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Historically largest geomagnetic sudden commencement (SC) since 1868

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Abstract

Being stimulated by the previously reported large amplitude (202 nT at Kakioka) geomagnetic sudden commencement (SC) on 24 March 1991, we searched larger amplitude SCs in the past. We tried to collect old magnetograms and used the list of SC observed at Kakioka (27.5° gm.lat.) for the period 1924 to 2013 and Colaba (10.5°)-Alibag (10.3°) for 1868 to 1967. We found that the largest amplitude SC occurred on 24 March (the same day as 1991 SC), 1940. The H-component amplitude is larger than 273 nT at Kakioka and 310 nT at Alibag. We could also obtain the copy of the magnetogram of Cape Town (−33.3°) which shows 164 nT amplitude. The statistical analysis shows that the occurrence rate of SCs is less than 5% for amplitude larger than 50 nT and less than 1% for amplitude larger than 100 nT at both Kakioka and Alibag. Large amplitude SCs tend to occur during the declining phase of the solar activity. Finally, we discussed the possible increase of the dynamic pressure associated with the interplanetary shock causing the largest SC.

Keywords: Geomagnetic sudden commencement (SC); Solar activity; Largest SC; Interplanetary shock

Introduction

An anomalous geomagnetic sudden commencement (SC) occurred at 03:41 UT on 24 March 1991. It was characterized by a large and short duration (1 to 2 min) magnetic pulse in the very initial stage of the SC which propagated from the day side to the night side (Araki et al. 1997). The H-component amplitude and rise time were measured as 202 nT and 28 s, respectively, by 1-s sampled values of Kakioka (27.5° gm. lat.) near 12-h LT. Since SCs with amplitude larger than 100 nT is rare (less than 1% as shown later) at Kakioka and the rise time is mostly 3 to 4 min (Maeda et al. 1962), the amplitude of this pulse is anomalously large and the rise time is anomalously short. One-minute routine geomagnetic observations could not resolve accurately such a rapid variation.

It was the largest in the list of the SSC (storm sudden commencement) after IGY (1957 to 1958) prepared by Kakioka observatory. In the separate list of the SI (sudden impulse) which is also provided by Kakioka, there was a larger SI with 220 nT amplitude that occurred on 13 November 1960. The 24 March 1991 SC, therefore, is the second largest among SSCs and SIs observed at Kakioka after IGY. The term SC used here includes both SSC and SI.

The CRRES satellite observed this anomalous SC at 2.6 Re geocentric distance and 2.5-h LT near the equatorial plane (Blake et al. 1992, and Wygant et al. 1994). It detected a large magnetic pulse of about 130 nT amplitude and an associated bipolar electric pulse of the peak-to-peak amplitude of about 80 mV/m. It also observed a drift echo event of high-energy charged particles which were locally accelerated and appeared periodically with the drift period. This means instantaneous formation of the inner radiation belt. The high-energy electron data of EXOS-D (Akebono) satellite indicated that this radiation belt lasted more than 1 year (Yukimatsu et al. 1994).

The source of this SC is presumed to be a solar flare which occurred at 22:47 UT on 22 March 1991 (Blake et al. 1992). The flare effect was transmitted to the earth in about 29 h.

A computer simulation by Li et al. (1993) shows that a propagating electromagnetic pulse due to a sudden magnetospheric compression at 15-h LT accelerated magnetospheric charged particles to form the inner radiation belt. Although it is interesting to see the corresponding solar wind variations near earth, no data were available in the interplanetary space. Ulysses detected large disturbances

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of the coronal mass ejection at 2.5 AU from the sun and 60° east of Earth in ecliptic longitude (Phillips et al. 1992), but it was difficult to find the variation corresponding to the 24 March storm at Earth.

This SC provided a rare chance to study the particle acceleration mechanism due to sudden magnetospheric compressions and the theoretical analyses have been continued afterward (e.g., Gannon et al. 2005). The high time variation rate of this SC is interesting also as a space weather event. Large amplitude SCs are also important to study the possible maximum limit of the interplanetary shock strength.

From these points of view, it is worth studying that larger amplitude SCs occurred in the past. Here, we report the results of our survey of the largest amplitude SC since 1868.

Data analysis

Being stimulated by the 24 March 1991 SC described above, we surveyed all normal-run magnetograms accumulated at Kakioka observatory for the period 1924 to 1957 and found the largest amplitude SC which occurred on 24 March (the same day as the 1991 SC) 1940. Kakioka reported that the amplitude was larger than 273 nT. We could also obtain the magnetogram copy of the day at Alibag (10.3° gm. lat.) which shows the similar time variation with Kakioka. The amplitude was registered as 310 nT.

Microfilm copies of old magnetograms before IGY (1957 to 1958) had been collected by National Geophysical Data Center (NGDC), NOAA, Boulder but once they were sent to the Denver Office of National Archive and Record Agency (NARA), and they were totally lost there accidentally. It was a great loss in geomagnetism. It becomes difficult to study old geomagnetic events.

We asked copies of the original magnetograms to the WDC for Geomagnetism, in Copenhagen, Edinburgh, and Kyoto, and Institut de Physique du Globe de Paris. Although we could obtain data of several stations, most of them were not clear to identify the SC because it occurred during a severe geomagnetic storm triggered by a preceding SC. A few printed magnetograms were available, however, in published data books (stored in NGDC) of Cape Town (−33.3° gm. lat.), Greenwich (53.3°), and Niemeg (51.7°). The record of Cape Town was clear, showing the time variation similar to that of Kakioka and Alibag.

The magnetograms of Kakioka, Alibag, and Cape Town are shown in Figure 1. The record of Cape Town seems to be manually traced and deformed when it was copied from the data book and so the accurate measurement of the amplitude was difficult. Noisy dark spots were deleted from all magnetograms.

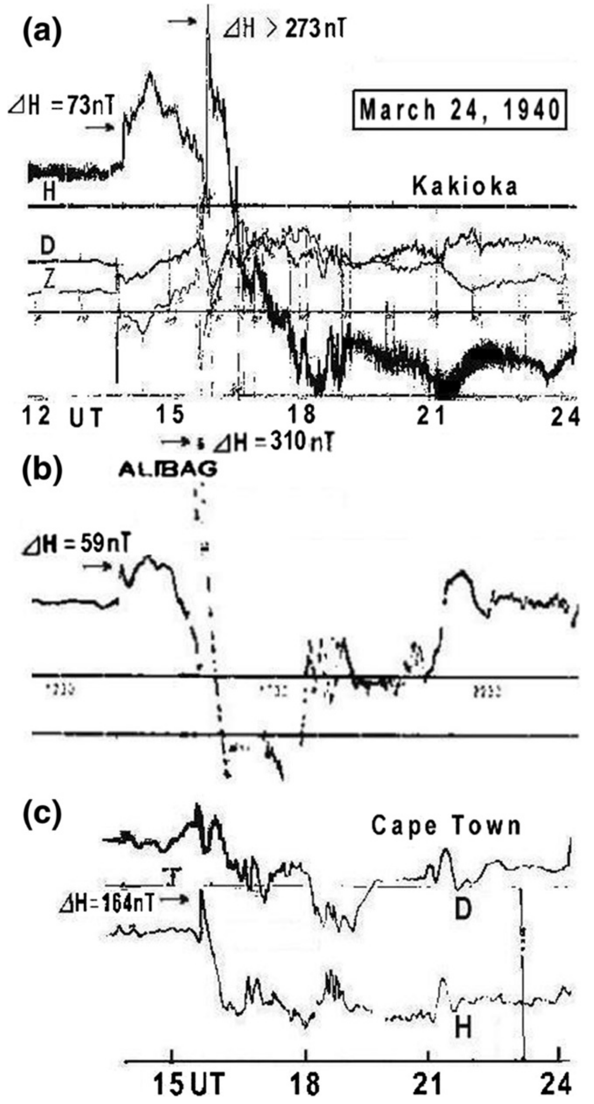

Figure 1 Geomagnetic records of 24 March 1940 SC event. (a) Kakioka (gm. lat. = 27.5°), **(b)** Alibag (10.3°), **(c)** Cape Town (−33.3°).

In Figure 1, two successive SCs occurred around 13:48 UT and 15:38 UT on 24 March 1940. The H-component amplitude of the first SC was 73 nT and 59 nT at Kakioka and Alibag, respectively. The onset of the SC was not clear at Cape Town. A typical magnetic storm developed after the first SC. The initial phase lasted for about 1 h and then the second SC with larger amplitude occurred during the beginning part of the main phase. The amplitude of the second SC was 310 nT at Alibag and larger than 273 nT at Kakioka as mentioned above. We measured 164 nT amplitude from the magnetogram copy of Cape Town.

The H-component of all three stations rapidly decreases after the second SC. It suggests that the IMF was strongly southward when the second SC occurred and the ring current development was accelerated after the second SC. It is faster in the afternoon side (Alibag and Cape Town) than the night side (Kakioka). The geomagnetic field was highly disturbed during the main phase after the SC and severe space weather events occurred which disturbed telegraph communication lines. LIFE Magazine (1940) reported 'Spots on the face of the sun mess up Earth's communications'. This storm was described as one of the largest geomagnetic storms since 1859 (Cliver and Svalgaard 2004).

It is said that a large solar flare of importance occurred around 11:30 UT on 23 March 1940 (Newton 1940). If this is the source of the geomagnetic storm under consideration, the time for transit to the earth is about 28 h. It is very near to the transit time, 29 h for the 24 March 1991 SC.

Now, Kakioka observatory provides the list of SSC (including SI after IGY) for the period from 1924 to the present but it does not include the second SC because SCs occurring during preceding magnetic storms are registered as SI according to the rule of Kakioka. The amplitude (>273 nT) of the second SC was found in the list of the principal magnetic storm prepared separately by Kakioka observatory.

Mayaud (1973) compiled a list of SSC for 100 years after 1868. He classified geomagnetic stations into two groups, Tropical stations and North-South stations. The main station of the former is Colaba-Alibag, India, and Batavia (−16.1° gm. lat.), Indonesia and nearby stations are used as the secondary stations. The geomagnetic observation at Colaba (10.5°) in the south part of Bombay (present Mumbai) city moved to the outskirts, Alibag, in the beginning of the twentieth century when the electric railway was constructed in Bombay. European stations in the geomagnetic latitude range of 49° to 53°, Kew, Saint-Mauer, Val Joyeux, and Chambon-la Foret, were used for the North stations and Melbourne and Toolangi were used for South primary stations. Christchurch, Amberly, and Watherroo were the secondary South stations. The geomagnetic latitude of these South stations is between −40° and −46°. The list shows the amplitude of SCs at Tropical station (AT) and North-South station (ANS) but there is no AT data for 1868 to 1870. The two SSC lists described above register 1,805 SCs at Kakioka for 1924 to 2013 and 2,307 SCs at Colaba-Alibag for 1871 to 1967, respectively.

The annual variations of the 3-year running averages of the occurrence frequency and amplitude of SCs are shown together with the averaged sunspot number (SSN) in Figure 2. The upper left panel (a) is for Colaba-Alibag and the lower right panel (b) is for Kakioka. Large SCs with amplitude larger than 100 nT are also plotted by blue triangles. Number of these large SCs was 18 and 19 for Colaba-Alibag and for Kakioka, respectively.

Figure 2 shows that the SC of 24 March 1940 is the largest at both Colaba-Alibag and Kakioka. There is the second largest SC in the plot for Colaba-Alibag which occurred on 7 July 1928. The amplitude AT is 308 nT but ANS is 235 nT which is much smaller than 1,161 nT for 24 March 1940 SC. Also, the corresponding amplitude at Kakioka is only 8 nT. We consider, therefore, that 7 July 1928 event is not so large on a global scale but is locally enhanced near Alibag. The third and fourth

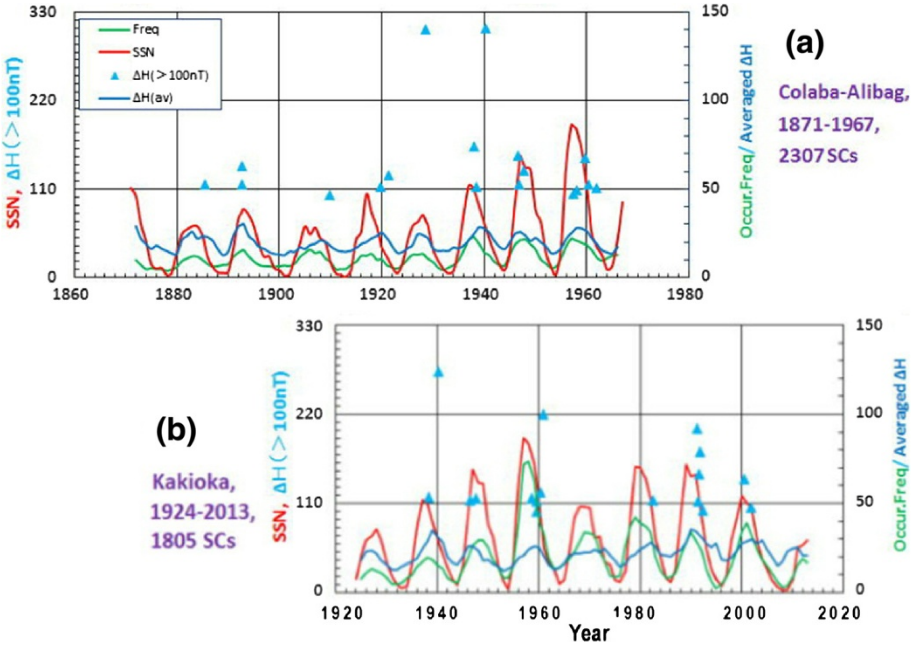

Figure 2 Annual variation of the averaged occurrence frequency, amplitude of SCs and sun spot number. (a) Colaba-Alibag, **(b)** Kakioka. Blue triangles indicate amplitude of SCs larger than 100 nT.

largest SC in the Mayaud list occurred on 16 January 1938 and 26 July 1946 with the amplitude [AT, ANS] = [163, 129] and [151, 100] nT, respectively. The ANS amplitude, 1,161 nT, of the 1940 SC is the largest ANS among all 2,307 SCs in the list. This amplitude is extremely large compared with the SCs below the second rank. The second and third largest ANS are 249 nT (9 September 1909) and 246 nT (22 September 1946), respectively.

The Mayaud list did not give the AT values at all for the period 1868 to 1870 when the amplitude ANS were given to 86 SCs. Also, there is no AT value of 18 SCs out of 75 SCs registered by ANS for 1871 and 1872. The ANS of the total of 104 (=86 + 18) SCs with no AT data, however, is less than 89 nT and then we presume that SCs with AT larger than 100 nT did not occur in the period 1868 to 1872. The AT values of 29 SCs are taken from Batavia but the maximum is 61 nT. On the basis of these considerations, we concluded that the SC on 24 March 1940 is largest since 1868.

From Figure 2, we can also see that large amplitude SCs tend to occur in the maximum or declining phase of the sunspot cycle. This tendency is similar to the annual variation of large magnetic storms. Mayaud (1975) analyzed yearly variations of the amplitude and occurrence frequency of SC but he did not pay special attention to large amplitude SCs.

Watari (2012, private communication) defined the normalized sunspot phase (NSSP) where the period of each sunspot cycle is normalized to 11 years. The phase of the maximum sunspot number is 4.3 year which was determined as the statistical average. Figure 3 shows the NSSP dependence of the amplitude of SCs larger than 50 nT at Kakioka. From this figure, we can say that SCs with amplitude larger than 100 nT occur during the SSN phase 3 to 7. The three SCs larger than 150 nT were observed in the declining phase 6 to 7.

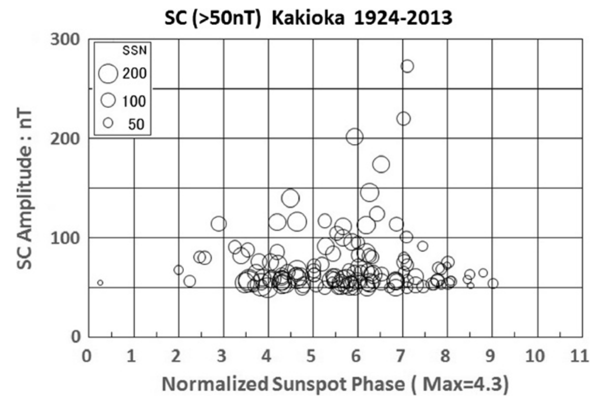

Figure 3 Amplitude of SC larger than 50 nT at Kakioka versus the normalized sunspot phase (NSSP). The size of the circle of the data point is proportional to the sunspot number.

In Figure 4, the occurrence frequency of the SC amplitude is plotted in each 10 nT bin together with the cumulative percentage. The open red diamonds indicate occurrence of only one SC in a 10 nT bin. Figure 4 tells us that the SC amplitude is mostly 10 to 30 nT at both Kakioka and Colaba-Alibag. The ratio of SCs with amplitude larger than 50 nT is 4.6% at Kakioka and 4.7% at Colaba-Alibag. The percentage of SCs larger than 100 nT is less than 1% at both stations. We can recognize again that the amplitude of 24 March 1940 SC was extremely large.

Discussions

Siscoe et al. (1968) assumed a linear relationship, $\Delta H = C \Delta(Pd^{0.5})$ between the SC amplitude (ΔH) and the jump of the square root of the solar wind dynamic pressure (Pd), and determined experimentally the linear coefficient, C. After them, several values have been proposed for C which are summarized in Araki et al. (1993). The coefficient actually given by $C = \alpha kf$ where α denotes effects of the electric currents induced in the earth, k indicates direct Pd effects, and f is determined by the manner of interaction between the solar wind and the magnetosphere (usually taken as 1). Usually, α is taken as 1.5 which means that the SC amplitude is enhanced 1.5 times on the ground by the induced earth currents. We assume here that $C = 15\ nT/(nPa)^{0.5}$ as the most appropriate value. If 2 nPa is taken as the initial Pd, the SC amplitude 300 nT needs increase of Pd to 457 nPa. Figure 5 shows the calculated relationship between the solar wind density (N) and velocity (V)

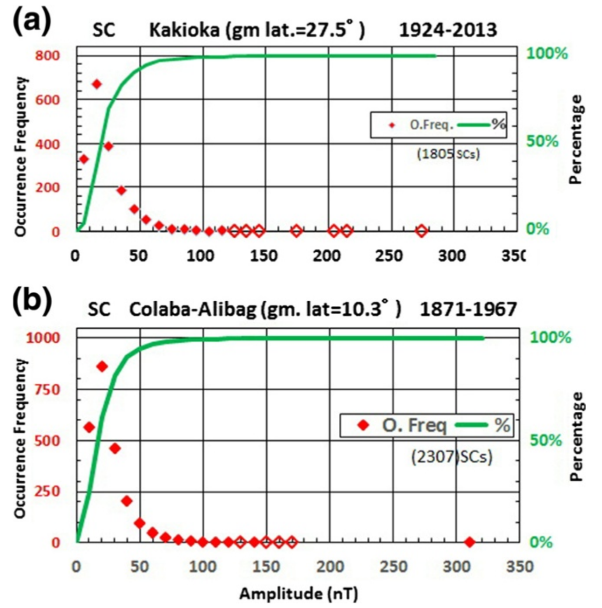

Figure 4 Occurrence frequency of SC amplitude in each 10 nT bin and the cumulative percentage. (a) Colaba-Alibag, **(b)** Kakioka.

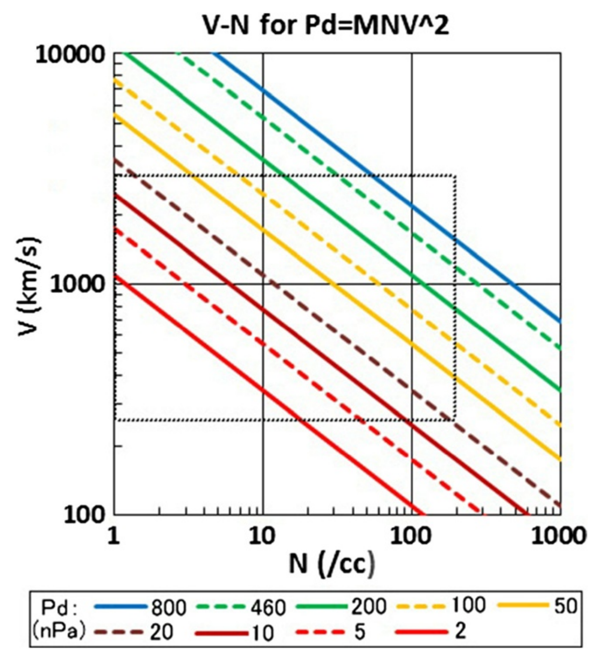

Figure 5 Relationship of N and V of the solar wind for constant Pd = MNV^2. The dotted rectangle indicates a region of (N, V) which might be actually observed.

for several values of *Pd = MNV^2* where *M* is the mass of positive ions of the solar wind.

Siscoe et al. (1968) assumed existence of 4% helium ions in the solar wind which leads to the equivalent mass, *M = 1.16 Mp* where Mp is the proton mass. They also converted the observed upstream dynamic pressure to that at the stagnation point of the magnetopause multiplying the coefficient $[(\gamma + 1)/2]$^$[(\gamma + 1/(\gamma - 1)]$ (γ)^$[-\gamma/(\gamma + 1)]$ where γ is the ratio of the specific heat. The coefficient is 0.881 for $\gamma = 5/3$ and the final expression for the dynamic pressure becomes *Pd = 1.02 MpNVs^2.* Here, we use the simple expression, *Pd = MpNVs^2.* Numerically it is almost same as the expression of Siscoe et al (1968).

The dotted rectangle in Figure 5 indicates an area bounded by *N = 200/cc*, *V = 250 km/s*, and *3,000 km/s*. The values, 200/cc and 3,000 km/s, are assumed as the possible maximum values for *N* and *V*, respectively (Cliver et al. 1990; Tsurutani et al. 2003; Russell et al. 2013).

Table 1 indicates sets of (*N*, *V*) which give 460 nPa (green dashed line in Figure 5). We consider that (*N*, *V*) = (*50/cc*, *2,348 km/s*) and (*100/cc*, *1,660 km/s*) for *Pd = 460 nPa* can be accepted as possible extreme cases.

Table 1 Solar wind density (N) and velocity (V) which give the dynamic pressure Pd = 460 nPa

N (/cc)	10	50	100	200	300
V (km/s)	5,250	2,348	1,660	1,173	958

If the non-linear effect is taken into account, however, the Pd jump larger than what is required from the linear relationship above will be needed. On the other hand, the effect of the current induced in the earth might require a smaller Pd jump because larger amplitude SCs have higher time variation rate (Araki et al. 2004) and so the coefficient α for the induction effect might be larger than the usual value 1.5. Takeuchi et al. (2002) showed the relationship between the SC rise time and solar wind parameters. It is difficult to judge which of these two competing processes is dominant but we consider that the estimation above for the Pd jump could be accepted as the first-order approximation.

Although the amplitude of SCs shows a clear dependence on local time and latitude (Araki et al. 2006, 2009; Shinbori et al. 2009), the previous papers did not pay attention to it in the selection of SC events to calculate the coefficient C. We need to check this point for more detailed analysis.

Competing interests

The authors declare that they have no competing interests.

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