Nighttime enhancement of the amplitude of geomagnetic sudden commencements and its dependence on IMF-Bz

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We present a statistical study of the diurnal variation of the occurrence frequency of geomagnetic sudden commencements (SCs) observed at Kakioka (geomagnetic latitude, $\theta = 27.4^\circ$). SCs with an H-component amplitude (ΔH) larger than 40 nT occur more frequently in the nighttime than the daytime, while those with smaller amplitudes ($\Delta H < 39$ nT) occur more frequently in the daytime. Three large amplitude SCs ($\Delta H = 85$, 117 and 145 nT at Kakioka) were analyzed in detail. All three exhibited larger amplitudes during the nighttime at all low latitudes except those near the dayside equator. A statistical study reveals that the averaged amplitudes are slightly larger in the daytime at Alibag ($\theta = 10.2^\circ$) but considerably larger in the nighttime at three higher-latitude Japanese stations, Kanoya ($\theta = 21.9^\circ$), Kakioka and Memambetsu ($\theta = 35.4^\circ$). Case studies of two moderate amplitude SCs which occurred at the same UT indicate that nighttime SC amplitudes at low latitudes are slightly (considerably) larger than daytime amplitudes when the interplanetary magnetic field (IMF) points northward (southward). We suggest that the diurnal variation of SC amplitudes can be explained by a combination of field aligned and resultant ionospheric currents produced during the main impulse of SCs.

Key words: Geomagnetic sudden commencement, diurnal variation, amplitude, interplanetary magnetic field, field aligned current, ionospheric current.

1. Introduction

Although geomagnetic sudden commencements (SCs) are observed globally everywhere on the ground, the amplitude and waveform greatly change depending upon latitude and local time. This problem is fundamentally important in consideration of the mechanism of SCs and has attracted attention of many investigators. Early in 1950's Ferraro and Unthank (1951) reported that the averaged amplitude of 55 SCs and 46 SIs (sudden impulses) observed at five low- and mid-latitude stations show a maximum around midnight and a minimum near 7 hour local time. They also reported that the diurnal variation of Huancayo station near the dip equator is quite different from that at other low latitude stations. It showed a much enhanced peak amplitude near noon. This is now well understood as the equatorial enhancement of the SC amplitude.

Russell *et al.* (1992, 1994) studied 18 and 7 SCs in order to know the relationship between the amplitude of the SCs/SIs and the dynamic pressure jump of the interplanetary shock or discontinuity. In their study they reported that the amplitude is larger in the daytime for the northward IMF but it is reduced in the daytime and enhanced in the nighttime when the IMF is southward. This means that the larger amplitude of SCs in nighttime is one of characteristics of SCs during the southward IMF. On the other hand, Clauer *et al.* (2001) showed that an SC event with the largest amplitude in nighttime occurred during a strong northward turning of IMF. They analyzed this SC as an unexpected special event. They seemed to believe that normal SCs should show the larger amplitude in the daytime. Wilson *et al.* (2001) analyzed a peculiar SC event which is characterized by a reduction in the X-component at day side middle latitudes unlike on the night side where it manifested as a sharp positive enhancement of the X-component. At low latitudes, a step-like increase were observed both in the day and night sides, but its amplitude is higher on the night side. Sastri (2002) demonstrated that in the interval over which the X-component reduced at mid-latitudes on the day side, a large eastward electric field manifested at the pre-midnight dip equator.

Being stimulated by an anomalously large geomagnetic sudden commencement (SC) occurred on March 24, 1991 (Araki *et al.*, 1997), we catalogued large amplitude SCs observed at Kakioka for 71 years from 1924 to 1994 (Araki *et al.*, 1996). The list includes 140 SCs with the amplitude larger than 40 nT and the SC on March 24, 1991 was second largest. Looking at this list, we noticed that large amplitude SCs occur more frequently in the nighttime than the daytime and began to study the local time dependence of the SC amplitude observed at low and middle latitude stations. We surveyed previous works and learned there is considerable evidence which suggests nighttime enhancement of the

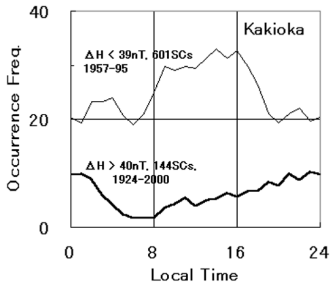

Fig. 1. Diurnal variation of occurrence frequency (3 hour running average) of SCs observed at Kakioka (geomagnetic latitude = 27.4°). Upper curve; for SCs with amplitude smaller than 39 nT. Lower curve; for SCs larger than 40 nT.

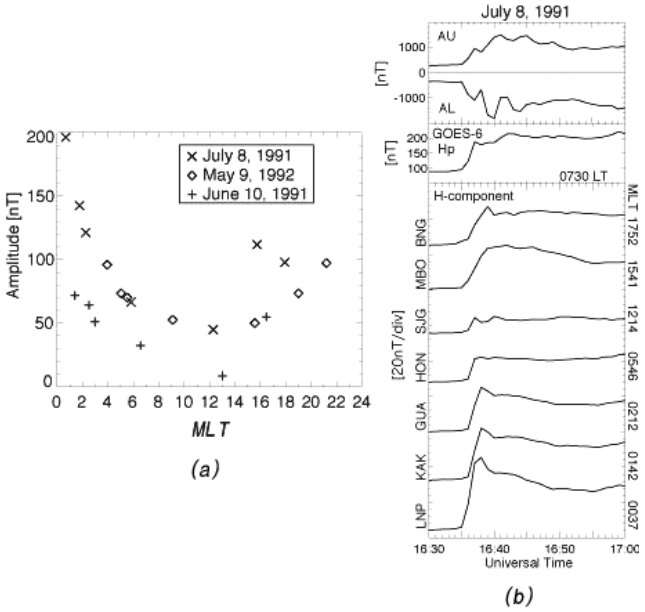

Fig. 2. (a) Diurnal variation of the amplitude of the 3 large amplitude SCs listed in Table 1. (b) Waveform of the largest SC on July 8, 1991. Upper panel; AU and AL indices, middle panel; Hp-component (parallel to the Earth's rotation axis) observed by the GOES-6 geo-synchronous satellite in the morning, lower panel; geomagnetic H-components at several low latitude stations.

SC amplitude as described above.

The disturbance field of SCs (Dsc) consists of two subfields, DL and DP. The DL-field dominates in low latitudes and is produced mainly by the magnetopause current enhancement associated with a sudden compression of the magnetosphere. It is slightly reduced by the tail current also enhanced during SCs. The DP-field is further decomposed into two parts, DPpi and DPmi, where pi and mi denote a preliminary impulse and a main impulse, respectively. Both DPpi and DPmi are produced by field aligned currents (FACs) and resultant ionospheric currents (ICs) of polar origin. The DP-field which is dominant in the polar region extend to lower latitudes and is significantly enhanced at the dayside dip equator where the strong equatorial enhancement occurs (Araki, 1977, 1994). This SC model is roughly consistent with the computer simulation by Fujita *et al.* (2003a, b).

Since the enhancement of the magnetopause current during SCs occurs mainly on the dayside magnetopause, the DL-field is expected to be larger in the daytime than the nighttime. The enhancement of the magnetotail current associated with SCs produces the negative H-component in low latitudes on the ground. It is largest near midnight and smallest near noon and so contributes to make the SC amplitude larger in the daytime. Actually the amplitude of SCs observed at geo-synchronous orbit (radial distance = 6.6 Re) shows the diurnal variation with a clear peak around noon (Kokubun, 1983; Kuwashima *et al.*, 1985). Shinbori *et al.* (2004) examined electric perturbations associated with SCs in the plasmasphere and reported that there is no significant LT dependence. Then a question arises; why can the SC amplitude be larger in nighttime in low and middle latitudes on the ground? Since the SC model above suggests that the FACs and ICs also produce significant geomagnetic fields on the ground, we have to check their roles.

As described above the LT dependence of the SC amplitude has been studied by statistical analyses using small number (less than several tens) of SCs in addition to a few case studies. It seems to be necessary to establish the more definite pattern of the diurnal variation by analyses on larger number of SCs. Based upon this established diurnal variation its IMF dependence should be investigated. In this paper we show results of the statistical analyses of the diurnal variation of the amplitude and occurrence frequency of SCs observed at low and middle latitude stations for several tens of years and then study its IMF-Bz dependence for specially selected SC events.

2. Data Analysis

Figure 1 shows the diurnal variation of the hourly occurrence frequency of SCs observed at Kakioka (geomagnetic latitude, $\theta = 27.4°$). The upper curve is for SCs with the H-component amplitude (ΔH) less than 39 nT and the lower curve is for SCs with ΔH larger than 40 nT. Four larger SCs are added to the catalog mentioned in the Introduction by extending the data period from 1994 to 2000. It is clearly seen that the large amplitude SCs occur more frequently in the nighttime while smaller SCs occur more frequently in the daytime.

As a case study we examined the amplitude of 3 SCs listed in Table 1. They are the second, third and fourth largest SCs to occur at Kakioka in the 11 years period from 1984 to 1994. The largest SC in this period was observed on March 24, 1991 as noted in the Introduction.

The peak amplitude of the 3 SCs at several low latitude stations is plotted versus local time in Fig. 2(a). Stations near the dip equator are not used because the SC amplitude is anomalously enhanced there as was mentioned in Introduction. We can confirm that the amplitude of all 3 large SCs is larger in the nighttime than in the daytime. No data was available for the afternoon of June 10, 1991 but the data points in the morning show a LT variation consistent with other two events. The AU and AL indices exhibited large disturbances before and after the 3 SCs suggesting the southward IMF.

Figure 2(b) shows the H-component variations of July 8, 1991 SC (largest among the 3 SCs under consideration) together with the AU and AL indices and the Hp-component

Table 1. Three large amplitude SCs analysed.

	Date	UT	ΔH (KAK): nT	rank in 1984–94
(1)	June 10, 1991	1716	85	4
(2)	July 8, 1991	1636	146	2
(3)	May 9, 1992	1958	117	3

Table 2. Stations, data period and number of SC for statistical analysis.

Station	Alibag	Kanoya	Kakioka	Memambetsu
Geomagnetic Latitude θ	10.2°	21.9°	27.4°	35.4°
Data period	1871–1967	1958–2003	1957–2003	1957–2003
Number of SC	2307	611	632	633

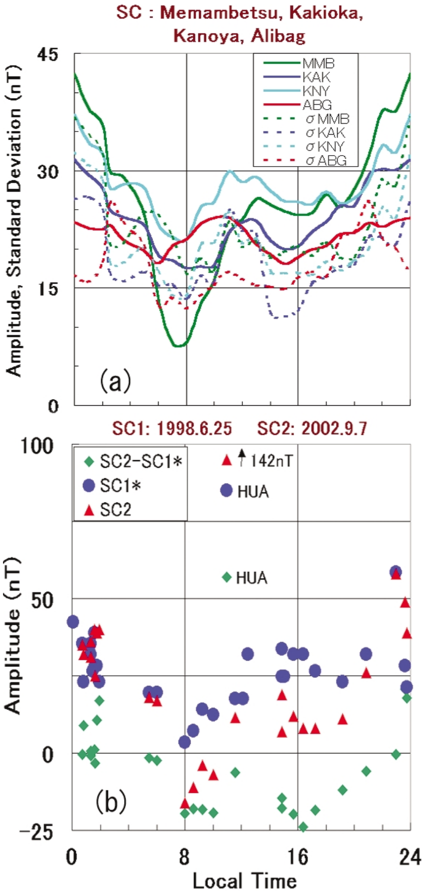

Fig. 3. (a) Diurnal variations of the averaged amplitude (solid line, 3 hour running average) of SCs observed at 4 stations in Table 2 and the standard deviations (dotted line). (b) Diurnal variations of the amplitude of the 2 SCs in Table 3 at low and middle latitude stations. The observed amplitude of SC1 is multiplied by a factor $1.77 = \Delta\sqrt{Pd}(SC2)/\Delta\sqrt{Pd}(SC1)$ to adjust the difference in the jumps of the solar wind dynamic pressure. Blue circles: adjusted amplitude of SC1, Red triangles: amplitude of SC2, Green square: difference in the two amplitude. HUA indicates Huancayo station near the dip equator.

(parallel to the rotational axis of the Earth) measured by the geo-synchronous satellite GOES-6. We can clearly see a nighttime enhancement of the SC amplitude. Also we note that the waveform is stepwise in daytime but the nighttime waveform seems to be superposed by an additional disturbance lasting about 20 min after the onset of the SC. Further a shorter impulsive enhancement for a few min seems to be superposed to form an overshoot at the post-midnight stations (LNP, GUA and KAK). The overshoot is not observed by GOES-6 in the morning. As mentioned above, the AU and AL indices show fairly large values.

Next we derived the diurnal variation of the hourly averaged ΔH of SCs observed for long periods at 4 stations indicated in Table 2. The list of SSCs prepared by Mayaud (1973) was used to pick up SCs at Alibag. The SSC lists for Kanoya, Kakioka and Memambetsu are provided by Kakioka Geomagnetic Observatory and SCs with amplitude larger than 5 nT are selected. The data period and total number of SCs analyzed are given also in Table 2.

The result is shown in Fig. 3(a) together with curves for the standard deviation. Since the SC amplitude is primarily determined by the dynamic pressure jump associated with the interplanetary shock or discontinuity, data points scatter much resulting the large standard deviation. From Fig. 3(a), we see that (a1) the diurnal variation shows two peaks around noon and midnight at all 4 stations, (a2) the noon peak is slightly larger than the nighttime peak at Alibag, (a3) the midnight peak is much larger than the noon peak at the three Japanese stations, (a4) the size of the diurnal variation is largest at the highest latitude station, Memambetsu, (a5) all 4 stations exhibit two minimums in the morning (6–8 h LT) and afternoon (15–17 h LT) and the morning minimum is much smaller than the afternoon minimum. (a6) the morning minimum is smallest at Memambetsu.

One of problems in previous case studies is that accurate separation of the LT and latitudinal dependence is difficult because of insufficient distribution of observatories. In order to improve this point here we analyze two SCs which occurred at almost the same UT and during different (positive and negative) IMF-Bz conditions. By choosing the same UT, we can compare the two SCs at each station which is at the same LT and same latitude.

We selected two SCs (SC1 and SC2) with moderate amplitude given in Table 3. Both SCs began at 1636 UT. We checked the solar wind parameters observed by the ACE, WIND and IMP-8 satellites for SC1 and ACE, WIND and Geotail for SC2. The three satellites show consistent solar wind variations for each SC. The IMF for both events was steady at least more than one hour in front of and behind the shock and clearly northward for SC1 and southward for

Table 3. Two SCs for detailed case study.

	Date	UT	ΔH (KAK): nT	IMF-Bz: nT	ΔPd: nPa
SC1	June 25, 1998	1636	19	northward (9→16)	2.8 (3.6→6.4)
SC2	Sept. 7, 2002	1636	33	southward (−6→−19)	3.5 (1.0→4.5)

Table 4. List of stations.

Stn	LT	Gm Lat	Stn	LT	Gm Lat	Stn	LT	Gm Lat	Stn	LT	Gm Lat	Stn	LT	Gm Lat
LNP	0.1	15.0	GUA	1.7	5.3	DLR	9.3	38.3	GUI	14.9	33.8	IRT	23.0	41.9
KNY	0.7	21.9	CTA	1.7	−28.0	BSL	10.0	40.1	ASC	15.0	−2.4	LRM	23.6	−32.4
KDU	0.8	−22.0	CNB	2.0	−42.7	HUA	11.0	−1.8	SPT	15.7	42.8	GNA	23.7	−41.9
HTY	1.3	24.2	HON	5.5	21.6	SJG	11.6	28.6	TAM	16.4	24.7			
KAK	1.3	27.4	PPT	6.0	−15.1	PST	12.1	−41.7	BNG	17.2	4.2			
CBI	1.5	18.3	FRN	8.0	43.5	KOU	12.5	11.9	TAN	19.2	−23.7			
MMB	1.6	35.4	TUC	8.6	39.9	MBO	14.9	20.1	ABG	20.9	10.2			

SC2. In order to measure the H-component amplitude of the SCs we used digital 1 min values from routine observatories (Table 4) collected by the WDC for Geomagnetism, Kyoto. The amplitude of both SCs was measured at 1641 UT when most of the stations manifested the peak values.

The difference in dynamic pressure jumps in the solar wind was adjusted by multiplying a factor $\Delta\sqrt{Pd}(\text{SC2})/\Delta\sqrt{Pd}(\text{SC1}) = 1.77$ to the amplitude of the SC1. Here $\Delta\sqrt{Pd}$ is the difference in the square-root of the dynamic pressure (Pd) in front of and behind the shock for each SCs. We denote SC1 with the multiplied amplitude by SC1* in this paper.

The anomalously large amplitudes of both SCs near 11 hour local time in Fig. 3(b) indicate the equatorial enhancement at Huancayo near the dip equator ($\theta = -1.8°$). We see that the equatorial enhancement rate is much larger for SC2 (southward IMF) than for SC1* (northward IMF). These anomalous data points are excluded in the consideration of the diurnal variations here.

From Fig. 3(b), we see the following characteristics of the diurnal variation of the amplitude of the two SCs; (b1) the amplitude of both SCs show similar diurnal variations with two peaks in the midnight and post noon, and two minimums in the morning (near 8 h LT) and afternoon (16–19 h LT), (b2) the nighttime peak is slightly larger than the daytime peak for SC1* (blue circles) and much larger for SC2 (red triangles), (b3) the daytime amplitude of SC2 is smaller than that of SC1*, and (b4) the morning minimum of SC2 is also smaller than that of SC1* and take negative values.

In Fig. 3(b) we also plotted the difference in the amplitudes of SC1* and SC2. Since available stations are slightly different for each SC, only stations where the data are available for both SCs were used to derive the difference. We again see that (c1) the daytime amplitude of SC1* is larger than that of SC2, and (c2) the midnight amplitude is lager for SC2 than for SC1*.

3. Discussion

According to Russell *et al.* (1992, 1994) the SC amplitude takes the largest values around noon during the northward IMF and near midnight during the southward IMF. Clauer *et al.* (2001) reported an SC event with the largest amplitude in nighttime which occurred during a northward IMF turning. They treated the SC as a very special and unexpected event.

The statistical analysis shown in Fig. 3(a), however, suggests that the amplitude of most of SCs should be largest at midnight at Japanese 3 stations. The case studies shown in Figs. 2 and 3(b) support this suggestion. Figure 3(b) (blue circles for SC1) shows that the SC amplitude is slightly larger in the nighttime than in the daytime even during the northward IMF. Shimbori *et al.* (private communication) also showed evidence to support this tendency by a different statistical analysis. We need more studies for the northward IMF but presently we consider that nighttime enhancement of the SC amplitude is one of general characteristics of the whole SCs. It occurs during both northward and southward IMF but is enhanced with increasing southward IMF.

Although the disturbance field of SCs in low (except the day side dip equator) and middle latitudes is dominated by the DL sub-field which is mainly caused by the magnetopause and tail currents, it might be modified by the following field aligned currents (FACs) and resultant ionospheric currents (ICs).

(1) When the IMF is southward, a substorm may be triggered by an SC (Kokubun *et al.*, 1977). The positive bay or wedge current system (McPherron *et al.*, 1973) in the night side can produce a positive H-component on the night side ground. This night side wedge current system produces a negative H-component in the dayside.

(2) The negative bay of the SC triggered sub-storm reduces the H-component in the dayside.

(3) A pair of FACs responsible for the DPmi flow into the polar ionosphere in the dawn side and goes out from the dusk side (Araki, 1994). The disturbance field due to the FACs (denoted DPmi(FAC) here) produces a negative and a positive H-component in the dayside and nightside, respectively.

(4) The FACs responsible for DPmi(FAC) induce twin vortex type ICs which, in turn, produce the disturbance field DPmi(IC).

Russell *et al.* (1994) used the current system (1) and (2) in addition to the H-component reduction due to the enhanced region-1 currents in the dayside in order to interpret the nighttime enhancement and daytime reduction of the SC amplitude for the southward IMF. Clauer *et al.* (2001) proposed the enhanced region-1 current connected with the NBZ current system to explain the nighttime SC enhancement during the northward IMF turning.

The SC triggered sub-storm is said to occur a few minutes after the onset of SC (Iyemori, 1980; Iyemori and Tsunomura, 1983). This delay is necessary for an SC to propagate tailward and for the triggered substorm to propagate back to the earth. Both SCs considered here begin at 1636 UT and take the peak value at 1641 at most of the stations. The peak time of the two SCs under consideration is almost the same. Further, triggered sub-storms, even if it could affect the SC amplitude, can explain the night time enhancement of the SC only for southward IMF. We have to find other mechanisms for nighttime enhancement during the northward IMF.

The disturbance field DPmi (FAC) is produced by a dawn to dusk electric field due to the enhanced convection in the magnetosphere compressed during SCs (Araki, 1994). It exists always during SCs for both northward and southward IMF. When the IMF is southward, an enhanced dawn-to-dusk electric field just after the interplanetary shock or discontinuity is transmitted directly to the polar ionosphere. The dawn-to-dusk electric field is enhanced by both the enhanced magnetospheric convection and direct transmission of the electric field in the solar wind.

The afternoon side vortex of the ionospheric currents for DPmi(IC) extends to the dayside dip equator to cause the equatorial enhancement as calculated by Tsunomura and Araki (1984). The larger rate of the equatorial enhancement for the southward IMF shown in Fig. 3(b) suggests that a larger dawn-to-dusk electric field is impressed on the polar cap. Larger horizontal scale of the impressed electric field on the expanded polar cap during the southward IMF may also contribute to the larger enhancement rate at the dip equator.

Based upon the physical model described in the Introduction, Osada (1992) calculated the contributions of the FAC and IC to DPpi and DPmi separately by assuming a pair of field aligned current sources on a thin shell spherical ionosphere with a realistic distribution of the electrical conductivities. The FAC for DPmi flows into the ionosphere at 9 h LT and 75° geomagnetic latitude with intensity of 10^6 Ampere and goes out at 15 h MLT of the same latitude. He calculated the DPmi(FAC) and DPmi(IC) every 4 hours local time and every 15° geomagnetic latitude. We here measured the H-component amplitude of the DPmi(FAC) and DPmi(IC) at 30° geomagnetic latitude from Fig. 6 of his paper and plotted it in Fig. 4.

The H-component of the DPmi(FAC) is negative in the dayside and positive in the night side reflecting the effect of the assumed FACs symmetric to the noon-midnight plane. The DPmi(IC) in low and middle latitudes is positive in a wide local time range except the early morning hours. This is caused by the larger afternoon current vortex producing positive H-component in low and middle latitudes. We see that the negative DPmi(FAC) and positive DPmi(IC) cancel each other on the dayside but positively strengthen each other at nighttime. The resultant DPmi field is much enhanced on the night side.

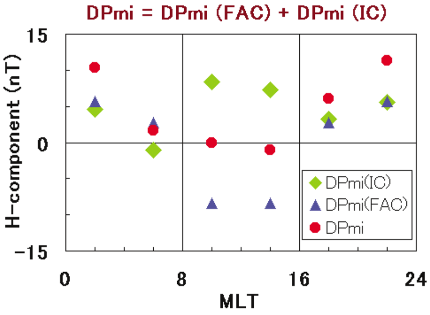

Fig. 4. The LT dependence of the H-component of the DPmi(FAC) and DPmi(IC) and Dpmi = Dpmi(FAC) + Dpmi(IC) at 30° geomagnetic latitude which were measured from figure 6 of Osada (1992).

The H-component of the total DPmi field in Fig. 4 is almost zero or slightly negative in the daytime. It can be more negative if the DPmi(FAC) is relatively stronger than DPmi(IC). Wilson *et al.* (2001) reported an SC event characterized by a negative H-component deviation at a dayside mid-latitude station (Fredericksburg). This suggests a stronger DPmi(FAC) effect. Sastri (2002) showed evidence of an eastward ionospheric electric field at the midnight equator associated with this SC. It is consistent with positive H-component contribution to DPmi(IC) at mid-night shown in Fig. 4.

Kikuchi *et al.* (2001) calculated the geomagnetic field of the DPpi(IC) and DPpi(FAC) to interpret preliminary positive impulses (PPIs) (Kikuchi and Araki, 1985) observed in the daytime at mid-latitude stations. In this calculation seasonally asymmetrical ionospheric conductivities were introduced and the FAC flows into the dusk side polar ionosphere and goes out from the dawn side. The resultant field of DPpi(IC) and DPpi(FAC) for the summer season at -35° latitude shows the largest negative peak at midnight, a secondary negative peak around noon, the largest positive peak at 7–8 h LT, and a secondary positive peak in the afternoon. If the sense of the variation is reversed, the curve is very much similar to the diurnal variation of the SC amplitude at Japanese 3 stations shown in Fig. 3(a).

The combination of the DPmi(IC) and DPmi(FAC), therefore, seems to explain well the diurnal variation of the SC amplitude analyzed here. The delay of the peak time does not occur contrary to the case of the current wedge model for the substorm. If the FAC for the DPmi has a transient impulsive time variation in its beginning part, it will be enhanced in the night side and reduced in the dayside, because the time variation of the DPmi(FAC) and DPmi(IC) are in phase on the night side and out of phase on the dayside. This is consistent with the time variations of the SCs in Fig. 2(b) which show a stepwise waveform at the dayside stations and an additional pulse in the night side stations. Now we have to recognize clearly that the disturbance field of SCs is determined by a combination of the ionospheric and field aligned currents in addition to the magnetopause and tail current even in low and middle latitudes.

The DPmi field enhances the SC amplitude more in the night side than the day side as described above. Consequently larger amplitude SC occur more frequently in the nighttime and the frequency of smaller amplitude SCs relatively increases in the daytime as shown in Fig. 1.

Since the observed waveform of SCs is a superposition of the DL and DP sub-fields, the peak amplitude does not necessarily occur simultaneously even if each sub-field takes its peak simultaneously. For example, time of the peak amplitude at the dayside dip equator, sometimes, delays 1–2 min from other low latitude stations. This suggests enhancement of the DP-field at the dayside dip equator to produce the equatorial enhancement. Here we compared the simultaneous (at 1641 UT) amplitude of the two SCs instead of the peak amplitude at each station.

By choosing two SCs which occurred at the same UT and in the different IMF conditions, we could study the IMF dependence of the SC amplitude at each station (at the same latitude) for the same local time. This procedure should be utilized further to many pairs of SCs which occur at other UTs.

4. Summary

(1) We found that large amplitude SCs (the H-component amplitude (ΔH) larger than 40 nT) occur more frequently in the nighttime than the daytime at Kakioka (geomagnetic latitude, $\theta = 27.4°$). while smaller amplitude SCs ($\Delta H <$ 39 nT) occur more frequently in the daytime.

(2) Three large amplitude SCs ($\Delta H = 85$, 117 and 145 nT at Kakioka) showed the largest amplitude near midnight in low latitudes except the dayside equator.

(3) The diurnal variation of the averaged amplitude of SCs showed that the averaged amplitude is slightly larger in the daytime at Alibag ($\theta = 10.2°$) than the nighttime but much larger in the nighttime at Kanoya ($\theta = 21.9°$), Kakioka and Memambetsu ($\theta = 35.4°$).

(4) Two moderate amplitude SCs which occurred at the same UT and in different (positive and negative) IMF-Bz conditions showed that the SC amplitude in low and middle latitudes is larger at nighttime than daytime during the northward IMF and it is much larger during the southward IMF event.

(5) From the items (1)–(4) above we conclude that the largest amplitude in nighttime is one of fundamental properties of SCs observed in low (except the equator) and middle latitudes.

(6) The diurnal variation of the SC amplitude analyzed here can be explained by geomagnetic effects of field aligned currents and resultant ionospheric currents responsible for the polar originating part of the disturbance field of the main impulse of SCs.

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References

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

Araki, T., A physical model of geomagnetic sudden commencement, *Geophysical Monograph*, **81**, 183–200, 1994.

Araki, T., M. Emoto, K. Yumoto, K. Shiokawa, D. Orr, D. K. Milling, and H. Luehr, Large amplitude geomagnetic sudden commencements, Proc. Solar Terrestrial Predictions Workshop, January 23–27, Hitachi, 1996.

Araki, T., S. Fujitani, M. Emoto, K. Yumoto, K. Shiokawa, T. Ichinose, H. Luehr, D. Orr, D. Milling, H. Singer, G. Rostoker, S. Tsunomura, Y. Yamada, and C. F. Liu, Anomalous sudden commencement on March 24, 1991, *J. Geophys. Res.*, **102**(A7), 14075–14086, 1997.

Clauer, C. R., I. I. Alexeev, E. S. Belenkaya, and J. B. Baker, Special features of the September 24–27, 1998 storm during high solar wind dynamic pressure and northward interplanetary magnetic field, *J. Geophys. Res.*, **106**, 25,695–25,771, 2001.

Ferraro, V. C. A. and H. W. Unthank, Sudden commencements and sudden impulses in geomagnetism: their diurnal variation in amplitude, *Geofisica pure e appl.*, **20**, 2730, 1951.

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**(A12), 1416, doi:10.1029/2002JA009407, 2003a.

Fujita, S., T. Tanaka, T. Kikuchi, K. Fujimoto, and M. Itonaga, A numerical simulation of the geomagnetic sudden commencement: 2. Plasma process in the main impulse, *J. Geophys. Res.*, **108**(A12), 1417, doi:10.1029/2002JA009763, 2003b.

Iyemori, T., Time delay of the substorm onset from the IMF southward turning, *J. Geomag. Geoelectr.*, **32**, 267–273, 1980.

Iyemori, T. and S. Tsunomura, Characteristics of the association between an SC and a substorm onset, *Mem. Nat. Inst. Polar Res.*, Spec Issue, Jpn, 26, 139–148, 1983.

Kikuchi, T. and T. Araki, Prelminary positive impulse of geomagnetic sudden commencement observed at dayside middle and low latitudes, *J. Geophys. Res.*, **90**, 12195–12200, 1985.

Kikuchi, T., S. Tsunomura, K. Hashimoto, and K. Nozaki, Field-alinged current effects on midlatitude geomagnetic sudden commencements, *J. Geophys. Res.*, **106**, 15555–15565, 2001.

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

Kokubun, S., R. L. McPherron, and C. T. Russell, Triggering of substorms by solar wind discontinuities, *J. Geophys. Res.*, **82**, 74–86, 1977.

Kuwashima, M., S. Tsunomura, and H. Fukunishi, SSC associated magnetic variations at the geosynchronous altitude, *J. Atmos. Terr. Phys.*, **47**, 451–461, 1985.

Mayaud, P. N., Hundred years geomagnetic data, 1868–1967, IAGA Bulletin, No. 33, 1973.

McPherron, R. L., C. T. Russell, and M. P. Aubry, Satellite studies of magnetospheric substorms on August 15, 1968: Phenomenological model for substorms, *J. Geophys. Res.*, **78**, 3131, 1973.

Osada, S., Numerical calculation of the geomagnetic sudden commencement, Master thesis, Department of Geophysics, Faculty of Science, Kyoto University, 1992.

Russell, C. T., M. Ginsky, S. Petrinec, and G. Le, The effect of solar wind dynamic pressure changes on low and mid-latitude magnetic records, *Geophys. Res. Lett.*, **19**, 1227–1230, 1992.

Russell, C. T., M. Ginskey *et al.*, Sudden impulses at low latitude stations: Steady state response for southward interplanetary magnetic field, *J. Geophys. Res.*, **99**, 13403–13408, 1994.

Sastri, J. H., Penetration electric fields at the nightside dip equator associated with the main impulse of the storm sudden commencement of 8 July, 1991, *J. Geophys. Res.*, **107**(A12), 1448, doi:10,1029/2002JA009453, 2002.

Shinbori, A., T. Ono, M. Iizima, and A. Kumamoto, SC related electric and magnetic field phenomena observed by the Akebono satellites inside the plasmasphere, *Earth Planets Space*, **56**, 269–282, 2004.

Tsunomura, S. and T. Araki, Numerical analysis of equatorial enhancement of geomagnetic sudden commencement, *Planet. Space Sci.*, **32**, 599–604, 1984.

Wilson, G. R., W. J. Burke, N. C. Maynard, C. Y. Huang, and H. J. Singer, Global electrodynamics observed during the initial and main phases of the July 1991 magnetic storm, *J. Geophys. Res.*, **106**, 24,517–24,539, 2001.

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