Earth Planets Space, **56**, 269–282, 2004

SC related electric and magnetic field phenomena observed by the Akebono satellite inside the plasmasphere

A. Shinbori, T. Ono, M. Iizima, and A. Kumamoto

Geophysical Institute, Tohoku University, Sendai 980-8578, Japan

(Received October 8, 2003; Revised January 19, 2004; Accepted January 19, 2004)

Electric and magnetic field variations inside the plasmasphere associated with SCs identified on the ground are analyzed based on the Akebono satellite observations which have been carried out more than 13 years since March 1989. 126 electric field observation data corresponding to SCs show abrupt change of intensity as well as direction within a few minutes inside the plasmasphere. Temporal variations of the electric field showed a bipolar waveform with the amplitude range of 0.2–38 mV/m. The electric field signature is followed by a dumping oscillation with the period of Pc3-4 ranges. The magnetic field variations of 33 SCs also show an abrupt increase of 0.2–65 nT within a few minutes, which indicate the compression of the magnetosphere due to the discontinuity of solar wind. The initial excursion of the electric field during SCs tends to be directed westward. The amplitude does not show a dependence on magnetic local time that has been observed outside the plasmasphere. The magnitude of the electric field variations tends to be proportional with the power of 0.6 to the magnetic field variation in the plasmasphere. The Poynting vector of the initial SC impulse is directed toward the earth, which suggests that energy of magnetic disturbances associated with SCs propagates toward the earth inside the plasmasphere with the refraction due to the plasma density gradient. One of the most interesting results from the present study is that a DC offset of the Ey component of the electric field appears after the initial electric field impulse associated with SCs. This signature is interpreted to be a magnetospheric convection electric field penetration into the inner plasmasphere ($L = 2.5$). The intensity of the offset of the Ey field gradually increases by 0.5–2.0 mV/m about 1–2 minutes after the onset of the initial electric field impulse and persists about 10–30 minutes.

Key words: Sudden commencements, electric and magnetic field, Poynting vector plasmasphere, convection electric field, dumping oscillation, the Akebono satellite westward.

1. Introduction

Due to the arrival of an interplanetary shock wave and discontinuity of solar wind to the earth's magnetopause, fast mode hydromagnetic (HM) waves are generated in the dayside magnetopause. Then, they begin to propagate toward the earth passing through the magnetosphere, plasmasphere and ionosphere. When they arrive on the ground, the signature of sudden commencements (SCs) is recorded on the magnetogram giving an abrupt increase of geomagnetic H-component within a few minutes. The passage of the fast mode HM waves leads magnetic and electric field perturbations (e.g., Wilken *et al.*, 1982; Knott *et al.*, 1985; Laakso and Schmidt, 1989; Cahill *et al.*, 1990; Araki, 1994; Wygant *et al.*, 1994) and plasma wave phenomena in ULF-HF ranges (e.g., Hirasawa, 1981; Gail *et al.*, 1990; Gail and Inan, 1990; Wilson *et al.*, 2001; Shinbori *et al.*, 2002, 2003a, 2003b) in the magnetosphere. Because DC electric and magnetic field variations directly affect on the dynamics of the magnetosphere and plasmasphere plasmas as well as the ionospheric plasma via the magnetosphere-ionosphere coupling processes, the studies on these signatures have been one of the most basic subjects for understanding of physical processes in the magnetosphere. Knott *et al.* (1985) reported that the electric field data obtained by the GEOS-2 satellite show transient signatures of about 7 mV/m in the dayside magnetosphere associated with the onset of SC which occurred at 08:25:40 (UT) on March 22, 1979. These signatures are followed by Pc 4-5 oscillations with a period of about 200 seconds. Laakso and Schmidt (1989) reported a local time effect that the rotational sense of polarization of SC related ULF waves in the electric field is left-handed between 02:00 and 12:00 (MLT) and right-handed between 14:00 and 22:00 (MLT). They also pointed out that the electric field was directed duskward, which is due to the consequence of the temporal tailward plasma drift motion during the compressional phase at the geostationary orbit. Based on the DE1 satellite observation near the plasmapause ($L = 4.5$), SC related field phenomena which occurred on July 13, 1982 were reported by Cahill *et al.* (1990), who showed that poloidal and toroidal standing ULF waves are enhanced by the SC. The period and amplitude of the toroidal waves are 90 seconds and 5 mV/m, respectively; on the other hand, the poloidal waves consist of a compressional mode with a period of 100 seconds followed by a rapidly damped compressional pulsation with a life time of 300 seconds. In addition to these phenomena, Cahill *et al.* (1990) reported association of Pc1 ULF waves within a frequency range from 0.1–0.5 Hz. A case study of an SC event which occurred on March

---

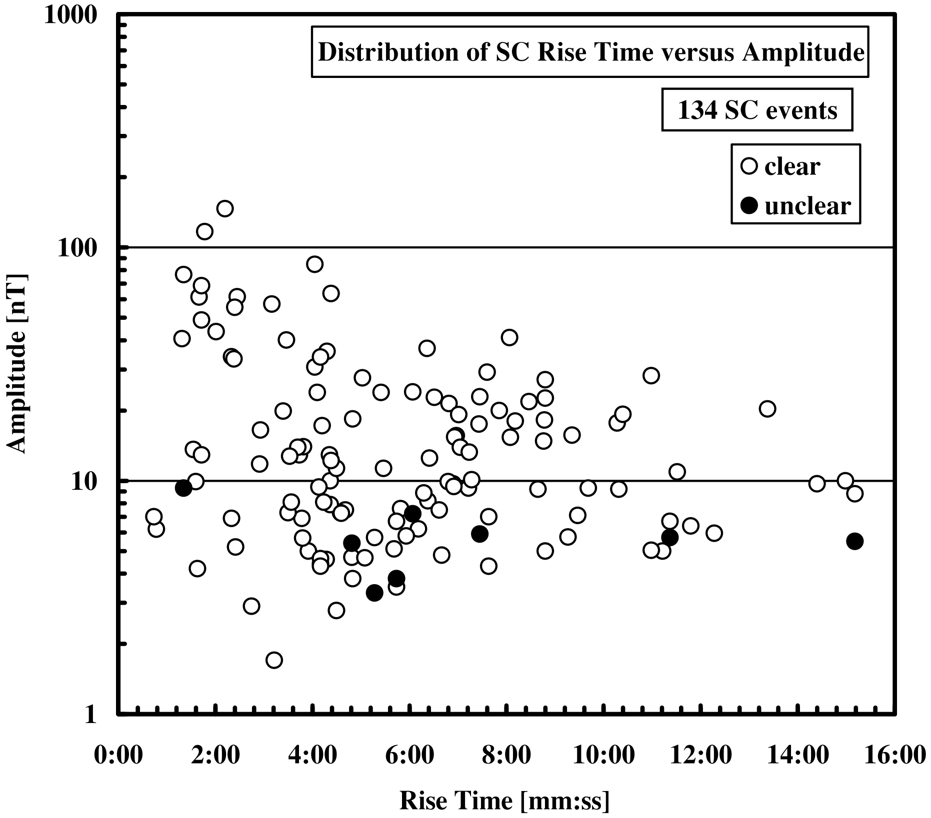

Fig. 1. Dependence of the electric field variation observed by the EFD detector onboard the Akebono satellite on SC amplitude measured at Kakioka. Observations are plotted with the rise time versus amplitude of SC. Circle SC events show the clear variation of the electric field associated with the onset of SC, while solid circle SC events do not show the electric field variation. The SC events with the amplitude of more than 10 nT indicate the clear change of the intensity and direction of the electric field during SCs.

24, 1991 observed by the CRRES satellite was reported by Wygant *et al.* (1994), who showed that the electric and magnetic field perturbations with the bipolar waveform in the inner magnetosphere ($L = 2.6$) at the nightside (02:40 MLT) have a large amplitude of about 80 mV/m and 140 nT, respectively. Furthermore, they also showed that the injection of the energetic electron within an energy range of 15 MeV occurs with correspondence to the period of the electric field perturbations. Wilson *et al.* (2001) also reported that the electric field perturbations of Ey component with peak-to-peak amplitude of 110 mV/m were observed by the CRRES satellite near the plasmapause ($L = 3.5$) due to a passage of fast mode (HM) waves associated with SC. In the recent study, plasma wave and field phenomena are found with one to one correspondence to each SC onset in the auroral zone, polar cap and plasmasphere by the Akebono satellite observation data (Shinbori *et al.*, 2002, 2003b) of long operation time period since March 1989 to December 2002.

However, because majority of these previous studies on the SC related field phenomena was based on the satellite observations outside the plasmasphere, signatures of the SC related field phenomena inside the plasmasphere have not been fully understood. In this paper, electric and magnetic field phenomena associated with SCs are studied by using electric field (Hayakawa *et al.*, 1990) and magnetic field data (Fukunishi *et al.*, 1990) for more than 13 years of the Akebono satellite observations with high time resolution. In the analyzed data, 126 cases of SC related electric field perturbations have been identified for SC onsets. The purpose of the present paper is to investigate the detail signatures of electric and magnetic fields associated with SCs, especially by analyzing propagation direction and speed of SC disturbances inside the plasmasphere observed by the Akebono satellite.

2. Observation Data

Observations of the Akebono satellite have been continued more than 13 years since the launch on February 21, 1989 when the satellite was put into a semi-polar orbit with an inclination of 75°, with initial apogee and perigee of 10,500 km and 274 km, respectively. In the present studies, electric and magnetic field data are provided by instruments of EFD (Hayakawa *et al.*, 1990) and MGF (Fukunishi *et al.*, 1990), respectively. The time resolution of the EFD and MGF data from the science data base of the Akebono satellite is 8 seconds. The data are presented in the Geocentric Solar Magnetospheric (GSM) coordinate system. The electric field measurement is made by two sets of double probes in the spin plane of the Akebono satellite. The spin axis component (the Ex component) has been calculated under the assumption of zero electric field along the magnetic field line, namely $\mathbf{E} \cdot \mathbf{B} = 0$. With calculating the IGRF90 model magnetic field, the corotation electric field is subtracted from three components of the electric field used in the present analysis. On the other hand, we also used variation of the magnetic field (δB) component referring the IGRF90 magnetic field model. The accuracy of the magnetic and electric field data

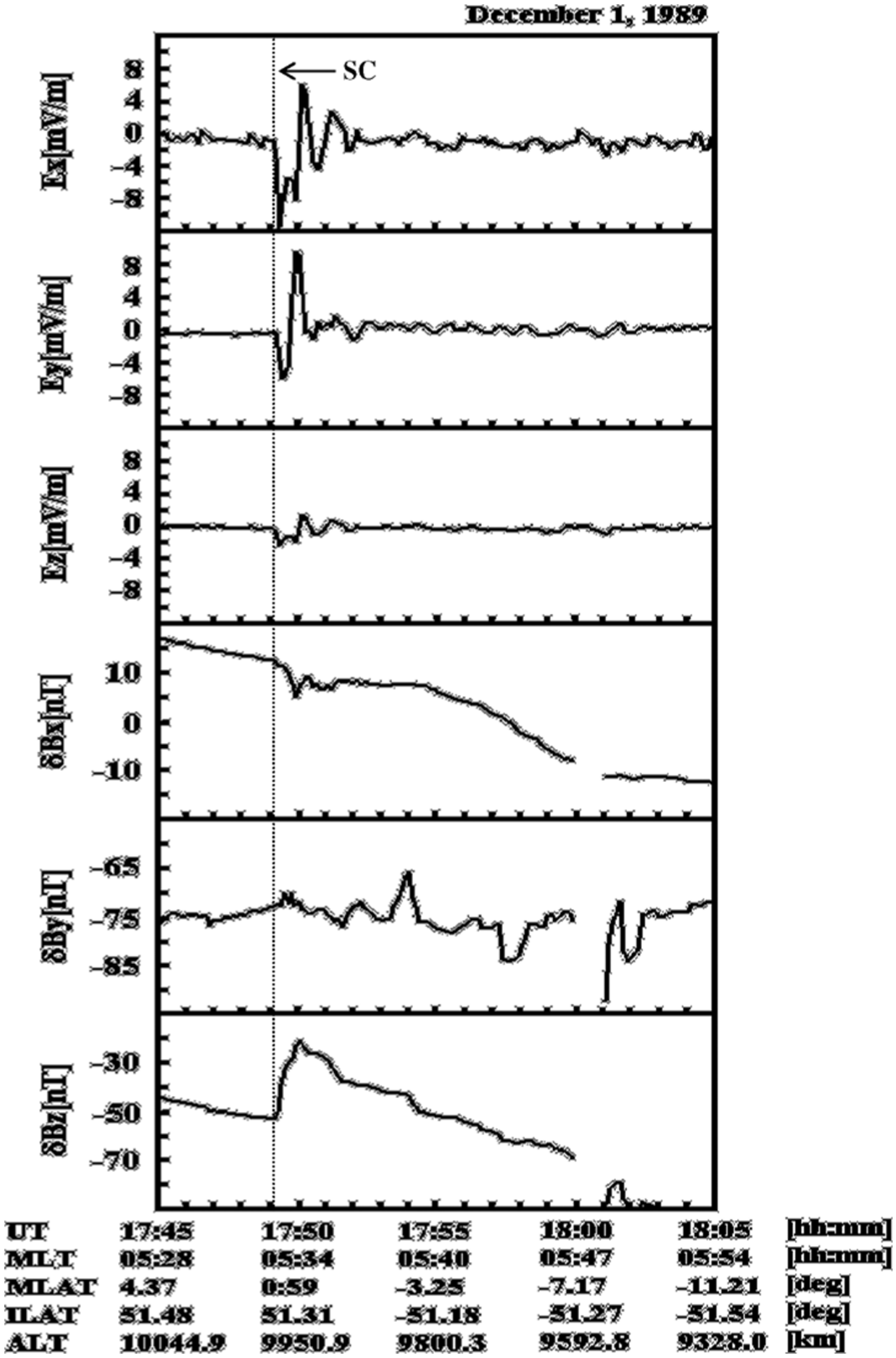

Fig. 2. An example of SC event at 17:49:08 (UT) on December 1, 1989 when the Akebono satellite passed near the geomagnetic equator. The three upper panels show the electric field of three components in a GSM coordinate. The Ex component is calculated by $\mathbf{E} \cdot \mathbf{B} = 0$. The three bottom panels show magnetic field data with an IGRF90 model field subtracted in a GSM coordinate. The electric and magnetic field perturbation associated with the passage of the SC disturbances has the peak to peak amplitude of about 4 mV/m to 17 mV/m and 8 nT to 32 nT.

is 0.1 nT and 0.1 mV/m, respectively.

Within a period from January 1989 to December 2002, 2803 SC events have been identified in term of SYM-H (Iyemori and Rao, 1996) with the time resolution of 1 minute. We picked up SC events as a rapid increase of SYM-H values with more than 5 nT within ten minutes in the SYM-H index data as has been described by Shinbori *et al.* (2002, 2003b). For each SC event, the precise onset time was identified by referring the H-component geomagnetic variation from the rapid sampling records with the time resolution of 1 second obtained at Kakioka Magnetic Observatory. The way of the detailed determination of the onset time has been described by Shinbori *et al.* (2002, 2003b). Among 276 low latitude SC events within a period from March 1989 to December 2002, the electric field data were available for 134 cases of the SC events. 126 cases of the 134 SC events show clear changes of the magnitude and direction of the electric field with correspondence to the enhancements of SC related

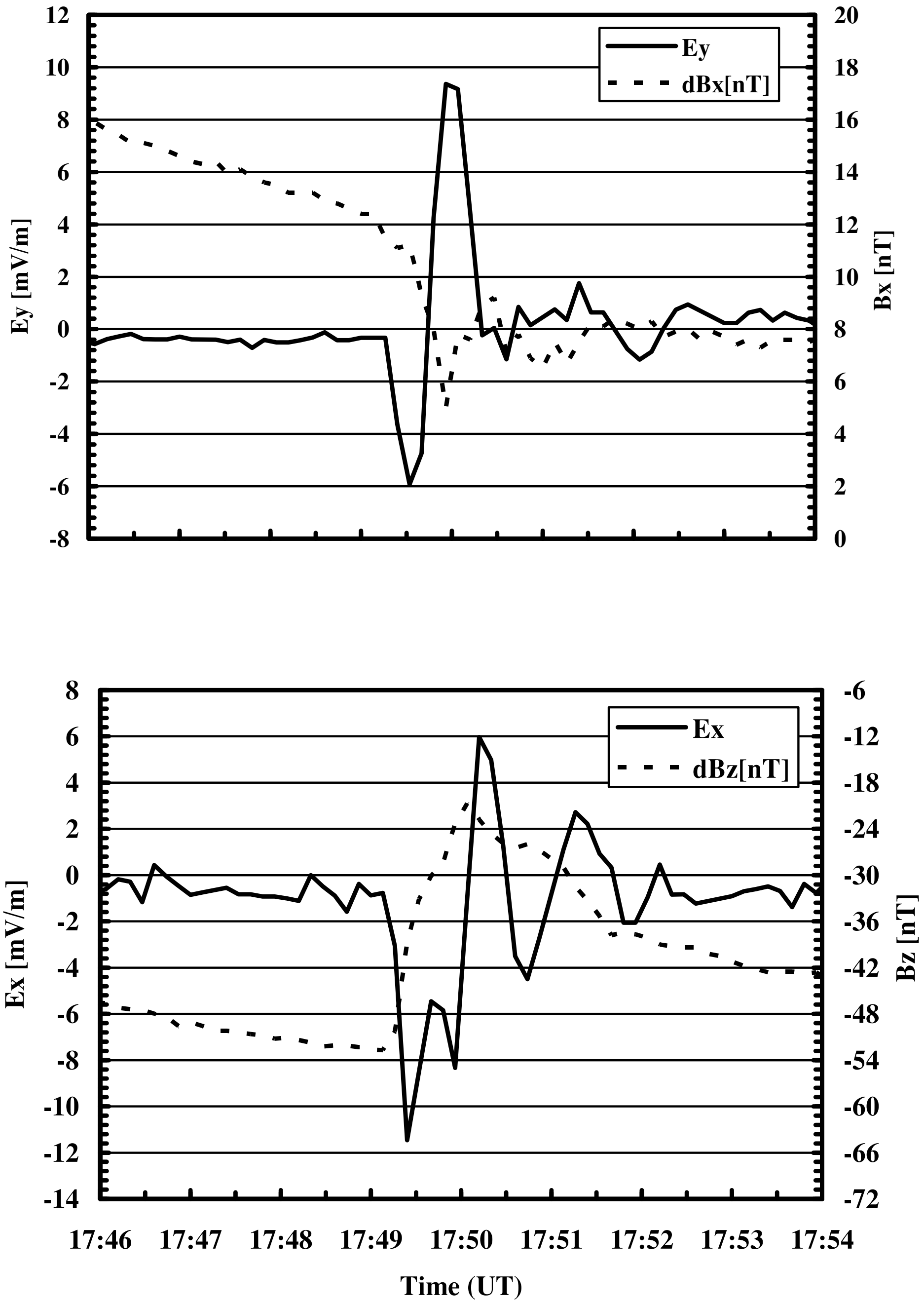

Fig. 3. Phase relationship between the orthogonal components (Ey, δBx, Ex, and δBz) of the electric and magnetic fields within a time range from 17:46 to 17:54 (UT) on December 1.

plasma waves. However, the rest 8 cases of the SC events do not show changes of the electric field. Due to the limitation of amplitude resolution (0.1 mV/m) of the electric field, SC events with small magnitude probably seem to be vanished in the electric field perturbation records.

Figure 1 shows a plot of the 134 SC events as a function of rise time and amplitude measured at Kakioka. Circles indicate the SC events for which a clear change of intensity and direction of the electric field was observed by the EFD detector onboard the Akebono satellite, while solid circles for which the change of the intensity and direction of the electric field was not found. It is noted that the SC events with the amplitude range of more than 10 nT show the significant signature of the electric field with one-to-one correspondence to the onset of SC. The majority of the 8 SC events at reset tend to distribute in a region of the small SC amplitude of less than 7 nT. On the other hand, 33 MGF data of SC related magnetic field perturbations were available showing an abrupt increase within several minutes at the SC onset.

3. Electric and Magnetic Field Signatures Associated with SCs

3.1 An example of SC event on December 1, 1989

An example of electric and magnetic field perturbations associated with SC is given in Fig. 2 which occurred at 17:49:03 (UT) on December 1, 1989. In this case, the Akebono satellite observation point was located at $L = 2.6$, 05:32 (MLT) and 1.0 degree (MLAT) just near the magnetic

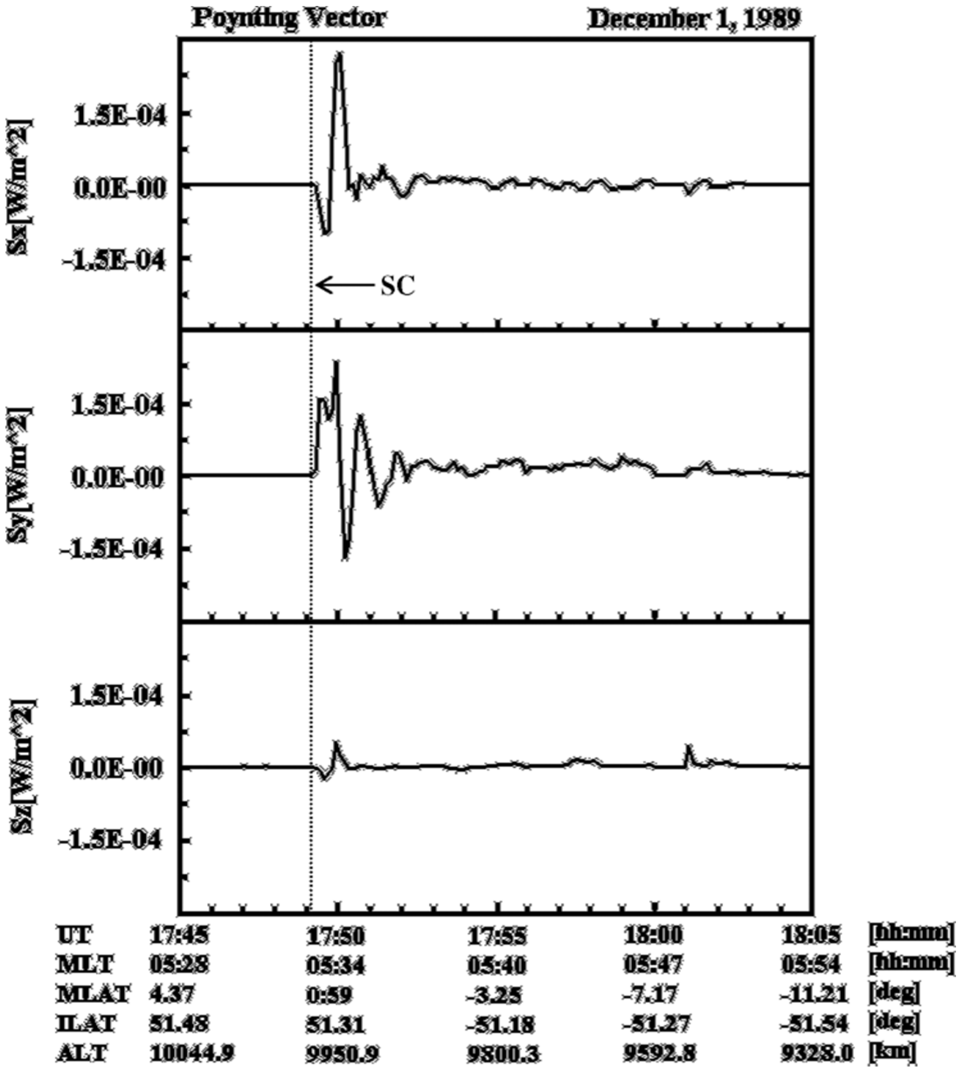

Fig. 4. This figure presents the Poynting vector of three components calculated from the electric and magnetic field data of SC event at 17:49:08 (UT) on December 1, 1989. The Poynting vector at the onset of the SC is roughly directed duskward.

equator regions of the plasmasphere. In the panels of Ex, Ey and Ez electric field data, the electric field perturbations started at 17:49:08 (UT) with delay time of about 5 seconds after the SC onset measured on the ground. The Ex component reaches its minimum value of -11.5 mV/m at 17:49:24 (UT) directing toward anti-sunward. About 48 seconds later, Ex changed its direction toward the sun with the maximum value of about 6 mV/m at 17:50:12 (UT). The Ex electric field perturbation is followed by a dumping oscillation with a period of 64 seconds which is in a range of Pc4 pulsation. This oscillation was damped out within about 4 minutes. The Ey component shows a bipolar waveform with the peak-to-peak amplitude of 15.3 mV/m. The period is about 64 seconds. The direction of this component changes from the dusk-to-dawn to dawn-to-dusk direction. After the bipolar signature, the Ey field also shows slight fluctuation with a period and amplitude of about 48–64 seconds and 0.6 mV/m, respectively. This perturbed electric field in the frequency range of Pc4 pulsation persisted until 18:00 (UT). The Ez field shows a similar waveform of the Ex field; however, its amplitude is five times smaller than that of the Ex component. It is indicated that all components of the electric field variations after the onset of SC still remain perturbations which are lager magnitude than the condition before that of SC. Moreover, it should be noted that such a large amplitude perturbation of the electric field associated with SCs which are more than 10 to 20 mV/m has not ever been observed in the geostationary distance (e.g., Laakso and Schmidt, 1989).

The $\mathbf{E} \times \mathbf{B}$ drift velocity associated with a peak total electric field of about 19 mV/m in the presence of the 2400 nT total magnetic field at the position of the Akebono satellite during SC is about 8 km/sec. The co-rotation velocity at the same position in the plasmasphere is about 1.2 km/sec. This fact indicates that the electric field drift velocity induced by the abrupt magnetic compression is larger than the co-rotation velocity. Therefore, this evidence suggests that plasmaspheric particles do not co-rotate on the magnetically disturbed condition such as SC. If the plasmaspheric particles maintained a constant phase relation with the electric field and encountered the full 19 mV/m over an entire drift period at $L = 2.6$, then, the total inward drift would be about 500 km in radius. Assuming the first adiabatic invariant conver-

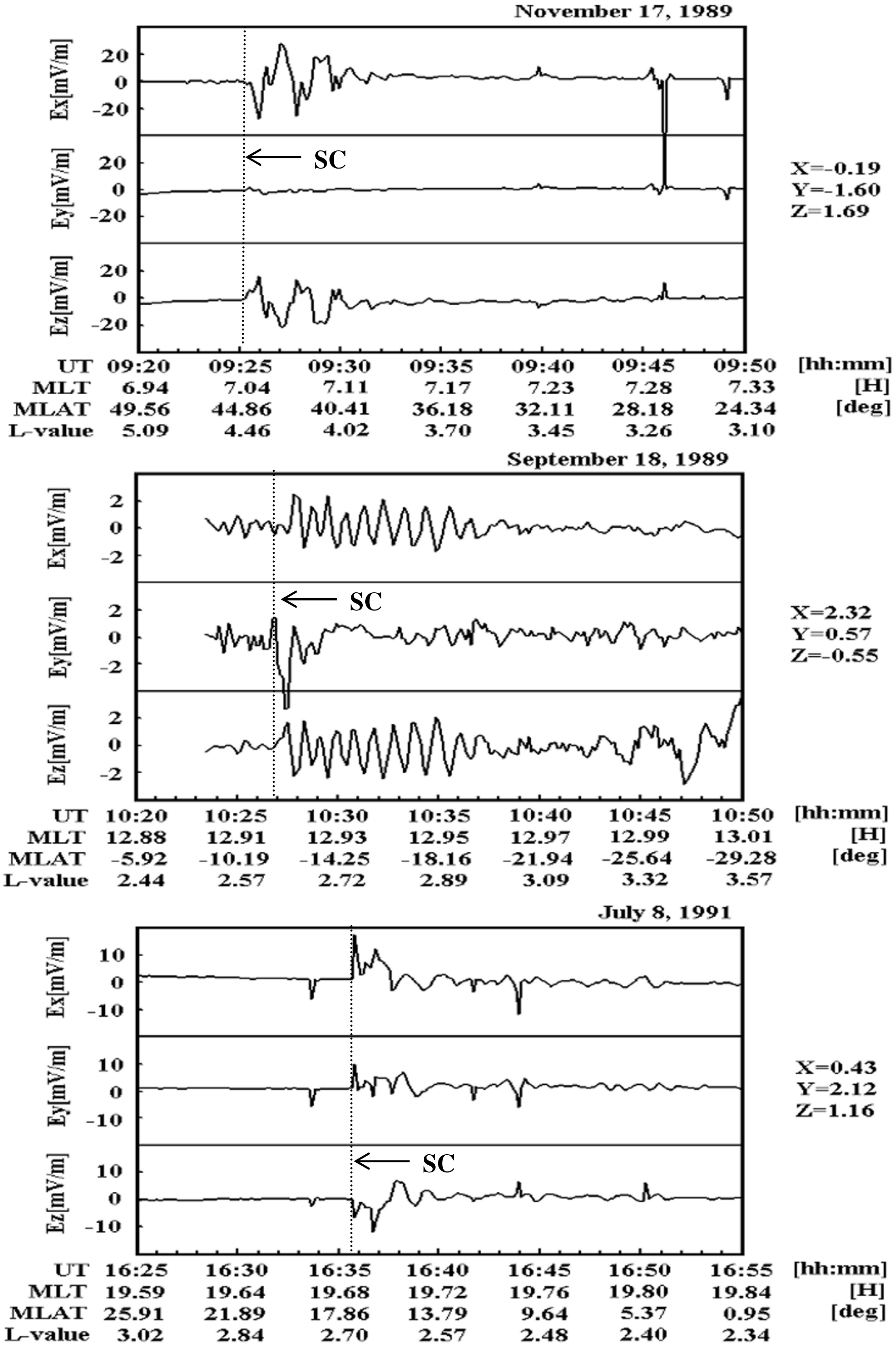

Fig. 5. The electric field fluctuation in three sectors of dawnside, dayside and duskside where the Akebono was located at the onset of SCs. The right of each panel shows the Akebono satellite position normalized by the earth's radius in GSM coordinate. The initial excursion of the electric field has clear local time dependence of the direction. All events show that the electric field oscillate with the amplitude of about 3 mV/m to 20 mV/m with a period of about 40 to 150 second which are recognized as Pc3-4 ULF waves followed by the SC.

sation in a dipole magnetic field, the suprathermal electrons and ions (~10 eV) would increase its energy by a factor 1.1.

On the other hand, almost at the same time with the onset of the electric field perturbations, the δBz magnetic field component shows a rapid increase of about 32 nT within about 1 minute. The maximum δBz value of -20 nT was appeared at 17:50:04 (UT) at the moment when the electric field of both the Ex and Ez components passed through zero. Gradual decrease of the δBz value which follows this signature indicates the effects of ring current due to the occurrence of a magnetic storm. The δBx component gave the minimum value of 5 nT within a time range of about 24 seconds. The perturbation of the δBy has amplitude of about 10 nT as given in Fig. 2. Figure 3 shows the phase relationship between the observed electric and magnetic fields within a time range from 17:46 to 17:54 (UT). The second large pulse of the orthogonal components of Ey and δBx indicates an oscillation with 180° out of phase; namely, the δBx com-

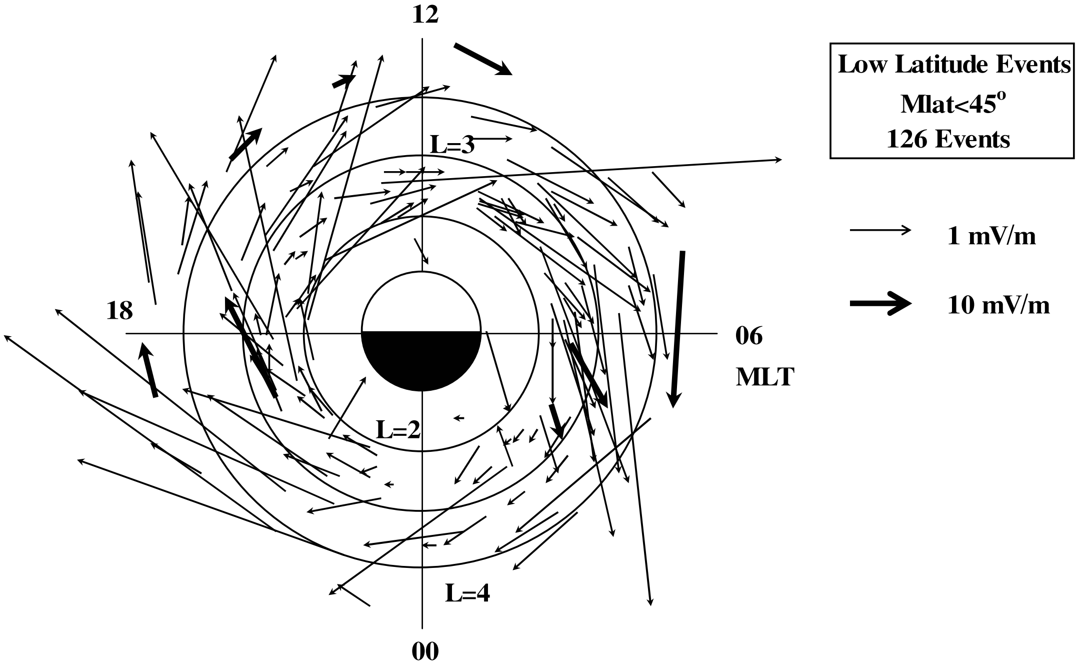

Fig. 6. The direction of the initial excursion of the electric field at the onset of 126 SC events. An arrow length shows a magnitude of the electric field. A start point of each arrow shows the L-value and magnetic local time at the location of the Akebono satellite at the onset of the electric field perturbations. The thin and thick arrows indicate the reference magnitude of 1 mV/m and 10 mV/m, respectively. The electric field is directed westward at the onset of SCs.

ponent gave the minimum value with correspondence to the peak value of about 11 mV/m of the Ey component. On the other hand, the first large pulse of the Ex and δBz components shows the oscillation with 90° phase lag; namely, the variation of the δBz components gave the peak value with correspondence to the passage of the Ex component through zero. These variations were due to a compression of the magnetosphere followed by a relaxation.

A Poynting vector **S** derived from a calculation of the electric and magnetic field data defined as

$$\mathbf{S} = \frac{\delta \mathbf{E} \times \delta \mathbf{B}}{\mu_0} \tag{1}$$

is given in Fig. 4. The three panels show the high-pass-filtered vector components whose cut-off period is 120 seconds. In Fig. 4, the Sx and Sy components of the initial excursion of the Poynting vector indicate -1.0×10^{-4} W/m^2 and 1.6×10^{-4} W/m^2, respectively. Then, the Poynting vector is directed toward the earthward direction. About 32 seconds after the SC, the Sx component is directed to the sunward side with the value of about 2.7×10^{-4} W/m^2; namely, it has a net energy flow with its value of about 5.5×10^{-4} W/m^2 to sunward. On the other hand, the Sy component shows clear dumping oscillations lasting about 3 minutes after the SC. Because the Sy component is perpendicular to the magnetic field at the Akebono satellite observation position, these dumping oscillations are recognized as fast mode HM waves with the period of about 64 seconds. The net energy flow is about 1.6×10^{-4} W/m^2. Therefore, the energy of these fast mode HM waves triggered by the passage of the SC disturbances is propagating to the earthward direction inside the plasmasphere of the equatorial regions. The Sz component shows a bipolar signature with the peak-to-peak amplitude of about 7.4×10^{-5} W/m^2. However, in the Sz component data, there is no signature corresponding to the Sy variations. Therefore, for this example, a little of energy of the fast mode hydromagnetic waves is converted into that of the shear Alfven mode HM wave.

3.2 Local time dependence of electric field fluctuation

Figure 5 shows the electric field data in three sectors; they are dawnside, dayside and duskside regions where the Akebono was located when the onset of SCs was measured on the ground. The right of this figure gives the Akebono satellite observation point normalized by the earth radius in the GSM coordinate system. Hence, we analyzed the initial excursion of the SC related electric field perturbations at the onset of SCs. The upper panel of Fig. 5 shows that the variation of the Ex and Ey components is -27.6 mV/m and 2.2 mV/m, respectively. This indicates that the electric field with the magnitude of about 27.7 mV/m is almost directed anti-sunward. The middle panel shows that only the variation of the Ey component is -5.7 mV/m at the SC onset. This indicates that the electric field with the magnitude of 5.7 mV/m is directed dawnward. The bottom panel shows that the variation of the Ex and Ey components is 15 mV/m and 8.7 mV/m, respectively. This indicates that the electric field with the magnitude of about 14.2 mV/m is almost directed sunward. According to the examples of three observations of the electric field, it is found that the initial excursion of the SC related electric field perturbations has clear dependence on geomagnetic local time. It is interesting that the middle panel shows that both the Ex and Ez components oscillate with the amplitude of about 3 mV/m and the period of about 40 seconds which are recognized as Pc3-4 ULF waves followed by the SC disturbances.

We analyzed electric field vector of the initial excursion

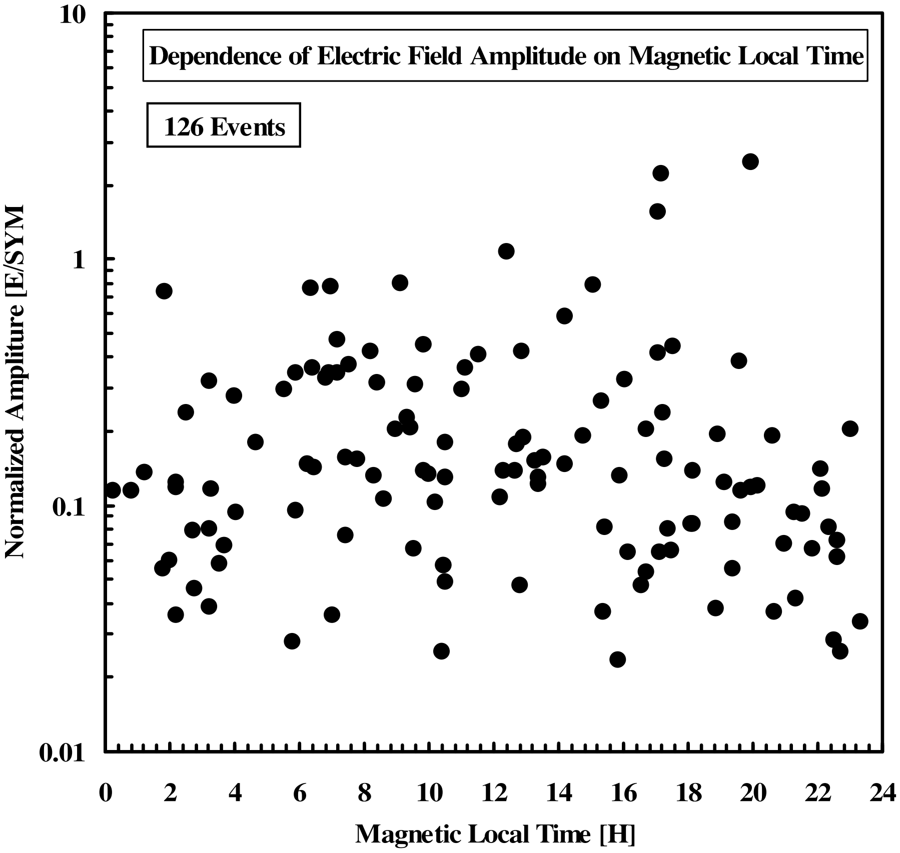

Fig. 7. Scatter plot of the electric field amplitude in the plasmasphere normalized by the SYM-H index as a function of magnetic local time. A remarkable dependence of SC related electric field amplitude on magnetic local time is not found inside the plasmasphere.

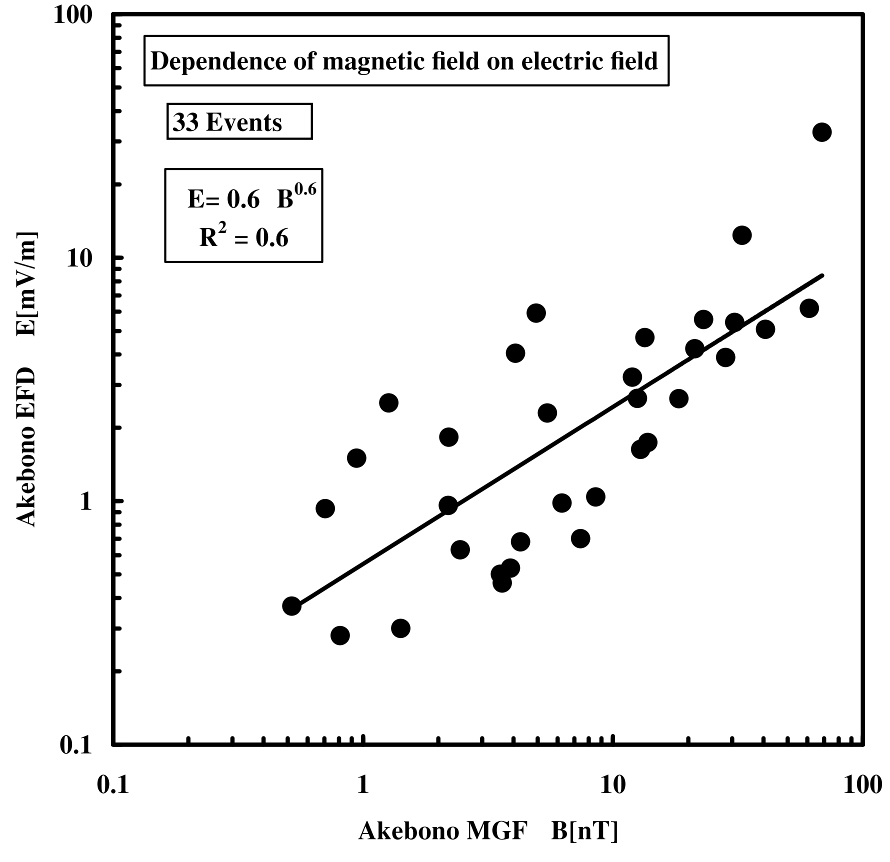

Fig. 8. Scatter plot of the perturbations of the magnetic field versus the electric field obtained by the Akebono satellite. The initial magnitude of the electric field associated with SCs inside the plasmasphere is proportional with the power of about 0.6 to that of the magnetic field.

for 126 SC events found within a period from 1989 to 1996 in Fig. 6. An arrow length in Fig. 6 shows a magnitude of the Ex and Ey components of the electric field variations. A start point of each arrow shows L-value and magnetic local time of the Akebono satellite observation position at the onset of the SC related electric field perturbations. The thin and thick arrows which are shown in the right side of this figure give the reference scales of the magnitude for 1 mV/m and 10 mV/m, respectively. This result indicates that the initial excursion of the electric field at the onset of SCs near the Akebono satellite observation points is aligned toward the west direction within the electric field intensity range from 0.2 mV/m to 40 mV/m. The direction shows that plasmaspheric plasmas including radiation belt particles drift toward the earth. In order to verify the dependence of the electric field amplitude in the plasmasphere, we normalized the amplitude of the 126 electric field perturbations with that of the SYM-H index. The analysis result is shown in Fig. 7. Figure 7 does not show a remarkable dependence of the electric field perturbations on magnetic local time in the plasmasphere. Therefore, the electric field intensity of the initial perturbations associated with SCs inside the plasmasphere does not depend on magnetic local time as is observed outside the plasmasphere in the geostationary orbit (Schmidt and Pedersen, 1987; Laakso and Schmidt, 1989).

3.3 Relation between electric and magnetic impulses associated with SC

In Fig. 8, ΔE and ΔB are given by the initial magnitude of the electric and magnetic field perturbations observed by the Akebono satellite, respectively. From the results given in Fig. 8, it is shown that the ΔE and ΔB components are correlated as

$$\Delta E = 0.6\Delta B^{0.6} \qquad (2)$$

with correlation coefficient R of about 0.8. Therefore, it can be concluded that the initial magnitude of the electric field associated with SCs inside the plasmasphere is proportional with the power of about 0.6 to that of the magnetic field.

3.4 Appearance of DC offset of the Ey field associated with SC

Figure 9 shows two examples of signatures appeared in the Ey component after the SC onset inside the plasmasphere. Panel (a) of Fig. 9 gives the Ey field variation during an SC which has already shown in Fig. 2. In this case, the Ey field of the DC component indicates a gradual increase after the bipolar signature associated with the SC onset. The intensity and temporal variation are about 0.5–1.0 mV/m and 10 minutes, respectively. The peak intensity of the Ey field gives about 1.7 mV/m at 17:51:24 (UT). As the coordinate of the three components of the electric field data has already been described in Section 2, the direction of the Ey field corresponds to the dawn-to-dusk direction. The direction is almost coincident with that of magnetospheric convection electric field. Then, this result suggests that the convection electric field penetrates inside the equatorial region of the dawnside plasmasphere ($L = 2.6$). Around 18:00 (UT), the intensity of the Ey field shows the increase by 0.7 mV/m again. This phenomenon indicates that the convection electric field is enhanced due to southward turning of the interplanetary magnetic field direction after occurrence of the SC.

Panel (b) of Fig. 9 shows the Ey field variation during the SC which occurred at 03:30:44 (UT) on July 28, 1990. In this case, the start time of the Ey field variation is delayed with 8 seconds at the onset of SC measured on the ground when the Akebono satellite was located at the altitude, magnetic local time and magnetic latitude of 9476.0 km, 18:08:43 and 6.04°, respectively. The signature of the Ey field shows the gradual increase after the initial electric field impulse associated with the SC. The peak intensity gives about 2.0 mV/m around 03:33 (UT). Later, the intensity gradually decreased to the pre-SC level for about 40 minutes. This event also shows that the convection electric field penetrate into the equatorial region of the duskside plasmasphere ($L = 2.5$).

In both the SC events, the electric field oscillation with the period of 50–120 seconds which corresponds to that of Pc4 pulsation are found after the SC onset. Furthermore, it is noted that the background electric field intensity for the two SC events is different prior to each SC onset. This result seems to be related to magnetic activity or condition before an SC onset.

4. Discussion

4.1 Characteristics of the electric field signature associated with SCs inside the plasmasphere

The present study showed that the transient response of the electric and magnetic field associated with the passage of the SC disturbances was observed inside the plasmasphere within an L-value range of 1.08 to 4.5. The initial excursion of the electric field is almost directed westward, which shows that the plasmaspheric plasma moves toward the earth. Statistical data analysis obtained by the GEOS-2 satellite observation at geoshynchronous orbit indicated that the electric field fluctuation during SCs were a factor of 5 to 10 times stronger near the noon than in the nightside sector (Schmidt and Pedersen, 1987; Laakso and Schmidt, 1989). However, our observational result shows that there is no tendency of local time dependence of the amplitude of the electric field fluctuation during SCs. The peak-to-peak amplitude of the electric field perturbations inside the plasmasphere and near the plasmapause is about 0.2 to 40 mV/m. This result is not consistent with statical analysis by Laakso and Schmidt (1989) who reported that the largest electric field perturbation documented in the GEOS-2 study is about 6 mV/m. On the other hand, based on the CRRES satellite observation, Wygant *et al.* (1994) reported that the electric and magnetic field perturbation in the nightside inner magnetosphere ($L = 2.6$, 02:30 LT) associated with the onset of the anomalous SC which occurred at 03:41 (UT) March 24, 1991 has large amplitude of about 80 mV/m and 140 nT, respectively. From these results, it can be understood that the magnitude of the electric and magnetic field fluctuations associated with SCs has dependence on magnetic local time near the geosynchronous orbit regions in the magnetosphere; however, this dependence seems to disappear inside the plasmasphere. The most significant result from the present study is verification of the direction of initial electric field impulse associated with SCs. As it has clearly been shown in Fig. 6, the initial electric field impulse is directed westward. This signature

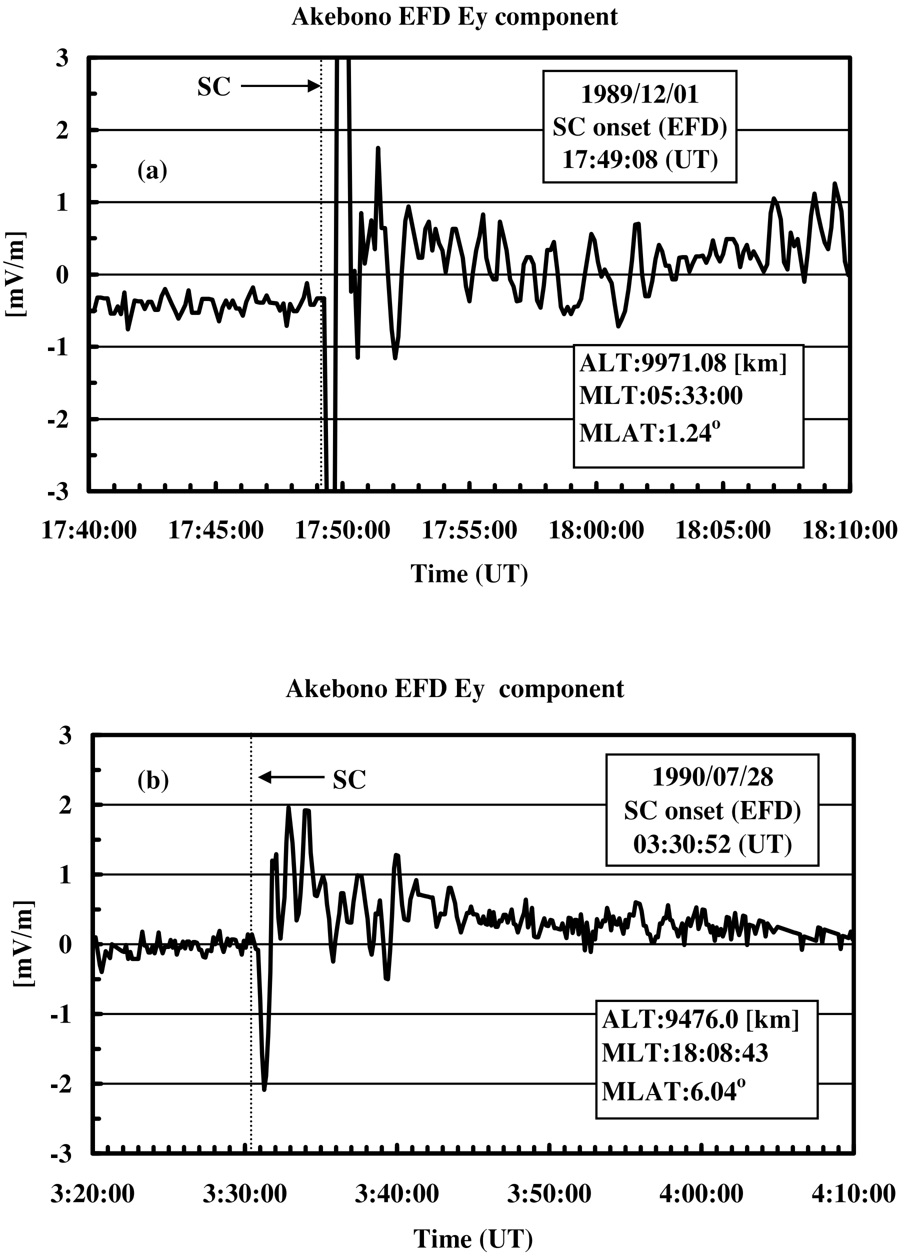

Fig. 9. Signature of the background electric field of the Ey component associated with SC. The upper panel gives the same SC event which has already been shown in Fig. 1. The bottom panel gives the SC event which occurred at 03:30:44 (UT) on July 28, 1990. Both the SC events shows that the intensity of the electric field gradually increases after the initial electric field impulse.

has been predicted by Kikuchi (1986), who showed that the positive frequency deviation on the record of HF Doppler observations at Kakioka corresponds to the increasing stage of the magnetic field in the nighttime as well as in the daytime sectors. Furthermore, the direction of the initial electric field impulse is also consistent with the recent study by using the CRRES satellite observations (Wygant *et al.*, 1994; Wilson *et al.*, 2001).

The recent 3-D MHD simulation study of the magnetospheric response to a magnetic impulse by Fujita *et al.* (2003) has shown the signature of the initial electric field impulse due to the passage of fast mode (HM) waves. The direction of the initial electric field impulse is dominantly dusk-to-dawn direction in the dayside magnetosphere within an L-shell range of 4–8. Fujita *et al.* (2003) also reported that the magnitude of the initial electric field impulse deceases with decreasing the distance from the earth. Their simulation result in the dayside magnetosphere is almost consistent with our observational result inside the dayside plasmasphere. However, the simulation result shows the direction of the electric field impulse is almost radial (earthward) direction inside the duskside plasmasphere; and this result is inconsistent with the result of the present analysis which shows that the direction is almost sunward direction in the same local time sector inside the plasmasphere. The discrepancy of the electric field direction should be solved in the future study.

One of the most important results from the present study is appearance of the DC offset of the Ey electric field associated with SC. It is interpreted as the penetration of the mag-

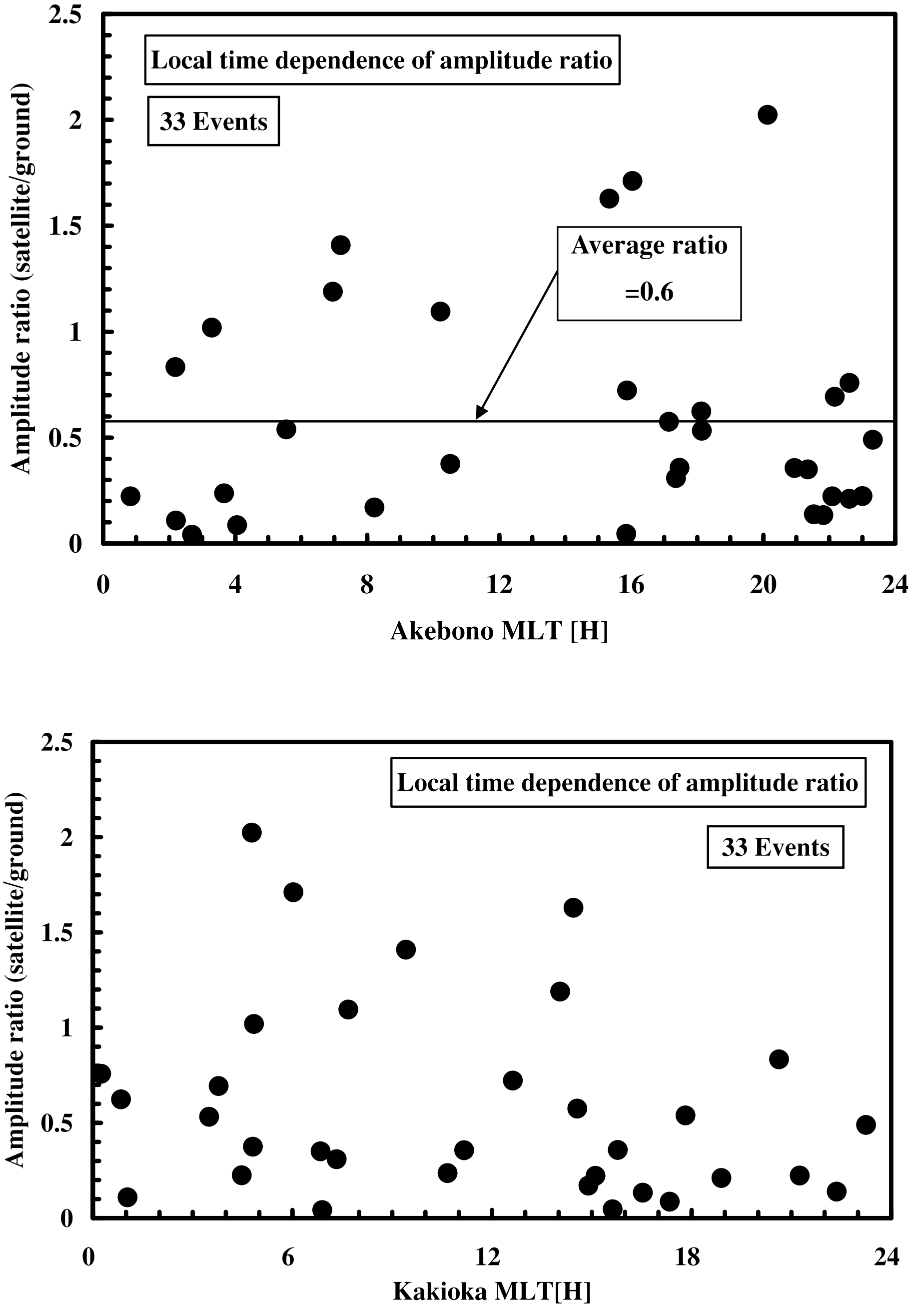

Fig. 10. Scatter plot of magnetic local time at the Akebono satellite position (upper panel) and at Kakioka (bottom panel) versus SC amplitude normalized by that measured on the ground. The upper panel shows the average SC amplitude ratio of satellite/ground.

netospheric convection electric field into the plasmasphere after the impulsive electric field associated with SCs. As it has been shown in Fig. 9, the intensity of the Ey field gradually increases by 0.5–2.0 mV/m about 1–2 minutes after the onset of the electric field impulse. As it has been studied by using the HF Doppler measurement, the dawn-to-dusk convection electric field appears in the ionosphere during the main impulse (MI) of SC (Kikuchi, 1986). Kikuchi (1986) showed that the penetration of the convection electric field into the ionosphere appear about 100 seconds after the SC onset measured on the ground. The delay time scale of the appearance of the convection electric field is almost coincident with the result of the present study. Furthermore, from the measured time scale, Kikuchi (1986) proposed the origin of the dawn-to-dusk electric field in the magnetosphere and ionosphere. As the first step, the dawn-to-dusk convection electric field is generated near the magnetopause around the dawn-to-dusk meridian due to the solar wind-magnetosphere interaction. Then, the convection electric field is propagating along the open magnetic field lines toward the polar cap ionosphere region with Alfven velocity. Second, the convection electric field is transmitted instantaneously from the polar cap to the low latitude regions by electromagnetic waves in the earth-ionosphere waveguide with light speed. On the other hand, Araki (1994) pointed out that the convection electric field plays an important role on generation of MI observed on the ground. However, the problem whether the Ey field observed in the plasmasphere during the SC is identical to the electric field observed near the low latitude ionosphere is still remained. This problem should be solved in future study.

4.2 Characteristics of the magnetic field perturbations associated with SCs

It has been well known that amplitude of magnetic field perturbation associated with SC has strong dependence on magnetic local time in the outer magnetosphere beyond the plasmapause (e.g., Ondoh, 1968; Patel and Coleman, 1970; Kokubun, 1983; Kuwashima and Fukunishi, 1985). Ondoh (1968) reported the existence of a day-night asymmetry of SC amplitude by using the Rb-magnetometer data obtained by the OGO 3 and 5 satellites. The amplitude ratio measured in space to SC amplitude measured on the ground was found to be 1.6 in the daytime, while 1.3 for $L \leq 20$ and 0.9 for $L \geq 20$. Statistical surveys of the 81 transient magnetic field variations obtained by the GOES 1, 2 and 3 satellites within a period of two years show compressive magnetic field variations during SCs by Kokubun (1983). He showed that the SC amplitude normalized by that measured on the ground is nearly one order of magnitude stronger at local noon sector (9–15 LT) than the case obtained in the nightside sector (21–03 LT).

To establish the magnetic field signature for magnetic local time dependence during SCs inside the plasmasphere, we examined 33 SC events. Since the SC amplitude itself changes considerably depending on the condition of an interplanetary shock wave and discontinuity of solar wind, we tried to normalize the magnetic field perturbations obtained by the Akebono satellite by the H-component variations measured at Kakioka. Figure 10 shows the magnetic local time dependence of the normalized SC amplitude observed by the Akebono satellite. In Fig. 10, the distribution of the SC amplitude shows no clear dependence on magnetic local time inside the plasmasphere. Thus, magnetic field signatures in the plasmasphere deviated from those observed outside the plasmasphere (Kokubun, 1983). From these results, it can be concluded that the SC amplitude has a strong dependence on magnetic local time in the region of the outer magnetosphere beyond the plasmapause, while it does not inside the plasmasphere. Kokubun (1983) also pointed out that the magnetic field signatures associated with SCs in the midnight sector at the geoynchronous orbit show decrease of the magnitude of magnetic field. He interpreted these phenomena as the response of local ring current particle associated with SCs. However, such phenomena are not observed by the Akebono satellite in this sector. Furthermore, as has been shown in the upper panel of Fig. 10, the average SC amplitude ratio of satellite to ground is 0.6. This result suggests that SC amplitude measured on the ground tends to be larger than that measured in the plasmasphere. Araki (1977, 1987 and 1994) proposed that the magnetic disturbances of SCs (Dsc) observed on the ground consist of two components as follows;

$$D_{SC} = DL + DP \tag{3}$$

where DL represents a step-function component due to fast mode (HM) waves and DP represents two pulse structure due to ionospheric current originated near the polar ionosphere. Furthermore, DP component is divided into two parts corresponding to the preliminary impulse (PI) and the following main impulse (MI) as

$$DP = DP_{pi} + DP_{mi}. \tag{4}$$

The dependence of these decomposed fields on magnetic local time in the low latitude region (Kakioka) has been shown in Fig. 11 (Araki, 1994). Although not so remarkable as in the high latitude regions, SC waveform observed in the morning-afternoon low latitude regions is also modulated by the DP field. Therefore, the average amplitude ratio of less than 1.0 shown in the upper panel of Fig. 10 can be interpreted as an effect on the DP field produced by the ionospheric current. On the other hand, the bottom panel of Fig. 10 shows dependence on the Kakioka magnetic local time. In this panel, the amplitude ratio of more than 1.0 tends to distribute in the early morning to noon sector (5–14 LT), while the amplitude ratio of less than 1.0 tends to concentrate in the afternoon to night sector (15–04 LT). This tendency in the early morning to afternoon sector at Kakioka can be explained by the above description of SC amplitude modulation on the ground in Fig. 11 (Araki, 1994). However, according to our result, the SC amplitude on the ground in the nightside sector tends to become larger compared with that in the plasmasphere. This signature of SC amplitude on the ground in the nightside sector has not been described in detail by Araki (1994). The detail investigation of these features should be established in future study.

4.3 Propagation nature of field phenomena associated with SCs

The electric and magnetic field signature obtained by the Akebono satellite is originated primarily due to the magnetic compression, which shows that the field perturbations mainly occur in the δBz component parallel to the ambient magnetic field line and the Ex and Ey components perpendicular to it. This signature is almost consistent with the previous works (Cahill *et al.*, 1990; Wygant *et al.*, 1994). In order to obtain the propagation speed of the field phenomena associated with SCs, the wave fields are assumed to be a plane wave with frequency ω and wave vector $\mathbf{k}$. Then, $\delta\mathbf{E}$ and $\delta\mathbf{B}$ are related through Faraday's law as $\omega\delta\mathbf{B} = \mathbf{k} \times \delta\mathbf{E}$. Since ion sound velocity is about 2–5 km/sec inside the plasmasphere, we can approximate fast mode HM wave velocity as Alfven wave velocity, that is, $V_f \approx V_A$. Then the propagation velocity of the SC related field phenomena is

$$V_f \approx V_A = \frac{\omega}{k} = \frac{\delta E}{\delta B}. \tag{5}$$

From the above relation the propagation velocity can be estimated and then compared with the Alfven velocity, given by

$$V_A = \frac{B_0}{\sqrt{\mu_0 n_e m_i}}, \tag{6}$$

where B_0 is the strength of the ambient magnetic field at the location of the Akebono satellite, μ_0 is the magnetic permeability, n_e is the electron number density, and m_i is the effective ion mass.

As it has already been shown in Fig. 2, the example of SC event which occurred at 17:49:08 (UT) December 1, 1989 shows that the values of the electric and magnetic field perturbations are about 12 mV/m and 32 nT, respectively. In this case, the propagation velocity of the field perturbations is about 360 km/sec at the location of the Akebono satellite in the equatorial region of the plasmasphere. The propagation velocity of a fast mode HM wave has been studied for less extreme conditions and compared to several satellites' and ground based data by Wilken *et al.* (1982). In their model, the plasmasphere has a fast mode HM wave speed of 300 km/sec and the outer magnetosphere beyond the plasmapause has a speed of 900 km/sec. Our result is consistent with the velocity range of 300–900 km/sec derived by Wilken *et al.* (1982). Hydromagnetic waves are refracted with an abrupt increase of the plasma density gradient at the plasmapause. Furthermore, the propagation velocity derived by the electric and magnetic field perturbations is also almost consistent with the propagation velocity of about 390 km/sec derived from the time difference between the onset times of SCs measured at Kakioka and that of enhancements of electromagnetic whistler mode plasma waves observed by the Akebono satellite by Shinbori *et al.* (2003b).

On the other hand, in the case of SC events described in Section 3.1, the electron number density at the position of the Akebono satellite near the SC onset is 1793 el/cm^3, which is calculated from the upper frequency of upper hybrid resonance (UHR) waves measured by the PWS instrument (Oya *et al.*, 1990). From this electron number density, we can estimate Alfven speed using (6). Assuming that the ions are all protons; that is, $m_i = m_p$, where m_p is the proton mass, the Alfven speed is about 1100 km/sec. For this SC event, the Alfven speed is larger than $\delta E/\delta B$ by a factor of 3. The discrepancy in velocity can be solved if we allow for the presence of heavy ions such as helium and oxygen ions. In this case, the effective ion mass which is provided from this velocity of the fast mode HM wave is about 8.5 at the Akebono satellite position of the plasmasphere. This result is consistent with the propagation velocity of Pi2 pulsations in the plasmasphere by Osaki *et al.* (1998), but they doubted such oxygen rich plasma condition in the plasmasphere. On the other hand, the OGO-5 satellite observation results (Chappell *et al.*, 1970; Harris *et al.*, 1970) showed that helium and oxygen ions as well as proton is more dominant inside the plasmasphere ($L < 3$) than outer the plasmapause. These results lead us to conclude that there are abundant heavy ions such as helium and oxygen ions in the plasmasphere.

The k-vector of the fast mode HM waves has been derived from a calculation of the Poynting vector using the electric and magnetic field data. The Poynting vector is roughly directed duskward (toward the earth) at the dawnside as has been shown in Fig. 4. This result indicates that the Poynting vector is roughly directed in the direction predicted for the normal vector to the phase front calculated by Wilken *et al.* (1982) and provides evidence of the large refractive index of fast mode HM waves inside the plasmasphere.

5. Conclusion

Electric and magnetic field phenomena associated with SCs are analyzed by using the Akebono satellite observations which have been carried out more than 13 years since March 1989. The simultaneous electric field observation data of 126 SC events show clear changes of the magnitude and direction within a few minutes inside the plasmasphere associated with the onset of SC measured at Kakioka. The response of the electric field perturbation shows a bipolar waveform with the amplitude range of 0.2–38 mV/m. The period of the perturbed field is about 64–120 seconds. The electric field signature is followed by a dumping oscillation with the period of Pc3-4 ranges. The magnetic field signatures of 33 SC events mainly show an abrupt increase of 0.2–65 nT within a few minutes in the δBz component, which indicates the compression signature of the magnetosphere due to interplanetary shock waves or discontinuity of solar wind. The initial excursion of the electric field associated with SCs is almost directed westward. The direction suggests that particle within all energy range in the plasmasphere moves toward the earth with conservation of magnetic moment. The amplitude does not show clear dependence on magnetic local time as shown in the previous works but is proportional with the power of 0.6 to that of the magnetic field in space. The Poynting vector of the initial impulse of SC is directed toward the earth with the order of the magnitude of 10^{-4}–10^{-5} W/m^2. These facts indicate that energy of magnetic disturbances associated with SCs propagates to the earth inside the plasmasphere with the refraction due to the plasma density gradient.

On the other hand, propagation velocity of SC disturbances derived from the amplitude ratio of the electric field to magnetic field ($\delta E/\delta B$) is about 360 km/sec near the equatorial region of the plasmasphere. The velocity is much smaller than the Alfven velocity on the assumption that ion composition consists of only proton. The effective ion mass which is provided from this velocity of the fast mode HM wave is about 8.5 at the Akebono satellite position of the plasmasphere. This result leads us to conclude that there are abundantly heavy ions such as helium and oxygen ions in the plasmasphere.

One of the most important results of the present study is that the magnetospheric convection electric field seems to penetrate into the inner plasmasphere ($L = 2.5$) after the initial electric field impulse associated with SCs. As it has been shown in Fig. 6, the intensity of the Ey field gradually increases by 0.5–2.0 mV/m about 1–2 minutes after the onset of the initial electric field impulse. The duration of the convection electric field is about 10–30 minutes.

The long-term and continuous observation data of the Akebono satellite reveal a picture of the electric and magnetic field phenomena associated with SCs in the plasmasphere. To establish the further understanding of the plasmasphere, detailed observations including feature of high energy particles as well as thermal plasma are needed to explain the problems of the effective ion mass and penetrating convection electric field in the plasmasphere derived by the electric and magnetic field data of the Akebono satellite in the present study.

Acknowledgments. The Akebono satellite was established by the Institute of Space and Astronautical Science (ISAS). Authors thank Dr. Hayakawa, Dr. Matsuoka and Dr. Nagatsuma for providing science data set of EFD and MGF and valuable discussions. Authors used magnetic field data at Kakioka Magnetic Observatory and SYM indices obtained from WDC-C2 in Kyoto University. Present work is supported by the 21st century COE program "Advanced Science and Technology Center for the Dynamic Earth" at Tohoku University.

References

Araki, T., Global structure of geomagnetic sudden commencements, *Planet. Space Sci.*, **25**, 373–384, 1977.

Araki, T., A model of geomagnetic sudden commencement, Proc. of Symposium on Quantitative Modeling of Magnetosphere-Ionosphere Coupling Processes, 47–52, March, 1987.

Araki, T., *A Physical Model of the Geomagnetic Sudden Commencement,* AGU Geophys. Monogr., 81, pp. 183–200, 1994.

Cahill, L. J., N. G. Waite, M. J. Engebretson, and M. Sugiura, Toroidal standing waves excited by a storm sudden commencement: DE1 observations, *J. Geophys. Res.*, **95**, 7857–7867, 1990.

Chappell, C. R., K. K. Harris, and G. W. Sharp, A study of the influence of magnetic activity on the location of the plasmapause as measured by OGO 5, *J. Geophys. Res.*, **75**, 50–56, 1970.

Fujita, S., T. Tanaka, T. Kikuchi, K. Fujimoto, K. Hosokawa, and M. Itonaga, A numerical simulation of the geomagnetic sudden commencement: 1. Generation of the field-aligned current associated with the preliminary impulse, *J. Geophys. Res.*, **108**, 1416, doi:10.1029/2002JA009407, 2003.

Fukunishi, H., R. Fujii, S. Kokubun, K. Hayashi, T. Tohyama, Y. Tonegawa, S. Okano, M. Sugiura, K. Yumoto, I. Aoyama, T. Saito, T. Iijima, A. Nishida, and M. Natori, Magnetic field observations on the Akebono (EXOS-D) satellite, *J. Geomag. Geoelectr.*, **42**, 385–409, 1990.

Gail, W. B. and U. S. Inan, Characteristics of wave-particle interactions during sudden commencements 2. spacecraft observations., *J. Geophys. Res.*, **95**, 139–147, 1990.

Gail, W. B., U. S. Inan, R. A. Helliwell, D. L. Carpenter, S. Krishnaswamy, T. J. Rosenberg, and L. J. Lanzerotti, Characteristics of wave-particle interactions during sudden commencements 1. Ground based observations, *J. Geophys. Res.*, **95**, 119–137, 1990.

Harris, K. K., G. W. Sharp, and C. R. Chappell, Observation of the plasmapause from OGO 5, *J. Geophys. Res.*, **75**, 219–224, 1970.

Hayakawa, H., T. Okada, M. Ejiri, A. Kadokura, Y.-I. Kohno, K. Maezawa, S. Machida, A. Matsuoka, T. Mukai, M. Nakamura, A. Nishida, T. Obara, Y. Tanaka, F. S. Mozer, G. Haerendel, and K. Tsuruta, Electric field measurement on the Akebono (EXOS-D) satellite, *J. Geomag. Geoelectr.*, **42**, 371–385, 1990.

Hirasawa, T., Effects of magnetospheric compression and expansion on spectral structure of ULF emission, Mem. Natl. Inst. Polar Res., Spec. Issue Jpn., 18, 127–151, 1981.

Iyemori, T. and D. R. K. Rao, Decay of the dust field of geomagnetic disturbance after substorm onset and its implication to storm-substorm relation, *Ann. Geophys.*, **14**, 608–618, 1996.

Knott. K., A. Pedersen, and U. Wedeken, GEOS 2 electric field observation during a sudden commencement and subsequent substorm, *J. Geophys. Res.*, **90**, 1283–1288, 1985.

Kikuchi, T., Evidence of transmission of polar electric fields to the low latitude at times of geomagnetic sudden commencements, *J. Geophys. Res.*, **91**, 3101–3105, 1986.

Kokubun, S., Characteristics of storm sudden commencement at geostationary orbit, *J. Geophys. Res.*, **88**, 10025–10033, 1983.

Kuwashima, M. and H. Fukunishi, Local time asymmetries of the SSC-associated hydromagnetic variations at the geosynchronous altitude, *Planet. Space Sci.*, **33**, 711–720, 1985.

Laakso, H. and R. Schmidt, Pc 4-5 pulsation in the electric field at geostationary orbit (GEOS2) triggered by sudden storm commencements, *J. Geophys. Res.*, **94**, 6626–6632, 1989.

Ondoh, T., Magnetospheric sudden impulses, *J. Radio Res. Labs. Jpn.*, **17**, 199–213, 1968.

Osaki, H., K. Takahashi, H. Fukunishi, T. Nagatsuma, H. Oya, A. Matsuoka, and D. K. Milling, Pi2 pulsations observed from the Akebono satellite in the plasmasphere, *J. Geophys. Res.*, **103**, 17605–17615, 1998.

Oya, H., A. Morioka, K. Kobayashi, M. Iizima, T. Ono, H. Miyaoka, T. Okada, and T. Obara, Plasma wave observation and sounder experiments (PWS) using the Akebono (EXOS-D) satellite—Instrumentation and initial results including discovery of the high altitude equatorial plasma turbulence, *J. Geomag. Geoelectr.*, **42**, 411–422, 1990.

Patel, V. L. and P. J. Coleman, Jr., Sudden impulses in the magnetosphere, observed at synchronous orbit, *J. Geophys. Res.*, **84**, 7213–7222, 1970.

Schmidt, R. and A. Pedersen, Signature of storm sudden commencements in the electric field measured at geostationary orbits (GEOS-2), *Physica Scripta,* **491**, 1987.

Shinbori, A., T. Ono, and H. Oya, SC-triggered plasma waves observed by the Akebono satellite in the polar regions and inside the plasmasphere, *Adv. Polar Atmos. Res.*, **16**, 126–135, 2002.

Shinbori, A., T. Ono, M. Iizima, A. Kumamoto, and H. Oya, SC-related kilometric and hectometric radiations observed by the Akebono satellite in the polar regions, *Adv. Polar Atmos. Res.*, **17**, 60–76, 2003a.

Shinbori, A., T. Ono, M. Iizima, A. Kumamoto, and H. Oya, Sudden commencements related plasma waves observed by the Akebono satellite in the polar region and inside the plasmasphere region, *J. Geophys. Res.*, **108**, 1457, doi:10.1029/2003JA009964, 2003b.

Wilken, B., C. K. Goertz, D. N. Baker, P. R. Higbie, and T. A. Fritz, The SSC on July 29, 1977 and its propagation within the magnetosphere, *J. Geophys. Res.*, **87**, 5901–5910, 1982.

Wilson, G. R., W. J. Burke, N. C. Maynard, C. Y. Huang, and H. J. Singer, Global electrodynamics observed during the initial and main phase of the July 1991 magnetic storm, *J. Geophys. Res.*, **106**, 24517–24539, 2001.

Wygant, J., F. Mozer, M. Temerin, J. Blake, N. Maynard, H. Singer, and M. Smiddy, Large amplitude electric field and magnetic field signatures in the inner magnetosphere during injection of 15 MeV electron drift echoes, *Geophys. Res. Lett.*, **21**, 1739–1742, 1994.

A. Shinbori (e-mail: atsuki@stpp1.geophys.tohoku.ac.jp), T. Ono, M. Iizima, and A. Kumamoto