Seasonal Dependence of SC-Field in Middle and Low Latitudes*

By Rikio MAEDA**, Naoshi FUKUSHIMA and Takesi NAGATA

Geophysical Institute, University of Tokyo

(Read May 25, 1962; Received Dec. 30, 1964)

Abstract

An analysis of world-wide geomagnetic field-change for eight SC's during IGY indicates that the uniform northward external magnetic field for SC in middle and low latitudes shows a systematic seasonal dependence, namely, the uniform external magnetic field inclines towards the sunlit side in the summer hemisphere, and towards the night side in winter. This systematic seasonal dependence of the SC-field may be explained as due to the geometrical relation between the incident direction of the solar wind and the geomagnetic dipole axis.

1. Introduction

The behaviour of sudden commencements of magnetic storms (SC) has recently been examined in detail with the aid of world-wide data during the International Geophysical Year, especially for the purpose of studying the electromagnetic induction within the earth (Maeda et al., 1965). While the analysis was being performed, a systematic seasonal dependence of SC in middle and low latitudes was found.

For convenience, the disturbance field for SC, denoted by $D(SC)$, is separated into two parts: i.e.,

$$D(SC) = Dst(SC) + DS(SC).$$

When a great number of SC's occurring in all seasons are averaged, the $Dst(SC)$ current-system consists of an eastward electric current parallel to the geomagnetic latitude circle. The electric current intensity is nearly proportional to the cosine of the geomagnetic latitude in middle and low latitudes, except just on and near the geomagnetic equator, where an equatorial enhancement is observed (Sugiura, 1953; Obayashi and Jacobs, 1957). Most of the $Dst(SC)$ -field is attributable to a northward external magnetic field parallel to the geomagnetic dipole axis. On the other hand, most of the electric currents for $DS(SC)$ are concentrated in the high-latitude regions, revealing a complicated feature of SC in high latitudes, as studied by Oguti (1956), Sato (1961, 1962), Sano (1962), Matsushita (1962), and others. The current-system for SC*, the reverse impulse which precedes the main SC, is shown to be expressed by a current flow in the reverse direction to that in the developed stage of SC in high latitudes (Nagata, 1952; Nagata and Abe, 1955).

* Contribution from Division of Geomagnetism and Planetary Physics, University of Tokyo, Series II, No. 186.

** Now at the Radio Research Laboratories, Kokubunji, Tokyo.

In the present paper, the electric current-system for the developed stage of SC is examined in detail for eight selected SC's. The seasonal dependence of the electric current-system in middle and low latitudes is discussed, and the current pattern in high latitudes is not dealt with.

2. Data used in the present analysis

Four SC's each for the summer and winter seasons during IGY are analyzed. The times of these selected SC's and of their developed stages, and the magnitude of SC in H , denoted by ΔH , at three low-latitude stations are summarized in Table I. The observatories,

Table I. The SC's used for the present analysis.

Event No.	Time of SC in U.T. (T_0)				T_1	Range of $\Delta H(\text{SC})$ at			$(Kp)_{\text{SC}}$	$(Kp)_{\text{max}}$
						Kaki-oka	San Juan	Huan-cayo		
1	1957	July 16 ^d	07 ^h	14 ^m	07 ^h 19 ^m	18 γ	14 γ	40 γ	3 ₀	4 ₀
2	1958	Feb. 11	01	25	01 28	36	52	167	9 ₀	9 ₀
3	1958	July 08	07	48	07 51	110	52	97	7—	9 ₀
4	1958	July 21	16	38	16 40	47	31	178	7—	7+
5	1958	Aug. 17	06	22	06 24	41	50	90	6 ₀	7+
6	1958	Sep. 25	04	08	04 13	37	23	32	6 ₀	7 ₀
7	1958	Dec. 13	00	01	00 03	16	18	45	5+	6 ₀
8	1958	Dec. 17	18	17	18 18	37	24	117	6+	7 ₀

Legend: T_1 : Time in U.T. of the developed stage of SC.
 $(Kp)_{\text{SC}}$: Kp -index during the 3-hour interval, in which SC took place.
 $(Kp)_{\text{max}}$: Maximum Kp value during the magnetic storm following SC.

Fig. 1. Distribution of magnetic observatories, whose data are used in the present analysis.

whose data are utilized in this study, are distributed over the world as shown in Fig. 1. The total number of stations amounts to 126 (31 stations in the arctic region, 26 in the north subauroral region, 22 in the north minauroral region, 11 in the northern equatorial zone, 15 in the southern equatorial zone, 6 in the south minauroral region, 3 in the south subauroral region, and 12 in the antarctic region).

3. Overhead current-system for SC's

The overhead current-systems are drawn for the developed SC-field (at time T_1), for each event given in Table I. Four examples of the current-systems in the northern hemisphere are shown in Fig. 2.

Fig. 2. Overhead current-system for the developed stage of SC, (a) 1957 July 16, 07h 19m; (b) 1958 February 11, 01h 28m; (c) 1958 July 21, 16h 40m; (d) 1958 December 17, 18h 18m U.T.

The current pattern is complicated in the polar region, while it is rather simple in the middle and low latitudes. The electric current flow in the middle and low latitudes is not exactly parallel to the geomagnetic latitude circle in each case. This problem is discussed quantitatively in the next section.

4. Spherical harmonic analysis of the $D(SC)$ -field

Based on the data in the middle and low latitudes, the $D(SC)$ -field is expanded into a spherical harmonic series. The magnetic potential W is given by

$$W = C + R \sum_{n=1}^{\infty} \left[\left(\frac{r}{R} \right)^n \sum_{m=0}^n \left\{ g_n^{m(e)} \cos m\lambda + h_n^{m(e)} \sin m\lambda \right\} P_n^m(\cos \theta) \right. \\ \left. + \left(\frac{R}{r} \right)^{n+1} \sum_{m=0}^n \left\{ g_n^{m(i)} \cos m\lambda + h_n^{m(i)} \sin m\lambda \right\} P_n^m(\cos \theta) \right]$$

referring to *geomagnetic* coordinates, with customary notations in the spherical harmonic expansion. In the middle and low latitudes, the $D(SC)$ -field on the earth's surface $r=R$ is well approximated by

$$X = -\{g_1^{0(e)} + g_1^{0(i)}\} \sin \theta + [\{g_1^{1(e)} + g_1^{1(i)}\} \cos \lambda + \{h_1^{1(e)} + h_1^{1(i)}\} \sin \lambda] \cos \theta \\ \equiv -g_1^0 \sin \theta + [g_1^1 \cos \lambda + h_1^1 \sin \lambda] \cos \theta, \\ Y = \{g_1^{1(e)} + g_1^{1(i)}\} \sin \lambda - \{h_1^{1(e)} + h_1^{1(i)}\} \cos \lambda \equiv g_1^1 \sin \lambda - h_1^1 \cos \lambda.$$

The coefficients obtained in the actual analysis are shown in Table II.

Table II. Spherical harmonic analysis of $D(SC)$ -field in low latitudes.

Event No.	Spherical harmonic g_1^0	g_1^1	coefficients h_1^1	φ_0	λ_0	φ_s	λ_s	$\lambda_0 - \lambda_s$
1	-32.6 γ	7.0 γ	-3.8 γ	76° .2	151° .2	12° .5	142° .1	9° .4
2	-106.8	-28.4	-25.6	70 .3	42 .0	-21 .7	231 .3	-189 .3
3	-92.1	15.8	-2.9	80 .1	169 .4	14 .6	135 .5	33 .9
4	-86.8	-23.7	-4.5	74 .5	10 .7	32 .1	0 .5	10 .2
5	-50.2	7.2	-1.9	81 .6	165 .2	3 .4	154 .2	11 .0
6	-47.5	-10.5	-1.8	77 .4	9 .7	-10 .9	187 .2	-177 .5
7	-32.5	3.7	-7.2	76 .0	117 .2	-26 .7	254 .5	-137 .3
8	-68.3	11.5	-0.4	80 .4	178 .0	-12 .9	336 .5	-158 .5

Legend: (φ_0, λ_0) : Geomagnetic coordinates of the point in the northern hemisphere, where the axis through the earth's centre parallel to the equatorial $Dst(SC)$ -field intersects the earth surface.

(φ_s, λ_s) : Geomagnetic coordinates of the subsolar point at the time of the developed stage of SC.

5. Seasonal dependence of the $Dst(SC)$ -axis

From the three coefficients, g_1^0 , g_1^1 and h_1^1 , the axis of the uniform external magnetic field at the time of an SC can be determined. In Table II, φ_0 and λ_0 denote the geomagnetic latitude and longitude of the point where the direction vector of the SC uniform external magnetic field through the earth's centre intersects the earth surface in the northern hemisphere. The point (φ_0, λ_0) will be referred to, hereafter, simply as the $Dst(SC)$ -axis pole. φ_s and λ_s in Table II indicate respectively the geomagnetic latitude and longitude of the subsolar

point at developed stage time of the SC in question.

Figs. 3 and 4 show that the $Dst(SC)$ -axis inclines towards the sunlit side in the summer hemisphere, because $|\lambda_0 - \lambda_s| < 90^\circ$ when the subsolar point is in the northern hemisphere ($\varphi_s > 0$). The $Dst(SC)$ -axis is shown to incline towards the night side in winter, on the other hand, because $90^\circ < |\lambda_0 - \lambda_s| < 180^\circ$ when $\varphi_s < 0$.

As mentioned before, the $Dst(SC)$ -field in low latitudes can be expressed by a northward external magnetic field parallel to the geomagnetic dipole axis, for the average of a great number of magnetic storms which take place throughout the year. In the present analysis, it is illustrated that the $Dst(SC)$ -axis shows a systematic dependence on the season. The observed relation between φ_0 and φ_s may be approximated by the dotted line in Fig. 3, which is a theoretical curve derived according to the following consideration.

6. Image dipole in the solar stream and its magnetic effect on the earth

It is now widely believed that SC is caused by an intense solar plasma stream arriving at the vicinity of the earth. Chapman and Ferraro (1931, 1932, 1933, 1940) first estimated the effect of plasma—magnetic field interaction

by a rough approximation that the front surface of the solar stream is a flat plane parallel to the earth's dipole axis. The magnetic effect on the earth of the approaching solar stream may be represented by the magnetic field of an image dipole on the sun-earth line in the solar stream. Although the front surface of the solar plasma stream is curved so as to form the geomagnetic cavity around the earth, the magnetic field on the earth caused by the solar stream can still be approximated by the field produced by an image dipole on the sun-earth

Fig. 3. The relation between the latitude φ_0 of the $Dst(SC)$ -axis and that of the subsolar point φ_s , in geomagnetic coordinates.

Fig. 4. The relation between the subsolar-point latitude and the longitudinal difference ($\lambda_0 - \lambda_s$) of the $Dst(SC)$ -axis and the subsolar point, in geomagnetic coordinates.

line, when the solar stream approaches the earth perpendicularly to the geomagnetic dipole axis. When the solar stream is not perpendicular to the earth's dipole, the geomagnetic cavity boundary is almost spherical, also in this case, at least in low latitudes, as calculated by Spreiter and Briggs (1962), and others. Therefore, the SC-field on the earth's surface may be approximated, even in this case, by the effect of an image dipole on the sun-earth line, although the magnetic moment for the image dipole may differ from that of the earth, because of the curved form of the geomagnetic cavity.

In the meridional cross-section containing the earth's dipole axis and the sun-earth line, the geometrical relation of the geomagnetic dipole and its image is such as given by Fig. 5, when the solar declination is φ_s , at the time of the northern winter season. The image dipole is

Fig. 5. Geometrical configuration of the earth's dipole and its image in the solar stream in the meridional plane containing the geomagnetic axis and the sun-earth line.

situated at $\left(r', \frac{\pi}{2} + \varphi_s, \lambda_s\right)$ referred to geomagnetic polar coordinates. The moment of the image dipole is M' , and the angle between the geomagnetic dipole and its image is $2\varphi_s$. From the geometrical configuration for the lines of magnetic force from the image dipole,

$$\tan \psi = 2 \tan \varphi_s,$$

$$\varphi_0^* = \pi - \psi - \left(\frac{\pi}{2} - \varphi_s\right) = \frac{\pi}{2} - \psi + \varphi_s,$$

$$\therefore \varphi_0^* = 90^\circ - \tan^{-1}(2 \tan \varphi_s) + \varphi_s,$$

where φ_0^* is the geomagnetic latitude of the $Dst(SC)$ -axis, and this value is independent of r' and M' . The dotted line in Fig. 3 is the calculated value of φ_0^* for a range of $0 \leq |\varphi_s| \leq 35^\circ$. It is shown that the minimum value of φ_0^* is $70^\circ 36'$ corresponding to $|\varphi_s| = 35^\circ 18'$, which

means that the $Dst(SC)$ -axis does not tilt away from the geomagnetic dipole axis more than 20° even in the solstice.

7. Summary and Discussion

It is shown in the present paper that the uniform external magnetic field corresponding to SC in the middle and low latitudes is not always parallel to the geomagnetic dipole axis, but its direction varies systematically, namely, the $Dst(SC)$ -axis inclines towards the sunlit side in the summer hemisphere and towards the night side in the winter region. The maximum tilt angle is about 20° even in the solstice.

This systematic seasonal dependence of the $Dst(SC)$ -field in the middle and low latitudes seems to be explained by the interaction with the geomagnetic field of the solar stream, the incident direction of which, with respect to the earth's dipole axis, systematically varies with season. In this simple consideration, the effects of the electromagnetic screening of the ionosphere, and the induction within the earth at the time of SC are not considered. Even when these effects are taken into account, the general conclusion on the seasonal variation in the external $Dst(SC)$ -field described in this paper, will remain unchanged. It will be important to check, whether the tendency of seasonal $Dst(SC)$ -field variation pointed out in this report is revealed in the seasonal dependence of the diurnal variation in SC-vectors in the middle and low latitudes, especially in the east-west component of the geomagnetic field-change. However, there are too few papers at present on the statistical study of this morphological problem, which are to be compared with the present result.

In concluding, the writers wish to express their hearty thanks to all the magnetic observatoris, which have sent their data to the IGY-WDC. The authors are grateful to Prof. T. Rikitake of the Earthquake Research Institute, and to our colleagues in the Geophysical Institute, University of Tokyo, for their useful comments and suggestions.

References

- Chapman, S., and V.C.A. Ferraro, A new theory of magnetic storms, *Terr. Mag.*, **36**, 77-97, 171-186, 1931; **37**, 147-156, 421-429, 1932; **38**, 79-96, 1933.
- Chapman, S., and V.C.A. Ferraro, The theory of the first phase of a geomagnetic storm, *Terr. Mag.*, **45**, 245-268, 1940.
- Maeda, R., T. Rikitake and T. Nagata, Sudden commencements of geomagnetic storms and their local irregularities, *J. Geomag. Geoelectr.*, **17**, in the press, 1965.
- Matsushita, S., On geomagnetic sudden commencements, sudden impulses, and storm durations, *J. Geophys. Res.*, **67**, 3753-3777, 1962.
- Nagata, T., Distribution of SC* of magnetic storms, *Rep. Ionos. Res. Japan*, **6**, 13-30, 1952.
- Nagata, T., and S. Abe, Notes on the distribution of SC* in high latitudes, *Rep. Ionos. Res. Japan*, **9**, 39-44, 1955.
- Obayashi, T., and J.A. Jacobs, Sudden commencements of magnetic storms and atmospheric dynamo action, *J. Geophys. Res.*, **62**, 589-616, 1957.
- Oguti, T., Notes on the morphology of SC, *Rep. Ionos. Res. Japan*, **10**, 81-90, 1956.
- Sano, Y., Morphological studies on sudden commencements of magnetic storms using the rapid-run magnetograms during the IGY, *J. Geomag. Geoelectr.*, **14**, 1-15, 1962.
- Sato, T., Sudden commencements of geomagnetic storms in high latitudes, *Rep. Ionos. Space Res. Japan*,

15, 215-234, 1961.

Sato, T., Structures of sudden commencements of geomagnetic storms and giant pulsations in high latitudes, Rep. Ionos. Space Res. Japan, 16, 295-333, 1962.

Spreiter, J.R., and B.R. Briggs, Theoretical determination of the form of the boundary of the solar corpuscular stream produced by interaction with the magnetic dipole field of the earth, J. Geophys. Res., 67, 37-51, 1962.

Sugiura, M., The solar diurnal variation in the amplitude of sudden commencements of magnetic storms at the geomagnetic equator, J. Geophys. Res., 58, 558-559, 1953.