960s^[1], they have attracted the attention of a large number of scientists. As shown in previous studies^[2~7], FACs are involved in many important physical processes in the geospace, such as magnetic reconnections, large scale plasma convection, field-aligned acceleration and transport of energetic particles and auroral activities. As elements of the current systems in the geospace, FACs interact with various large scale current systems, such as cross-tail current, magnetopause current, auroral electrojet and substorm current wedge, etc.

Substorm is one of the most common phenomena in space weather. It tends to happen on the nightside, lasting for 2~3 hours. Substorm can enhance magnetospheric and ionospheric current system, cause electron precipitation, produce aurora, heat polar ionosphere and thermosphere, and bring the energetic particles into the ring current and radiation belt. It is one of the basic global disturbances and the most important energy transfer processes in the magnetosphere and ionosphere. Substorm can be divided into three phases: growth phase, expansion phase, and recovery phase. The substorm activity can be indicated by AL index, and is influenced by IMF B_z and solar wind dynamic pressure.

Substorm current system is one of the important topics in space weather. During a substorm, energy from the solar-magnetosphere system is released into the ionosphere through direct driving or loading-unloading mechanism. Both processes are related to high latitude ionospheric currents. Therefore, it is important to study the characteristics of FACs during substorms for further understanding of the response of the ionosphere to solar wind and magnetosphere, the development of substorm and its trigger mechanism. Previous work has studied the variation of field aligned currents in the inner magnetosphere during substorm. This work will study the spatial distribution of the substorm time FACs by using the high resolution magnetic field data from CHAMP.

2 DATA ANALYSIS

2.1 CHAMP Magnetic Field Data

CHAMP was launched on 15 July, 2000 into a circular, near-polar (87.3° inclination) orbit. It cruises at a low orbit, with 456 km height at launch, decaying to 300 km after a 6-year mission period. The orbital plane proceeds with respect to local time (LT) at a rate of about 1 h per 11 days, thus covering all LTs within 4 months^[10]. During the period of substorm, CHAMP was nearly in the magnetic noon-midnight meridian (12:00~24:00 MLT) and dawn-dusk meridian (09:00~18:00 MLT).

The prime instrument on board CHAMP is the Fluxgate Magnetometer (FGM), which delivers vector field readings at a rate of 50 Hz, with a precision of 0.1 nT. The data used in this study are the 1 Hz pre-processed (Level 2) vector data in the north-east-center (NEC) frame.

2.2 Calculation Method of FACs

FACs are calculated according to Ampere-Maxwell law, $\mathbf{j} = 1/\mu_0 \nabla \times \mathbf{B}$, where μ_0 is the vacuum permeability, $\mathbf{B}$ is magnetic field. The main geomagnetic fields modeled by CO₂ (standing for CHAMP, Ørsted, Ørsted 2)^[11] are subtracted from the actual measurements. At 400 km altitude over polar ionosphere, the disturbed magnetic field is mainly caused by the auroral electrojet flowing at the height around 110 km and field-aligned (nearly vertical) current above this height. FACs are assumed to be infinite sheets aligned with auroral oval. Therefore, they produce such magnetic field deflections that mainly direct along the auroral oval. We make use of the MFA (Mean-Field-Aligned)-OPP (Oval Parallel Perpendicular) coordinate system, with its z axis being along the direction of local mean magnetic field (here it is the direction of main geo-magnetic field determined by CO₂ model), y pointing to eastward in the plane perpendicular to the mean magnetic field, and x being perpendicular to the auroral oval and completing the triads. In this study, only the orbits crossing the auroral oval at an angle larger than 45° are considered. For more information of FACs calculation please refer to [12].

3 TYPICAL EVENT ANALYSIS

3.1 Dawn-Dusk FACs

A sequence of substorms happened on March 23 2007. We have chosen 3 substorm events for study, which are during 05:00~07:00 UT, 10:00~16:00 UT (see Fig. 1, as indicated by AL index). During 10:00~16:00 UT, there are two substorm events. During the period of substorm, CHAMP is mainly in the dawn-dusk meridian (06:00~18:00 MLT).

Fig. 1 AL index as a function of UT on 23 March 2007

The yellow shadow bar indicates the substorm events under study.

Figure 2 shows the FACs densities during 10:00~12:00 UT. Positive denotes upward FACs and negative downward FACs. Figs. 2a and 2c are during substorm growth phase, the maximal FACs in the dawn/dusk are $0.28/1.25 \mu\text{A}/\text{m}^2$, at $70.8^\circ/72.0^\circ$ MLat, the minimal FACs are $-0.48/-0.43 \mu\text{A}/\text{m}^2$ at $78.1^\circ/69.3^\circ$ MLat. Figs. 2b and 2d are during substorm expansion phase. The maximal FACs in the dawn/dusk are $1.41/1.05 \mu\text{A}/\text{m}^2$, at $70.1^\circ/68.4^\circ$ MLat, the minimal FACs are $-1.04/-1.23 \mu\text{A}/\text{m}^2$ at $73.9^\circ/65.6^\circ$ MLat. From the above analysis, it can be seen that FACs densities are enhanced by a factor of 5 from growth phase to expansion phase.

Figure 3 shows FACs peak densities and AL index as a function of UT and MLat on March 23 2007. During the first two substorms (05:00~07:00 HH, 10:00~13:00 HH), the magnitude and location of the dawnside FACs (left) has no obvious variations, but during the third substorm (13:00~16:00 HH), the FACs densities in the dawn sector get obviously enhanced when AL reaches minimum. FACs seem to shift equatorward as AL decreases. In the dusk sector FACs (right) get enhanced during the three substorm periods. The upward FACs are larger than the downward. During the last two substorms, the latitudes of FACs peaks shift equatorward as substorm evolves. The FACs in the dusk sector are located equatorward of those in the dawn sector.

Fig. 2 Substorm time field-aligned currents as a function of Mlat

The FACs maximum and minimum, time and location are given. Positive means currents flowing out of the ionosphere, negative into the ionosphere. The red (black) vertical dashed line indicates the maximum (minimum) current density.

Fig. 3 The time and location of the peak field-aligned currents observed by CHAMP in the dawn and dusk sectors in the north pole on 23 March 2007

Overplotted is the AL black curve. The FACs densities are indicated by circle size.

Red indicates currents flowing out of the ionosphere, black into the ionosphere.

3.2 Dayside-Nightside FACs

A series of substorms occurred on Sept. 3 2001. We have chosen three substorms for analysis, which are during 08:00~15:00 HH and 21:00~23:00 HH (See Fig. 4 as indicated by AL index). There are two substorms occurring during 08:00~15:00 HH. During the period CHAMP is on the dayside-nightside meridian (12:00~24:00 MLT).

Fig. 4 Same as Fig. 1, but for 3 September 2001 event

Figure 5 shows FACs distribution on the day-side and nightside during 08:00~10:00 UT. Left is during growth phase and right is during expansion phase. During growth phase, FACs on the day-side/nightside peak at $77.9^\circ/66.6^\circ$ MLat with a value of $2.02/0.97 \mu\text{A}/\text{m}^2$, and are minimized at $76.3^\circ/69.1^\circ$ MLat with a value of $-2.21/-1.40 \mu\text{A}/\text{m}^2$. During substorm expansion phase, the maximum FAC on the dayside/nightside is $2.24/1.94 \mu\text{A}/\text{m}^2$, at $76.0^\circ/67.5^\circ$ MLat, the minimum FAC is $-3.90/-1.39 \mu\text{A}/\text{m}^2$ at $74.2^\circ/70.7^\circ$ MLat. It can be seen that FACs get enhanced as AL decreases.

Fig. 5 Same as Fig. 2, except that the substorm events occur on 3 September 2001 and CHAMP was on the dayside - nightside orbit

Figure 6 shows FACs peaks and troughs as well as AL index as a function of UT and MLat during 00:00~24:00 UT on Sept. 3 2001. On the dayside (left) during the first substorm (08:00~12:00 HH), FACs increase in magnitude as AL decreases. During the last two substorms (12:00~15:00 HH, 21:00~23:00 HH), FACs densities decrease as AL decreases. During the first two substorms, FACs shift equatorward as AL

Fig. 6 Same as Fig. 3 except for the 3 September 2001 events

decreases. During the last substorm, FACs location has no obvious variations. On the nightside for the first and last substorm, FACs increase as AL decreases. For the second substorm, FACs decrease as AL decreases. FACs shift equatorward as AL decreases.

4 DISCUSSION

We have statistically studied several substorm events on March 23 2007 (three events) and September 3~5 2001 (9 events). We have selected the peaks and troughs of FACs densities as well as their locations, and studied their relationship with AL index. The results are shown in Figs. 7~8.

Fig. 7 The peak FAC densities observed by CHAMP in the dawn-dusk (a,b) and day-night (c,d) versus AL index. Positive means those flowing out of the ionosphere, negative into the ionosphere. R is the correlation coefficient.

Figure 7 shows FACs peaks and troughs as a function of AL index at dawn and dusk and on the dayside and nightside. It can be seen that with larger AL , FACs tend to get enhanced. Good correlation can be seen in the dusk sector and on the nightside, while poor correlation can be found in the dawn sector and on the dayside. It is well-known that the westward auroral currents peak around 03:15 MLT^[13]. Since AL index can indicate the strength of the westward auroral electrojet, it is expected that AL index is better correlated with current strengths in the postmidnight than with those on the dayside and dawnside. On the other hand, as substorm occurs around the midnight, cross tail current is disrupted, and the substorm current wedge is developed through a circuit consisting of FACs downward and upward of the ionosphere. Therefore, nightside FACs are more directly related to substorm process in the magnetotail.

The calculation of FACs from single satellite measurements has certain errors: (1) we have assumed that during the satellite passage the current keeps stationary. Using the satellite velocity perpendicular to the current sheet (about 7.8 km/s), the spatial variation can be converted to temporal variation; further, making use of discrete magnetic field samples, we obtain $j_z = \frac{1}{\mu_0} \frac{dB}{dx} = \frac{1}{\mu_0 v_x} \frac{dB}{dt}$. If the current sheet changes during the satellite passage, the results will have uncertainties; (2) we have assumed that FACs are infinite sheets aligned with auroral oval. During magnetic storms such assumption may not exist. But studies^[15] show that only the current densities are affected with maximum errors not exceeding 50%, while the polarity and locations are very little affected. During magnetic storms, the errors may become even larger.

Figure 8 shows FACs peaks and troughs and their locations versus AL index in the dawn-dusk sectors and

Fig. 8 The MLat of the peak FACs observed by CHAMP versus AL index in the dawn-dusk (a,b) and day-night sectors

Red indicates the currents flowing out of the ionosphere, black into the ionosphere. R is the correlation coefficient.

on the day-nightside. It can be seen that the latitudes of FAC peaks are not well correlated with AL index. The MLat of the upward FACs in the dawn-dusk sectors correlate better with AL , while those of the downward FACs do not correlate well with AL . On the other hand, the FACs at dusk are located equatorward of those at dawn: the dusk FACs can reach 64° MLat, while the dawn FACs seem to get saturated at 68° MLat as $AL < -300$ nT. The nightside FACs can reach as low as 60° MLat, while the dayside can only reach 70° MLat. If the FACs location can be regarded as the average location of aurora, it can be said that during substorm the aurora oval is asymmetric in local time. The nightside FAC locations do not correlate well with AL , indicating that substorm current does not necessarily shift equatorward as substorm evolves. IMAGE FUV measurements also show that the aurora breakup (substorm onset) normally occurs around midnight, in the following 20~30 minutes the aurora brightening will shift both poleward and azimuthally^[16]. Previous studies also show that around midnight the upward and downward FAC locations coincide with the aurora breakup^[17]. Thus, substorm current wedge may shift together with the aurora brightening poleward and azimuthally. This has been validated by previous event studies that after substorm the ionospheric current system tends to move duskward instead of equatorward^[18].

5 SUMMARY

We have analyzed the characteristics of substorm time FACs in the dusk and dawn sectors on March 23 2007 and on the dayside and nightside on September 3 2001. The results can be summarized as follows.

(1) FACs intensities are related to substorm phases. With larger AL , FACs get enhanced. Substorm time FACs can get enhanced by 5 times than quiet time. The duskside and nightside FACs correlate better with AL index than the dawnside and dayside.

(2) The region of FAC peaks is $68^\circ \sim 80^\circ$ MLat in the dawn and $64^\circ \sim 80^\circ$ MLat in the dusk, $70^\circ \sim 82^\circ$ MLat on the dayside, and $60^\circ \sim 78^\circ$ MLat on the nightside. FACs in the dusk and on the nightside are located equatorward of those in the dawn and dayside. However, FACs latitudes correlate not well with AL index.

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