Evolution of the concept of Sudden Storm Commencements and their operative identification

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In this paper, we review the evolution of both, the concept and the operative methods of detection of Storm Commencements (SC's) and we introduce suggestions for future improvements. Finally, a more precise definition of the events with consequences in terminology and detection is proposed.
Key words: SC, SSC, Sudden, Storm, Commencement, geomagnetic, detection, definition, terminology.

1. Introduction

After continuous records of magnetic variations became available, abrupt enhancements were sometimes observed at the beginning of episodes of magnetic activity. These events were originally classified as part of the disturbance and only noted as the beginning of the storm period. Only in later works, were these impulses studied separately and named "sudden storm commencements" (SSCs). However, some authors had the intuition that storminess, although very often being concurrent, was not constitutive of the SSC phenomena and used the term sudden commencement(s) (SC(s)) to name them, consequently emphasising that the suddenness in the change was the main substantial characteristic. Throughout history both names have been used.

Detection and classification of SSC events evolved with the concurrent efforts of the observers (including instrumentation advancements) and the modellers. The observers provided lists of events to the modellers. As the knowledge of the physical mechanisms which produced the SCs grew the criteria to detect and classify events refined, and the new lists of events provided by the observers influenced the theoretical studies based on these data so both the detection and the modelling advanced side by side.

The increasing interest in the study of these events can be traced through the publications that concentrate on the establishment of several committees by the International Association of Geomagnetism and Aeronomy (IAGA) to this aim and finally ending with the creation of the International Service of Rapid Magnetic Variations (SRMV) to which the elaboration of official lists of events and promoting the knowledge of them was commissioned (Curto *et al.*, 2007).

The development of satellite observations revealed that a sudden increase of dynamic pressure associated with the interplanetary shock or discontinuity is the origin of SCs. It also revealed that magnetic storms generally occur when the interplanetary magnetic field (IMF) is southward (negative B_z). Since an interplanetary shock or discontinuity is frequently accompanied by a southward pointing IMF it therefore follows that the incidence of SCs and geomagnetic storms occurring together will also be frequent. The availability of comprehensive models which are able to explain geomagnetic storms and SCs main morphological features can be considered milestones.

The term Sudden Impulse (SI) is used for a sudden H-component increase without a following magnetic storm. SIs, were first regarded as magnetic disturbances with a different nature from SSCs. However, SIs have been proved to be caused by the same physical mechanisms as SSCs (dynamic pressure increase) and should be classified complementary to SSCs.

2. Observational Aspects of SSC

2.1 Morphology

Generally the magnetic signature of an SSC on magnetograms resembles what is known to mathematicians as a step function. However, the amplitude of such a variation and the particular shape of the variation depend on the location (local time and latitude) of each magnetic observatory. Specifically, peaks (negative or positive) may appear before the leading edge of the perturbation at mid latitudes, but a definite two pulse structure dominates over the step wise variation at high latitudes (Araki, 1994).

Moreover, many other magnetic variations with morphology similar to an SC occur very often and can mislead the observers. There are many variations of the geomagnetic field (sudden changes with increments and decrements of the horizontal component simultaneous in the world) which are not directly related to SSC and SI (20% of every 1 hour period and 90% of all days near sunspot maximum) (Nishida and Jacobs, 1962).

Romañà, head of the SRMV for many years, insisted on the importance of a clear definition of the morphology of the reported phenomena to avoid the risk of making statistics inhomogeneous, and as a consequence, not very useful. To illustrate the basic traces, he chose paradigmatic cases and produced an *Atlas of rapid magnetic variations* (Romañà, 1959) which was designed to guide observers in their task of detection.

2.2 SSC definition

Given the variety of interpretations of an SSC, Romañà considered it necessary to provide a clear definition of an SSC commensurate to the level of knowledge at that time. After the Brussels IAGA Meeting (1955), he sent a circular to all collaborating observatories, with new instructions on the phenomena to be reported. **SSC** (and **SSC***) phenomena were defined as a sudden impulse followed by increased activity with storm characteristics for a sufficiently long period of storminess. **SSC*** is preceded by a sudden movement contrary to the principal (regardless of the direction of the principle). In the Madrid IAGA Assembly (1969) the minimum duration of the storm was assessed in the sense: "**SSC** [sic] are considered the sudden commencements followed by a magnetic storm or by an increase of activity lasting at least one hour".

Later, Mayaud (1973) presented a list of 100 years of SSC events selected with a different criterion from that normally used until then. The main difference had to do with the change of the concept of magnetic activity following the sudden impulse. According to the author, the key to determine the existence of a SSC was the "change of rhythm" of the magnetic activity after the sudden impulse. That would show the increasing of this activity, independently of its amplitude. The definition was adopted during the IUGG General Assembly of Grenoble (1975). However, this definition, still now in use, is vague and potentially misleading. As claimed by Cardús in several communications to IAGA meetings, the ambiguity of the SSC denomination has its origin in the actual rules for their classification. Moreover, a lot of people involved in magnetic storm studies use these lists to identify storms but some of these events—now so called SSC—only have a weak associated disturbance.

At the IAGA Toulouse Assembly (2005), Curto proposed a change in the classification following the terminology used in many works (Joselyn and Tsurutani, 1990). According to this system, the sudden increase of the magnetic field should be designed by the general term SC, which can be named as SSC if it is followed by a magnetic storm or as a SI if it is not. Now it is widely recognized that SC (SSC and SI) are produced by a sudden increase of the solar wind dynamic pressure and that magnetic storms after SCs are caused by the high possibility of the southward interplanetary magnetic field in either the turbulent sheath fields behind the shock, in the smooth magnetic cloud fields behind the sheath, or in both (Tsurutani *et al.*, 1988). The two phenomena, SCs and magnetic storms, have different physical mechanisms and one can happen without the other. Although the scientific foundation of the proposal was generally accepted, it was decided to postpone the proposal to the next IAGA General Assembly held in Perugia (2007) where it was voted upon and definitely accepted.

2.3 Lists

The availability of lists of classified events were necessary to undertake studies on this subject. Former studies started with particular lists elaborated with their own criteria: Moos (1910) at Bombay, with data of the period 1846–1905; Rodés (1932), with 213 cases at Ebro; McNish (1934), with 151 cases at Watheroo; and Newton (1948), with 681 cases at Greenwich. Newton (1948) missed the identification of many events, especially in the morning hours, because he used only a collection of subauroral observatories and ignored determinations from low-latitude observatories. Watson and McIntosh (1950) elaborated a list of 340 sudden commencements observed at Lerwick to find proportions of SC with a preliminary positive impulse, Sc(+), and SC with a primary double peak impulse, first negative and then positive, Sc(−+).

These lists were used to undertake several studies of frequency occurrence. Thus Rodés (1932) examined: a) the secular variation finding an eleven year period supporting the existence of a relationship between solar activity and the frequency of SCs; b) the annual variation, finding a two equinoctial maxima coinciding with the highest heliocentrical latitude of the Earth; and c) the diurnal variation with a minimum around 0800 (local time) LT and a maximum at 2100 LT. McNish (1934) confirmed Rodés results and found a seasonal variation which was reversed in the northern and southern hemispheres. The presence of a preliminary impulse subject to a diurnal effect was found by Newton (1948). In his study, inverted SCs were dominant around diurnal minimum in the H-component of the magnetic field (0800–0900 LT).

Later, amplitude studies followed. Ferraro and Unthank (1951) found that the greatest amplitudes occurred near 0000 LT, after which there was a fall to the minimum at about 0700 LT. SC and SI did not differ greatly in their behaviours. Sugiura (1953) found that there exists a solar diurnal variation in the SC during sunlit hours at Huancayo, located near the geomagnetic equator.

Meanwhile, studies on the recurrence of magnetic storms (Chapman, 1918a); on equivalent electrical currents during storms (Vestine, 1940); and on morphological aspects of storms (Sugiura and Chapman, 1960) improved the definition of a geomagnetic storm: a key aspect of the SSC classification. Again, each author used their own original list of events. These lists did not pretended to be exhaustive but the criteria for determining an SC event was determined by the authors and was therefore different for each study.

Ferraro *et al*. (1951) analyzed each magnetogram for the years 1926–1946 from the observatories; Cheltenham, Tucson, San Juan, Honolulu, Huancayo and Watheroo. They introduced the criterion of not including any sudden change in their list of SSC or SI unless it was shown by at least one observatory in two magnetic elements.

Mayaud (1973) set up a new list of SSC for the period 1868–1967 in accordance with his new definition (Section 2.2) which was complemented later by Mayaud and Romañà (1977) for the year 1969–1975. The data given in these SSC lists were: the hour of occurrence and the mean value of the duration and amplitude recorded by five low latitude but not equatorial observatories.

Since 1976, the SSC determination has been made by the Service of Rapid Variations, hosted at the Observatorio del Ebro, and is published regularly in the IAGA Bulletin no. 32 series by the International Service of Geomagnetic

Indices. A copy of them can be found in a digital form at (http://isgi.cetp.ipsl.fr/). The current list of global SSC events is a homogeneous compilation covering more than 120 years. The list does not indicate the type of SSC because this is location dependent, therefore the term SSC* is reserved for individual observatory lists.

2.4 Time determination and simultaneity

The temporal location of an event is necessary for predictability and modelling. Hence the starting time of an event is an important parameter. For SSC, the onset was taken at the point where a dramatic change in the slope occurred. The accuracy in this parameter depends on the sharpness of the discontinuity but also on the accuracy of the time signals in observatories and development of the recorders. Former magnetic recorders were driven by clockwork and time signals were originated by separate mechanical (in some cases wind-up) clocks. Thus, the degree of simultaneity between the different observatories was a major concern in the early stages of recording.

In the first Assembly after the creation of IAGA (Rome Assembly 1922), Rodés, at that time Director of the Ebro Observatory, introduced the problem of the non-simultaneity of the sudden storm commencements and presented a theory to explain this fact (Rodés, 1922; Bauer, 1923). The question of the simultaneity, or the propagation of the SSC, was still a debated issue, in part because of the difficulty to obtain accurate time reference in the data with the available instruments.

In 1924, Bauer proposed to organize the International Committee on SC in the Division of Terrestrial Magnetism and Electricity (STME), of the International Union of Geodesy and Geophysics, IUGG, and recommended Tanakadate as the chairman of the committee who, with time, became an important promoter of SC studies.

At the Assembly of Lisbon (1933), Tanakadate, using records made with rapid run magnetographs at Kakioka and Kanoya, selected three well-marked SSC events in the H-component that had been carefully measured. He compared the result with similar measurements on records of other far away observatories, and found only a few seconds of difference (Tanakadate, 1934). He deduced that the same event was registered almost simultaneously at all stations with characteristics dependent upon the local time. In the same report, he mentioned the difficulty of defining the exact initial point of the SSC, a problem not totally solved yet. The slow temporal development in the recorders (typically 2 cm per hour) reduced the precision of the determinations.

In 1937, Rodés sent a report to the President of the IAGA Committee on Sudden Commencements about the research on simultaneity or non-simultaneity of storm sudden commencements. He deduced that the highest temporal accuracy that can be obtained with the magnetometers in use was of the same order as the time differences of arrival of the perturbation to the different observatories. He therefore urged the observers to take great care to keep the exact time in the record time marks and in the measurements.

The Second Polar Year (1932/33) and the International Geophysical Year (IGY) (1957) produced a general improvement in timing and recording. Rapid run magnetographs (19 cm per hour) produced by LaCour gained popularity and allowed greater precision in time determination.

During the IGY, some observatories started the use of WWV signals (a shortwave radio broadcast disseminating beeps in phase with seconds of universal time) to synchronise timing. During the General Assembly of Berkeley (1963), Romañà considered time accuracy one of the major problems related to SSC determination and pointed out the necessity of observatories equipped with modern instrumentation to measure the SSC times accurately.

With the generalisation of digital equipment, sampling rate was what conditioned the accuracy in time determination. Menvielle (1996), using statistics of mean average duration, amplitude and rate of field variation of SSCs, showed the influence of sampling rate on the accuracy of these parameters describing the sudden commencements in analog and digital data. In digital data, a one second sampling rate is necessary to get the same accuracy as analog data.

2.5 Notation

Notation is another important point in the process of standardisation of SCs.

In older studies (Chapman, 1918b; Rodés, 1922) there was no special nomenclature to refer to these events. E.g., in the Colaba list of magnetic storms (Banerji, 1926) there were only additional notes with the comment "Commencement sudden" when it was appropriate.

Later, Chree (1925) used the nomenclature S.C.s to name them in the paper: "Sudden Commencements (S.C.s) of magnetic storms: Observation and theory".

In the IAGA Assembly of Edinburgh (1936) it was proposed a code-system of 5-number groups for broadcasting gradual commencements and sudden commencements of magnetic storms be used.

Howe (1939) found SCs not followed by storms and Ferraro *et al.* (1951) distinguished between sudden commencements of magnetic storms (SCs) and sudden impulses (SIs) in his notation. After an IATME recommendation, the acronyms s.s.c. and s.i. were used by Yamaguchi (1958).

Matsushita (1957) proposed a type of notation (Sc, $^{-}$Sc, Sc^{-}) where the sign on the left indicates a negative impulse preceding the main impulse and on the right indicates a sudden increase followed by a decrease lasting some minutes. Following this kind of classification and using data from the IGY he studied the complexity of the local variations of the horizontal components (Matsushita, 1960, 1962). He found their local time and latitudinal distribution: Sc^{-} dominated morning hours at high latitudes, $^{-}$Sc dominated afternoon hours at high latitudes and Sc were present at any hour of the day at mid and low latitudes.

Following this, Akasofu and Chapman (1959) proposed a new type of notation according to the sign and order of the sudden changes in H variations (Sc(+), Sc(−+), Sc(+−), Sc(−), Sc(++)) to replace the current notation in use then (SSC, SSC*, reversed SSC, reversed SSC*). With the nomenclature Sc, (++) will apply to two successive increases of H. They, quoted Yamaguchi (1958), stating that most Si events were followed by a storm time variation Dst, though its range was much less than the usual storms. Although they proposed the above change in the nomenclature, in the discussion, Dr. Bartels, in the name of Committee 10 on Rapid Magnetic Variations and Earth Currents, chose not to adopt the proposed change and continued with the classical SSC denomination. However, the two nomenclatures are used today. We wish to end this discrepancy.

A new list of 100 years of SSC was presented by Mayaud (1973) which was accepted by IAGA as the official list. Although he did not change the wording, he represented events not included previously in the concept, such as sudden commencements not followed by a magnetic storm but for a slight or moderate increase of magnetic activity.

From 1976 onwards, the SSC lists, elaborated by the Service of Rapid Variations which is hosted at the Observatorio del Ebro, follow the recommendations of Mayaud adopted by IAGA.

The interest of continuing the cataloguing of SCs has been explicit in several IAGA resolutions: Madrid (1969), Grenoble (1975) and Upsala (1997) and, of course, by the researchers who appreciate this job and value these lists as the starting point of studies oriented to understanding the response of the magnetosphere and ionosphere to the impact of interplanetary shocks (Joselyn and Tsurutani, 1990).

2.6 Collaborating observatories and its distribution

As the appearance of SSC events depends on the observatory location on the Earth the distribution of the observatories collaborating in the identification tasks has been fundamental in ensuring the completeness of the lists. The uneven distribution of magnetic observatories around the world has made difficult the study of phenomena such as magnetic storms and other world-wide effects like SC. This topic was discussed at the General Assembly of Stockholm (1930). During the General Assembly of Berkeley (1963), Romañà, acting as a coordinator, pointed out the necessity of sorting a series of observatories latitudinal and longitudinally well distributed, and equipped with state of the art instrumentation.

Since the beginning, the SRMV used the general network of collaborating observatories which after inspection of their records produces a list of candidate SSCs. The norms decided at the IAGA Madrid Assembly (1969) were introduced in Bulletin 32a. Since then, the SSCs and SIs were only considered if the number of the reporting stations was high enough: Only cases reported by a minimum of 10 stations were considered. However, the required number of stations varied in regions where there existed a low density of stations. After Mayaud's (1975) proposal, the SRMV uses additionally the records of five low latitude, not equatorial observatories, evenly distributed around the globe to determine the true SSC from the list of possible SSC and to measure their parameters. At these latitudes the auroral and equatorial electrojet disturbances are eliminated. The selected low-latitude observatories are MB (Mbour), FQ (Fuquene), HO (Honolulu), PM (Port Moresby), and AL (Alibag), and as supplementary: TA (Tamanraset), PA (Paramaribo), AP (Apia), KY (Kanoya), and HY (Hyderabad).

The method used to detect rapid magnetic variations in the observatories is based on visual inspection of each magnetogram. It is time consuming. This fact has caused a progressive diminution in the number of reporting observatories. This compromises the coverage of the wide areas in the world and the completeness of the lists. With the decrease of collaborating observatories, in the General Assembly of Seattle (1977), the Working Group V-6 insisted in the necessity that as many observatories as possible report to Ebro Observatory on possible detected SSC events, to help better the selection of the SSC events to be published in Bulletin no. 32.

To prevent this lack of information, since the year 2000, the SRMV takes advantage of the new facilities in data access provided by the INTERMAGNET network and a modification was introduced on the procedure of data treatment. Data from non collaborating observatories is consulted directly by the Service. However, a lot of work falls on the Service. A complementary solution is foreseen in the utilization of new semi-automatic methods. In this line, Curto presented in the General Assembly of Boulder (1995) a system for automatic detection of SSC based on evaluating algorithms of magnetic fluctuation levels. In the General Assembly of Sapporo (2003), the same author presented the actual strategies for the SSC detection, comparing the traditional and the actual methods and showed a prospective for the future. And in the General Assembly of Toulouse (2005), he also presented the progress in methods applied to automatic detection of SSC and the convenience of using solar wind data as a complement for the observation of magnetic variations. The need for an automatic detection of SSC in real time to alert forecasters and costumers of potential geomagnetic storm conditions was treated by Joselyn (1985). More recently, the same need for mid-term forecasting of magnetic storms has been pointed out by some authors such as Khabarova *et al.* (2006) who used a moving gradient of the SYM-H index as a detecting algorithm.

3. Concept of SSC

3.1 First studies on SSC

It is said that von Humboldt (1769–1859) first used the term "magnetic storm" for severe geomagnetic disturbances and suggested the global occurrence of magnetic storms (Tsurutani *et al.*, 1997; Schlegel, 2005). However, Tsurutani *et al.* (2006a) have shown that, most probably, von Humboldt's observed auroras and magnetic needle oscillations, that originated the term "magnetic storm", were not associated with a magnetic storm, but with a High-Intensity, Long-Duration, Continuous AE Activity, or HILDCAA event. It was Gauss (1777–1855) who organized the Gottingen Union to promote geomagnetic observations which were going to give a global view of the Earth magnetic phenomena (Stern, 2002).

Continuous accurate observations of the Sun and Earth phenomena promoted the connection between solar activity and geomagnetic variations. In 1852 Sabine (Director of the British Colonial Observatories) found a certain correlation between sunspot numbers and the number and size of magnetic disturbances in the period 1843–1848 (Cliver, 1994). In 1859, Carrington presented his results on the comparison of the observation of the first reported solar flare (seen with the naked eye) with the magnetic records of Kew Observatory. He found a definite but short-lived magnetic disturbance at the time of the flare while a great geomagnetic storm began about 18 hours later. It was the most intense magnetic storm in recorded history, as recently shown by

Tsurutani *et al.* (2003) with a thorough analysis of the storm itself, and of the predictability of similar or greater intensity events.

Ellis, in 1880, using Wolf's sunspot numbers and the daily range of magnetic variation observed at Greenwich, found that solar and geomagnetic activity occurred approximately in phase. These and other works in the same vein showed that at the beginning of the 1890's, the relationship between the solar and magnetic disturbances was almost universally accepted (Meadows, 1970 as cited by Cliver, 1994). But only almost, in 1892 Lord Kelvin (1892) theorised that the amount of energy needed by the Sun as whole, radiating in all directions through space, to produce a magnetic storm was too large to produce a magnetic storm on the Earth, he therefore deduced that there was no connection between magnetic storms and any kind of dynamical action area on the Sun. He recommended pursuing the idea of the relationship between magnetic storms and aurora and Earth currents in future research to find the origin of the magnetic storms. In the same Journal, Ellis (1892) studied 17 storm sudden commencements in 9 observatories well distributed around the world. He also studied the relationship between magnetic variations and Earth currents during storms and suggested that both kinds of variations were caused by an external agent, possibly the Sun.

Adams (1892) showed that the different phases of the magnetic storms take place at different stations at the same instant of time. Although the electromagnetic wave was theoretically predicted by Maxwell in 1869 and proved by laboratory experiments of Hertz in 1888, it was not understood as a physical reality connected with SCs. Thus it seems that global simultaneous SC occurrence was not yet proved at that time and volcanic eruptions as a possible cause was discussed (Bauer, 1910). Only later would simultaneous occurrences of geomagnetic sudden commencements (SCs) around the world within several minutes be widely recognized.

Maunder (1906), observing the recurrences of magnetic storms at intervals equal to the synodic rotation period of the Sun, deduced that magnetic storms should be occasioned by some solar agent which was not radiated but transmitted along narrow, well-defined streams, issuing from a "restricted area" and rotating with the same period as the Sun. At present we know that recurrent solar wind streams cause magnetic storms with totally different characteristics than those by flares/ICMs (Tsurutani *et al.*, 2006b). These ideas were not known then and these findings constituted a great advance with respect to the idea of the whole sun radiating in all directions.

Schuster (1911) evaluated the necessary energy of a swarm of electrified particles, coming from the Sun, to produce a magnetic storm, and deduced that this production is only possible indirectly, by increasing the ionization of the outer regions of the atmosphere. Bauer (1910) deduced that small magnetic storms propagated over the Earth more often eastward and completed the circuit of the Earth in about 3–4 minutes. For bigger and more complex magnetic disturbances the velocity of propagation might be cut down considerably. Several authors opposed these results and the theory behind. Chapman (1918a) opposed Bauer's method and sustained Maunder's view on the origin of the magnetic storms. He showed that the time of commencement of a magnetic storm at different stations depended mainly on their orientation relative to the Sun. In a posterior paper, Chapman (1918b) gave an outline of the way he understood the origin and evolution of the magnetic storms. He considered that they were caused by a stream of charged particles, mainly or entirely of the same sign, coming from the Sun. Lindemann (1919) showed that Chapman's theory of magnetic storm was untenable, and suggested that the storms are produced by a neutral stream of electric particles of different signs.

The magnetic storm model of Chapman and Ferraro (1931, 1932, 1933) assumed Lindemann's hypothesis that the corpuscular flux emitted from the Sun (now termed solar wind) constituted a neutral stream of electric particles of different signs. This stream collides with the geomagnetic field and forms a magnetic cavity and electric currents flowing on the surface of the cavity causes SCs. This is essentially the same as the present theory of formation of the magnetosphere and the magnetopause current by the solar wind. It is amazing that they could propose such a theory which is very consistent with present in situ observations only from the few ground observations at that time. In two subsequent papers, Chapman and Ferraro (1940) and Ferraro (1951), clarified the difficulty of the penetration of the electrons, until the distance of a few Earth radii, into the Earth's magnetic field to produce the SC. When Chapman and Ferraro proposed their SC production model, the space at the distance where the original currents were produced was considered empty, so the electromagnetic field changes were propagated with the speed of light "in vacuo" towards the Earth's surface, until the ionosphere was reached. After the knowledge of the presence of ionized gas out to distances of a few earth radii, Hines (1957) and Hines and Storey (1958) gave arguments in favour of the transmission of the magnetic changes from the solar stream to the Earth's surface by hydromagnetic waves, a view soon adopted by the other scientists in the field such as Dessler and Parker (1959), Piddington (1959), Francis *et al.* (1959), Green *et al.* (1959), etc.

3.2 Morphological studies on SC and hypothesis on their nature

Since the SCs are global geophysical phenomena which can be clearly detected everywhere on the Earth, studies of SCs have attracted many scientists. For example, global simultaneity of the SC occurrence, described earlier, has been a long standing unsolved problem. Several papers were written on this topic by using high time resolution data from rapid-run magnetographs installed during the IGY period (1957–1958) (Gerald, 1959; Williams, 1960; Yamamoto and Maeda, 1960; Nishida and Jacobs, 1962) but the results of the analyses diverged greatly. Another important characteristic of SCs is the strong enhancement of the amplitude of the main impulse (MI) of SCs in the dayside equator (Sugiura, 1953). It suggests importance of the role of the Cowling conductivity (Hirono, 1952).

The preliminary reverse impulse (PRI) which appears in the very initial stage of SCs was also puzzling. Nagata and Abe (1955) showed a twin vortex equivalent current system for PRI. Matsushita (1962) reported that the PRI statistically appears in the afternoon side at high latitudes and the dayside equator. Sano (1962) showed, also statistically, that the PRI appears dominantly at high latitude in the afternoon whereas in the morning side at high latitudes the preliminary positive impulse (PPI) appears. Rastogi and Sastri (1974) showed that the equatorial enhancement rate is larger for PRIs than for MIs.

Maeda *et al.* (1964) proposed that a seasonal dependence of the SSC field should exist due to the geometrical relation between the incident direction of the solar wind and the direction of the geomagnetic dipole axis. Fukushima (1966) discussed seasonal and local time dependence of the D-component SC at Kakioka.

Burlaga and Ogilvie (1969) concluded that SSCs and SIs are essentially the same and both can be caused either by shocks or tangential discontinuities. The same idea was proposed by Nishida (1978).

With his list of 100 years, Mayaud (1975) performed statistical studies of SSC occurrence for different parts of the world: subauroral and low-latitude observatories. He found that yearly numbers of SSCs are much better correlated with yearly averages of sunspot numbers than with yearly averages of the magnetic activity. He didn't find a daily or semi-annual variation of occurrences. He detected two components in the SSC: one appearing at low latitude (already reported by Maeda *et al.*, 1964) not very sensitive to any modulation by the Earth movement around the Sun, and the other superposed on the preceding one, being originated in high latitudes with a very large annual variation. This effect was described by Obayashi and Jacobs (1957) as related to the flow of ionospheric vortices and changes in the electric conductivity.

Simon and Legrand (1989) and Legrand and Simon (1989, 1991) identified four different signatures in the geomagnetic activity using long geomagnetic data series (SSC among them) to study the long term behaviour of the Sun as a major contribution to Solar-Terrestrial physics. Simon *et al.* (1995) reviewed the above results.

Sastri *et al.* (2006) analyzed the appearance of the two basic forms of SCs in the dayside dip equatorial region. SC(+) related with negative IMF B_z and SC(−, +) related with positive IMF B_z. In the equatorial stations, they found that the average value of the amplitude of the positive main impulse (MI) of SC* is higher than that of the conventional SC(+).

Wilson and Sugiura (1961) and Tamao (1964) wrote papers which hypothesised about physical mechanisms of SCs. The former showed elliptical polarization of the horizontal vector of SCs as evidence of hydromagnetic waves in the magnetosphere. The latter proposed that the high latitude PRI is caused by twin vortex ionospheric currents produced by transverse hydromagnetic (HM) waves incident to the polar ionosphere. This transverse HM wave is converted from the wave front of the compressional HM wave propagating earthward in the dayside magnetosphere.

3.3 Physical models

3.3.1 Construction of model The papers referred to above provided important key parts which should be assembled into a physical model. But until the 1970s, the way to assemble them into a unified physical model had not been known. The first step to construct a physical model of the SC is to interpret the separate appearance of PRIs in the dayside equator and the high latitude afternoon (Matsushita, 1962). The equatorial dayside PRIs could occur almost with or without a relationship with the high latitude PRIs. Araki (1977) checked the one-to-one correspondence of the PRIs in the two regions and found that the PRIs occur simultaneously in high latitudes and the dayside equator with a similar waveform. Then global distribution of the SC waveform was checked and the following characteristics were found for the H-component variation; (1) the waveform of SCs is step-function like in low latitudes except the dayside equator, (2) it consists of two pulses in auroral latitudes; a positive pulse followed by a negative pulse in the morning side and a negative pulse followed by a positive pulse in the afternoon side, (3) the two pulse structure with a smaller amplitude is superposed on a step-function like increase in the middle latitudes, (4) the waveform at the dayside equator resembles that in the high latitude afternoon (Araki, 1994). Any SC models to be proposed must explain the fundamental characteristics of SCs summarized here.

Araki (1977, 1994) proposed to interpret SCs by superposition of a step-function like variation dominant in low latitudes and a two pulse structure dominant in high latitudes. The former was denoted the DL-field and the latter the DP-field. The DP-field is further decomposed into the DPpi- and DPmi-fields where pi and mi denote a preliminary impulse and a main impulse, respectively. Thus the disturbance field of SCs is expressed as

$$\mathrm{Dsc} = \mathrm{DL} + \mathrm{DP} = \mathrm{DL} + \mathrm{DPpi} + \mathrm{DPmi}.$$

Although the decomposition above seems to be rather arbitrary and intuitive, it would be meaningful if an appropriate physical mechanism could be found for each subfield. According to the model proposed, the DL-field is produced mainly by the enhanced dawn-to-dusk (east-to-west) magnetopause current and the dusk-to-dawn (west-to-east in the dayside) polarization current along the wave front of the compressional HM wave propagating earthward in the magnetosphere. The DPpi is caused by a pair of field-aligned currents (FACs) and the FAC-induced twin vortex ionospheric currents (ICs) as proposed by Tamao (1964). Although this current system was originally proposed to explain the high latitude PRIs, the model considers that the afternoon current vortex extends to the day side equator. This explains the simultaneous appearance of PRIs with similar waveform in the high latitude afternoon and the dayside equator. It is difficult to produce the equatorial PRI by direct vertical incidence of the compressional HM wave in the equatorial plane.

After the initial compression of the magnetosphere, the magnetospheric convection is enhanced by the increased velocity and density behind the shock or discontinuity in the solar wind and also by the distance between the convection vortex centres decreasing in the compressed magnetosphere. As a result, the dawn-to-dusk convection electric field is enhanced and transmitted along field lines to the polar ionosphere accompanying FACs. This FAC and the FAC-induced twin vortex ICs produce the DPmi-field. The sense of the FACs is opposite to the FACs for the DPpi and so the vortex sense of the IC is also opposite. Again the afternoon vortex extends to the dayside equator to produce the equatorial enhancement of the DPmi. It is also difficult to produce the equatorial enhancement of MI by direct vertical incidence of HM waves because the wave field below the ionosphere is reduced by a shielding current flowing in the ionosphere. The shielding is more effective in the dayside equator where the ionospheric Cowling conductivity is especially higher.

The model described above assumes that the FAC induced ionospheric current vortices for the DPpi and DPmi extend almost instantaneously to the equatorial region. Actually the onset of PRIs at afternoon auroral latitudes and the dayside equator is almost simultaneous (within 10 seconds). If a horizontal electric field impressed on the polar ionosphere is transmitted to the equator in the ionospheric E-region, it takes more than one hour for the equatorial electric field to rise up, because the transmission is governed by a diffusion equation (Watanabe, 1962). There is a duct for HM wave propagation in the F-region minimum of the HM wave velocity but it has a lower cut off frequency, around 0.1 Hz and a longer period disturbance, such as the DPpi and DPmi, cannot propagate in the duct. The only way, at present, to solve this difficulty is to utilize electromagnetic transmission in the space between the ground and the ionosphere. After proving the difficulty of producing the equatorial PRI by HM wave incidence, Kikuchi and Araki (1979) proposed the zeroth order mode propagation in the earth-ionosphere wave guide. Here, we stress that the polar electric field is observed very near the source current even if the observation is made at the equator because of the long wave length of the DPpi and DPmi. The observation is made within one wave length where the static field dominates over the wave field. The quasi-static polar electric field which extends to lower latitudes attenuates greatly but can still allow enough flow of ionospheric electric currents with help of the enhanced Cowling conductivity in the dayside equator.

To prove that a pair of the FACs could produce the observed ionospheric current vortices, Tsunomura and Araki (1984) made static calculations of the FAC produced electric fields and currents giving a realistic conductivity distribution on the spherical thin shell ionosphere. The results were consistent with the observed current pattern for SCs. Osada (1992) synthesized an SC using similar calculations. The calculated results could explain the observed latitudinal and local time distribution of the amplitude and waveform of the SC. Ionospheric currents consistent with the proposed model have been detected by MAGSAT (Araki *et al.*, 1984) and Oersted (Han *et al.*, 2007).

Thus the SC model (called hereafter ATK model) which was proposed by Araki (1977) taking the basic processes of Tamao (1964) and Kikuchi and Araki (1979) is considered to have physical bases (Araki, 1994).

3.3.2 Diurnal variation of SC amplitude Since the DL field dominates over the DP field in low and middle latitudes, the amplitude of SCs was expected to be larger in the dayside than the night side. However, actual observations indicate larger night time amplitudes as shown in 1951 by Ferraro and Unthank analyzing 55 SCs and 40 SIs determined from latitudes 21–49 deg. From analyses of several tens of SCs, Russell *et al.* (1992, 1994) and Russell and Ginskey (1993) reported that the SC amplitude is larger in the night time during the southward IMF while it is larger in daytime during the northward IMF. Araki *et al.* (2006) analyzed more than 600 SCs observed in Memambetsu (geomagnetic latitude = 35.2°), Kakioka (27.2°), Kanoya (21.7°) and Alibag (10.0°), and obtained the diurnal variation of the averaged H-component amplitude which has the maximum around midnight and the second maximum near noon at 3 Japanese stations. They also showed, by case studies, that the diurnal variation indicates a similar pattern for both, northward and southward IMF, but the amplitude of the diurnal variation becomes larger during the southward IMF. Shinbori *et al.* (private communication to Araki) studied the IMF dependence of the diurnal variation of the averaged SC amplitude using more than 2300 SCs and obtained results which support the analysis by Araki *et al.* (2006). This unexpected diurnal variation of the SC amplitude can be explained by a magnetic field due to the FACs for DPmi. This result and similar FAC effects for the DPpi field (Kikuchi *et al.*, 2001) shows that the FAC produced magnetic field is important even in middle latitudes.

3.3.3 Rise time of SC The rise time of an SC, defined as the time interval between the starting time (onset) and the maximum of the H-component, usually appears on the magnetograms as a monotonous increase only disturbed by small fluctuations. The rise time of SC distributes from 1 to 10 minutes with the most frequent occurrence at 3–4 minutes in low latitudes (Maeda *et al.*, 1962). Nishida (1966) pointed out the items below as mechanisms which may affect the rise time of SCs:

(a) The time taken for the front of the interplanetary shock or discontinuity to sweep the geoeffective distance along the magnetosphere,
(b) The difference in travel time of HM waves to an observing point on the ground,
(c) The thickness of the front of the shock or discontinuity in the solar wind,
(d) Inertia of the magnetospheric plasmas against a sudden deformation,
(e) The broadening of the wave front during the passage through the magnetosphere due to multi-reflection.

Several analyses were made on the rise time and the relationship between the rise time and amplitude of SCs (Yokouchi, 1953; Dessler *et al.*, 1960; Chapman and Bartels, 1962; Ondoh, 1963; Pisharoty and Srivastava, 1962; Nishida, 1964, 1966; Burlaga, 1970; Mayaud, 1975) suggesting item (a) above as the main mechanism for the rise time. Fowler and Russell (2001) also discussed the rise time based upon the mechanism (a).

Since the rise time shows a diurnal variation (Yokouchi, 1953), Araki *et al.* (2004) made an analysis using only night time SCs and concluded that item (a) principally determines the rise time with the averaged geoeffective magnetopause distance of about $30R_e$ (Earth radii). Magnetospheric compression in the distant magnetotail will not have much affect on the Earth. Further, the compression itself is small at the tail because the solar wind flow is nearly parallel to the magnetopause. Therefore, $30R_e$ seems to be a reasonable geoeffective distance. If we accept this distance, the rise time is roughly given by $30R_e/V_{sw}$, where V_{sw} is the speed of the interplanetary shock or discontinuity. This consideration on the rise time suggests that the source of SCs observed on the ground is distributed on the wide surface of the magnetopause.

3.3.4 Simultaneity of SC onset As was described in Section 3.2, simultaneity of SC occurrence has been a long standing problem since Adams (1892) and Ellis (1892). Before going further, we have to stop here to consider what the onset time of an SC is. Basically it represents the starting time of the event and is related to the point in the magnetogram where the inflection happens. We point out the following 3 key concepts;

(a) On a normal run magnetogram (what an observer would use) the rise of SCs looks very sharp. However, when the time scale is expanded the rise is often found to be too slow to accurately determine the onset. Even if we use the highest possible time resolution observations, it is difficult to determine the precise onset time if the onset is slow. A sharp rise SC is necessary in addition to high time resolution observations for precise determination of an SC onset.

(b) The onset time actually measured is not the time of the true onset of the event but the time when the amplitude of the magnetic field reaches a detectable level. There is a certain interval between the true onset and the measured onset. To be accurate this interval should be mentioned in addition to the measured onset time itself. This interval is shorter for shaper SCs.

(c) The disturbance field of SC (Dsc), consists of the subfields, DL and DP, and DP is further decomposed into DPpi and DPmi. We should always keep in mind that Dsc is a superposition of the DL and DP sub-fields. A negative increase of the DP may cancel out a positive increase of DL and as the result an apparently delayed onset may be observed. This superposition applies not only to the onset but also to the peak of the PRI and MI. The peak time of both PI and MI can differ depending upon LT and latitude. Examples of the global SC distribution with time delay of the onset and the PRI peak at some of the stations are shown in Araki (1977, 1994).

An anomalous SC occurred on March 24th, 1991 which showed a very sharp and large impulse (one minute duration and 202 nT H-amplitude at Kakioka) at the initial stage of the SC. The inner radiation belt was formed simultaneously with this SC and lasted more than one year (Blake *et al.*, 1992). Li *et al.* (1993) successfully simulated the magnetospheric particle acceleration due to this pulse propagating tailward from the 1500 LT magnetopause. Araki *et al.* (1997) checked the day-to-night propagation of this pulse, and found that the peak of this pulse propagated with the appropriate HM velocity above the ionosphere but the onset propagation was almost globally instantaneous (within 5 seconds accuracy). The observation of this pulse in the day and night in addition to the almost simultaneous onset of PRI's in afternoon auroral latitudes and the dayside equator led them to believe in the existence of a propagation mode much faster than an HM wave. Ohnishi and Araki (1992) studied the interaction of a plane compressional HM wave with a cylindrical Earth-ionosphere system. This showed that the ionospheric shielding current suppressed the build up of the ground magnetic field and the onset time delays, apparent from the onset of the magnetic field above the ionosphere but the onset on the ground was simultaneous at noon and midnight. They interpreted it as electromagnetic transmission in the space between the Earth and the ionosphere. Deformation of the wave front of the SC in the magnetosphere was calculated by Namikawa *et al.* (1964) and Stegelmann and von Kenschitzki (1964).

3.3.5 Criticisms to the proposed model Lam and Rodger (2001) tested the ability of the Osada's calculation referred in Araki (1994) to predict the signs of the preliminary and main impulses using a case study. Basic coincidences in high latitude signatures did not repeat at low latitudes, especially at night. The calculation is highly dependent upon the chosen electrical conductivity and the FAC model.

Chi *et al.* (2001) made a case study of one particular SC event observed at 35 ground stations. They specified the peak time of PRI as the arrival time of PRI and observed it differed 30 seconds at most between stations. Then they calculated travel time of the HM wave emitted from a point source in the magnetosphere based upon Tamao's concept of mode conversion from the compressional to Alfven mode. They reported that the observed delay of the arrival time of the SC agrees well with the HM wave propagation calculated but it is inconsistent with the theory of instantaneous propagation in the Earth-ionosphere waveguide.

As it was previously described, the ATK model insists that the onset of the PRI is almost simultaneous in the afternoon auroral latitudes and the dayside equator but it does not claim that the peak time of the PRI is simultaneous everywhere. Several figures of the waveform distribution in Araki (1977) and Araki (1994) show differing peak times of the PRI as a matter of fact. The peak time may be affected by superposition of the DL and DPmi field in addition to propagation from different source points. They should check the onset time of PRIs (not their arrival times) if they want reject the Earth-ionosphere propagation.

Chi *et al.* (2006) numerically calculated the travel time of a linear wave emitted from a point source in the magnetosphere and obtained almost simultaneous onset of the SC over the globe. They reported that almost simultaneous onset of SCs can be achieved without invoking horizontal propagation in the Earth-ionosphere waveguide. At present, the calculation is limited to the travel time of the wave. We want to see further development of their simulation if it can explain (1) global distribution of the waveform and amplitude of SC, (2) daytime equatorial enhancement of PRI and MI of SC, (3) almost instantaneous propagation of SC from day side to night side, (4) wider distribution of possible wave sources. As mentioned previously, any theories of SC have to explain all aspects of the SC.

3.3.6 Other comments The physical model described above has been constructed by analyzing mainly geomagnetic variations projected on the ground. It is not easy, however, to imagine what happens in the much larger magnetosphere from the limited observations on the small spherical earth even if in situ satellite observations were available. Three-dimensional computer simulations for the transient response of the magnetosphere greatly contributes to our knowledge of the behaviour of the whole system from discontinuous observations at limited points. For example, MHD simulations by Fujita *et al.* (2003a, b, 2005) are roughly consistent with the proposed ATK model but clarify more detailed responses which the ATK model could not predict. A simulation by Slinker *et al.* (1999) also supports the model above.

It should be noted that all interplanetary shocks or discontinuities do not necessarily cause SCs or SIs. If the shock or discontinuity is obliquely incident to the magnetosphere, the SC produced will have larger rise time because of the longer interaction time with the magnetosphere (Takeuchi *et al.*, 2002). Such an SC with a slow rise may not be identified as an SC under the present requirements.

3.4 SC as a probe

It is now established that SCs are caused by a sudden increase of the solar wind dynamic pressure associated with the interplanetary shock or discontinuity. It means that we can detect the pure magnetospheric response without contamination of the source disturbance. Properties of the source may be known in more detail with the development of the solar wind observations.

The response in the magnetosphere-ionosphere-Earth system can be studied in more detail by the 3D observations on the ground and in the magnetosphere. Utilizing the advantages of SC observations, we can use SCs as a probe to study transient responses of various kinds of magnetospheric phenomena. The SC triggers substorms (Kokubun, 1977; Iyemori and Tsunomura, 1983), geomagnetic pulsations (Psc), particle precipitation (Brown, 1973) and auroral break up (Lyons *et al.*, 2005). It sometimes forms instantaneously with the inner radiation belt (Blake *et al.*, 1992).

The SC model described above shows a way of transmitting the electric field from the magnetosphere to the equatorial ionosphere through the polar ionosphere. This is not limited to the case of SCs but one general way of penetration of the interplanetary electric field to the low latitude ionosphere and the plasmasphere.

Recently the prompt penetration of an interplanetary electric field to the low latitude ionosphere has been discussed (e.g., Mannucci *et al.*, 2005). We consider that the electric field transmission described above might be applicable also to this case. This mechanism is also consistent with global manifestation of the DP2 type geomagnetic variation (Nishida *et al.*, 1966; Kikuchi *et al.*, 1996). Hashimoto *et al.* (2002) proposed a model in which the magnetospheric convection electric field is transmitted to the inner magnetosphere through the mid-latitude ionosphere. Recently, Vasyliunas (2001) and Vasyliunas and Song (2006) proposed that the polar cap convection flow can be immediately propagated to all latitudes at the fast mode HM wave speed. If this is possible, we have two modes for quick transmission, electromagnetic transmission under the ionosphere and fast mode HM transmission in the magnetosphere. We have to make a more detailed analysis on the "prompt penetration"; how prompt is it? It is very interesting to check if the HM transmission can explain the almost simultaneous transmission within the 5 second time accuracy previously described.

4. Conclusions

Although the concept of SSC is becoming clearer, there is still a long way to run in the operative method of the event detection. Some improvements could be performed by: extensive patrol towards continuous world wide coverage; automatisation of the detection generating warnings useful in space weather now-casting by processing data in real time and more specific morphological characterization relating the expected parameter with the position of the magnetic observatory.

As SSC and SI have the same physical causes, it is proposed to use the general name of SC for both, being then classified in the lists as SSC or SI according to the magnetic character of the following hours.

With the aim to give operative criteria for detection, we propose (in line with Joselyn and Tsurutani (1990)) a quantification in the threshold values of the SC parameters for an event to be included in the official list: SI would be specified by a sharp change (with a minimum slope of the order of 10 nT in 3 min.) of the horizontal magnetic field at globally spaced observatories at low latitude, and SSC those which, additionally, are followed by an hour with the Dst index lower than about −50 nT within the 24 following hours.

Because of the local time dependence of the SC amplitude (Mayaud, 1975; Araki *et al.*, 2006), in addition to the mean amplitude and starting time given now in the official lists, the particular SC amplitudes of the 5 reference observatories—mentioned in Section 2.6—should be included in the official lists providing valuable material for future investigations.

As observatories have 1 second data available, these data should be employed to improve the accuracy in starting time detection.

The knowledge of SSC has experienced great improvements: from the clear association of the SC events to interplanetary shocks and discontinuities to the modelling of the three dimensional structures of the SCs. New challenges, such as mapping of magnetospheric electric fields penetrating in the equatorial ionosphere are waiting for new research.

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