CHARACTERISTICS OF POLARIZATION OF GEOMAGNETIC SUDDEN COMMENCEMENTS AT GEOSTATIONARY ORBIT

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Abstract: Local time dependence of polarization of geomagnetic sudden commencements (SC's) at geostationary orbit was statistically analyzed, using magnetic data from GOES 2 and 3 satellites for the interval from August 1978 to August 1980. The polarization in the plane perpendicular to the geomagnetic field is counterclockwise in the morning side and clockwise in the afternoon side, when viewed along the field direction. The demarcation line across which the polarization is reversed seems to be located between 11 h and 14 h LT. This time span may be due to different angles at which shock fronts or discontinuities propagating in interplanetary space collide against the magnetosphere. The latitudinal reversal of polarization of SC observed in high latitudes on the ground does not seem to occur at geostationary orbit.

1. Introduction

An energetic solar flare is well known to produce a shock propagating in interplanetary space. The shock collides against the magnetosphere and compresses it suddenly, which causes a geomagnetic sudden commencement (SC) observed worldwidely in the magnetosphere and on the earth's surface. Some of SC's are also caused by interplanetary tangential discontinuities. Many experimental and theoretical investigations on SC's have been carried out (see the reviews of MATSUSHITA, 1967; AKASOFU and CHAPMAN, 1972; NISHIDA, 1978). Recently, the Coordinated Data Analysis Workshop study on the physical characteristics and temporal development for the SC event of July 29, 1977 has been pursued by many researches, using the data obtained from several spacecraft and ground stations (J. Geophys. Res., **87** (A8), 1982).

WILSON and SUGIURA (1961) showed statistically, using the rapid-run magnetograms obtained during the IGY, that the polarization of horizontal SC vector on the ground is elliptical in high and higher-middle latitudes, and that the sense is counterclockwise in the morning side (2200–1000 LT) and clockwise in the afternoon side (1000–2200 LT) for the northern hemisphere, and it is opposite for the southern hemisphere. From their results they also interpreted SC in terms of hydromagnetic waves, that is to say, SC perturbations generated by the impact of a shock in interplanetary space are propagated to the earth primarily by longitudinal waves in low latitudes and by transverse waves in high latitudes. MATSUSHITA (1962) critisized the results of WILSON and SUGIURA (1961) by reporting that only about one-fifth of the total SC events examined by him agreed with their polarization rules. Afterwards this dispute continued for a while (WILSON and SUGIURA, 1963; MATSUSHITA, 1963), but remained unsettled. Recently, ARAKI and ALLEN (1982) studied latitudinal variations of SC polarization by the use of the North American IMS magnetometer data and showed that a polarization reversal exists in a geomagnetic latitude range 64°–72°N. In the theoretical standpoint, the hydromagnetic descriptions for SC have been developed by TAMAO (1964, 1975), NISHIDA (1964, 1978) and ARAKI (1977). NISHIDA (1964) showed that the ionospheric screening effect influences SC signatures on the ground, and that, as the result, the direction of the SC vector rotates during passage through the ionosphere.

Characteristics of SC's observed by satellites in the magnetosphere have been examined by several researchers, including NISHIDA and CAHILL (1964), PATEL (1968), SUGIURA *et al.* (1968), ONDOH (1970), PATEL and COLEMAN (1970), PATEL and CAHILL (1974), and WILKEN *et al.* (1982). ONDOH (1970) studied distributions of the amplitude and rise time of SC's in the magnetosphere by the use of the magnetic data obtained from OGO 3 and 5, and found that the amplitude is larger and the rise time is shorter in the daytime than in the nighttime. PATEL and CAHILL (1974) studied the polarization for nineteen SI (sudden impulse) and SC events, using Explorer 26 magnetic data observed in the magnetospheric region of $L=3$–6 and 11–15 h LT with geomagnetic latitude range $-6°$ to 27°. They reported that the polarization patterns for afternoon LT zone in the magnetosphere are in general agreement with the results of WILSON and SUGIURA (1961). Recently, using the magnetic data of GOES geostationary satellites, KOKUBUN (1983) showed that SC amplitude at synchronous altitude has a strong local time dependence. KUWASHIMA *et al.* (1985) found, by the use of SMS/GOES magnetograms, that direction of the initial movement of SC-associated pulsation (Psc) is eastward in the morning side and westward in the afternoon side. In the present paper, we study statistically the local time dependence of polarization of 123 SC's obtained by GOES 2 and 3 geostationary satellites in order to clarify the characteristics of SC polarization in the magnetosphere.

2. Data Analysis

The magnetometer on board the Geostationary Operational Environmental Satellites (GOES) has utilized two fluxgate sensors and the satellite spin to determine the magnitude and direction of the ambient magnetic field (GRUBB, 1975). The basic sensitivity was 0.2 nT, and the time resolution was 3.06 s. The digital magnetic data observed by GOES 2 and 3 from August 1978 to August 1980 are used here in order to study statistically the characteristics of SC polarization. GOES 2 was located near 75°W in geographic longitude until January 1979 and then was shifted to about 105°W. GOES 3 was placed near 135°W throughout the period. Geostationary positions at 75°, 105° and 135°W correspond to 11.4°, 9.3° and 4.7°N, respectively, in geomagnetic latitude. As SC's events we selected the ones which satisfy the following two conditions; (1) more than two observatories reported as an SC in 'Solar Geophysical Data'

(J. V. LINCOLN, ed.), (2) ΔH (jump in the horizontal component) was larger than 10 nT at Honolulu (21.4°N; 268.4°E in the geomagnetic coordinates). The number of SC's selected by these criteria was 64 in the period examined. As most of SC's could be simultaneously detected by both of satellites, the total number of SC's observed by the satellites was 123. Magnetic data of GOES 2 and 3 consist of three components, *HP* (parallel to the earth's rotational axis), *HE* (radially earthward) and *HN* (azimuthally westward) in the geographic coordinates. We converted the data into three components in the geomagnetic coordinates, *B* (parallel to the geomagnetic field), *V* (perpendicular to the *B* axis in the geomagnetic meridian plane) and *D* (azimuthally westward). SC's are classified according to the magnitude of SC amplitude (ΔB) and rise time (ΔT) into two groups; clear SC ($\Delta B \geq 5$ nT and $\Delta T < 10$ min) and not-clear SC ($\Delta B < 5$ nT or $\Delta T \geq 10$ min). Furthermore, we divided polarization

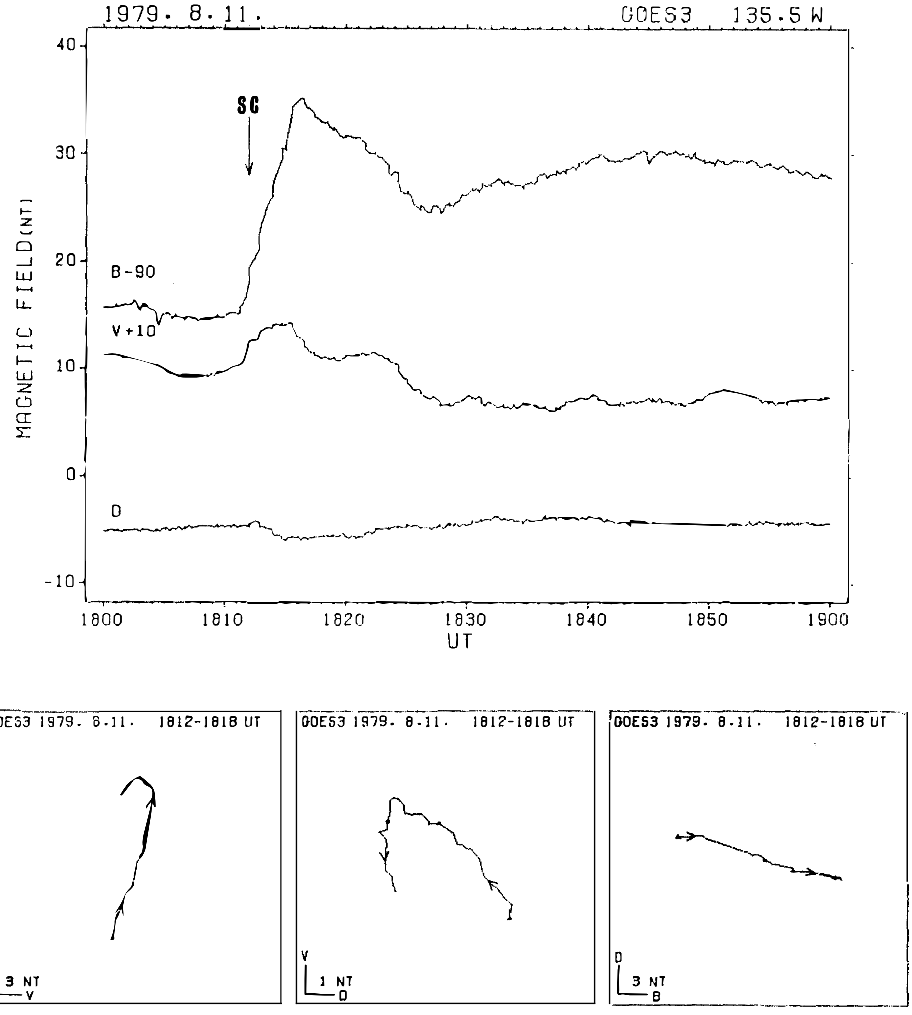

Fig. 1. Magnetograms of three components B, V and D for a clear SC event observed by GOES 3 at 1812 UT (0910 LT) on August 11, 1979 (the upper panel), and rotation of the SC vector in the B–V, V–D and D–B planes viewed from the −D, −B and −V directions, respectively, during the interval 1812 to 1818 UT (the lower panel). See the text for definition of the B, V and D components.

into five types; clockwise (clear), clockwise, linear or complex, counterclockwise, and counterclockwise (clear).

Figure 1 shows a typical example of a clear SC observed by GOES 3 in the morning. The SC occurred at 1812 UT, which corresponds to 0910 LT. In the GOES 3 magnetograms (the upper panel) the B component shows a large positive variation after the SC ($\Delta B \simeq 18$ nT, $\Delta T \simeq 5$ min), the V component also increases, and the D component decreases. The lower panel of Fig. 1 indicates the rotation of the SC vector in the B–V, V–D and D–B planes during six minutes after the SC. The polarization is approximately linear in the B–V and D–B planes, and elliptical with counterclockwise rotation in the V–D plane. Figure 2 shows an example of a not-clear SC observed by GOES 2 in the nighttime. The SC occurred at 0446 UT, which corresponds to 2206 LT. The B component decreases through a small positive variation after the SC ($\Delta B \simeq 1$ nT), and the V component indicates a negative variation. Large am-

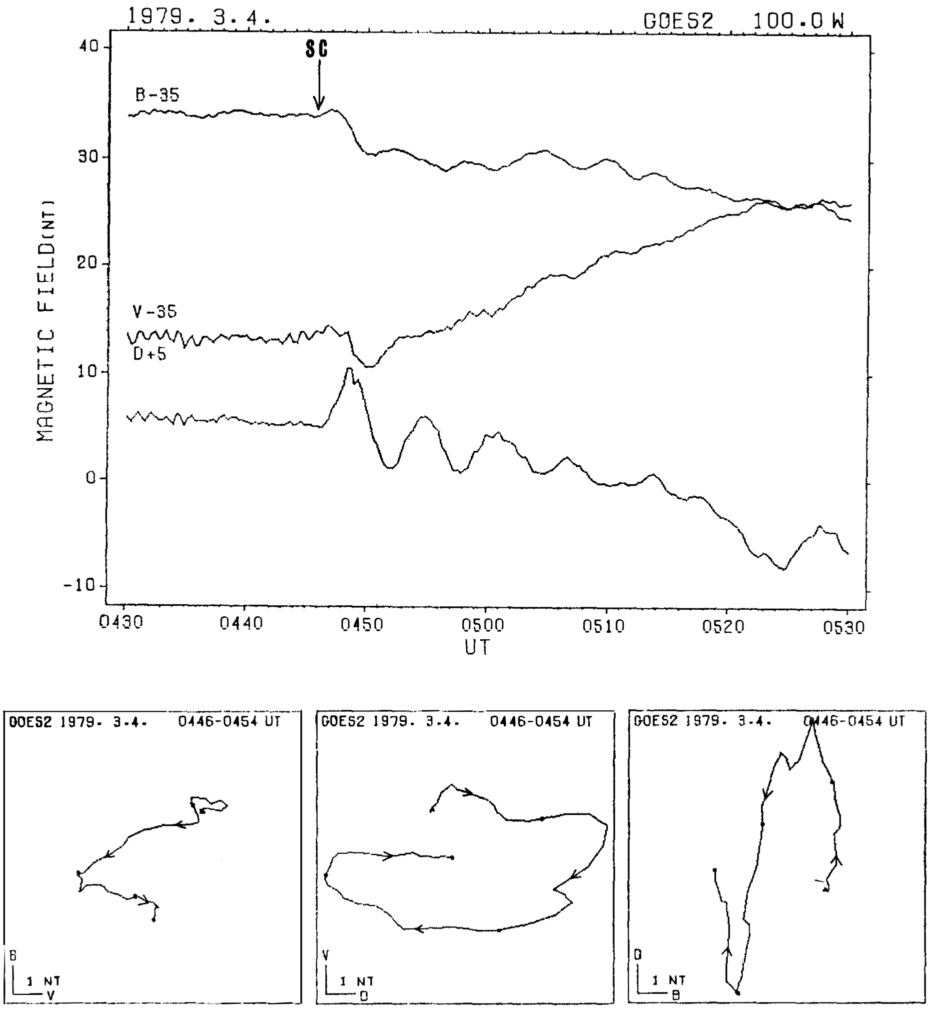

Fig. 2. Magnetograms of three components B, V and D for a not-clear SC event observed by GOES 2 at 0446 UT (2206 LT) on March 4, 1979 (the upper panel), and rotation of the SC vector in the B–V, V–D and D–B planes during the interval 0446 to 0454 UT (the lower panel).

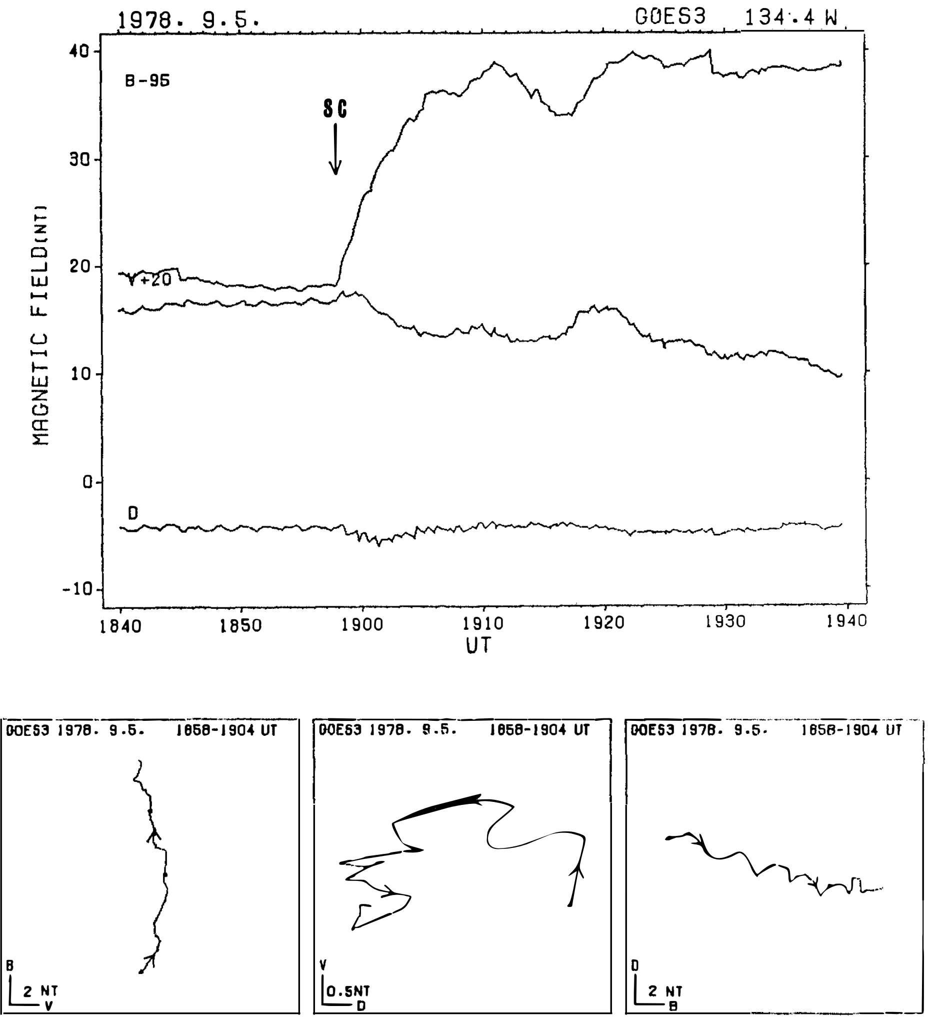

Fig. 3. Magnetograms of three components B, V and D for a clear SC event observed by GOES 3 at 1858 UT (1000 LT) on September 5, 1978 (the upper panel), and rotation of the SC vector in the B–V, V–D and D–B planes during the interval 1858 to 1904 UT (the lower panel).

plitude Psc with the period of about 6 min can be seen in the *D* component, and the initial movement is in the positive direction. The polarization is elliptical with clockwise rotation in the *V–D* plane, and complex in the *B–V* and *D–B* planes. Figures 3 and 4 show examples of another clear SC observed in the morning by GOES 3 and in the afternoon by GOES 2, respectively. The SC occurred at 1858 UT, which corresponds to 1000 LT for GOES 3 and 1358 LT for GOES 2. In the GOES 3 magnetograms (Fig. 3) the *B* component shows a large positive variation after the SC ($\Delta B \simeq$ 18 nT, $\Delta T \simeq 8$ min), the *V* component decreases after a small positive excursion, and the *D* component decreases slightly. The polarization is elliptical with counterclockwise rotation in the *V–D* plane, and linear in the *B–V* and *D–B* planes, as shown in the lower panel of Fig. 3. The sense of the variations of the *B* and *V* components at GOES 2 is the same as those for GOES 3, but the *D* component varies positively (Fig. 4). As the result, the polarization in the *V–D* plane is clockwise (the lower panel of Fig. 4).

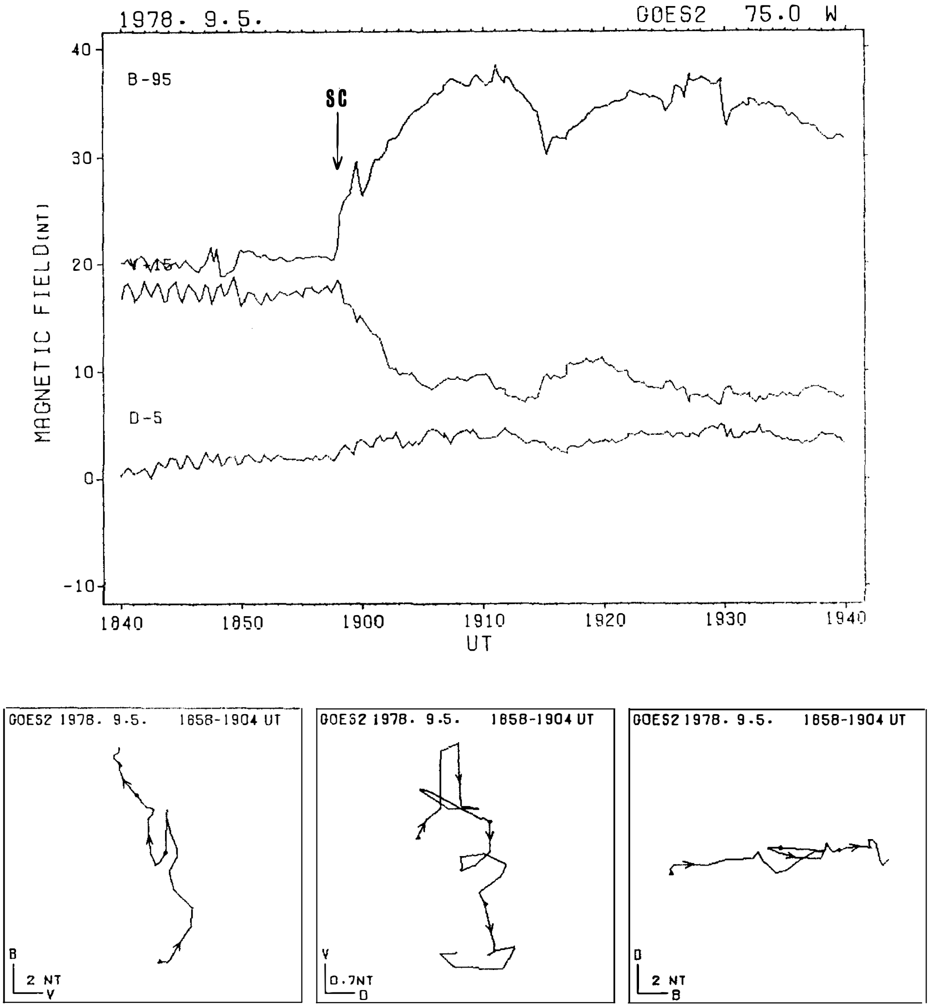

Fig. 4. Magnetograms of three components B, V and D observed by GOES 2 for the same SC event as Fig. 3 (the upper panel), and rotation of the SC in the B–V, V–D and D–B planes during the same interval as Fig. 3 (the lower panel).

In this case, pulsations having the period of about 1.5 min was produced in association with the SC, and the clockwise rotation of the wave vector is superposed on that of the SC vector. For this SC event, therefore, the polarization in the *V–D* plane is counterclockwise in the morning and clockwise in the afternoon.

Figure 5 shows the local time dependence of polarization sense in the *V–D* plane for total 123 SC's. Local time distribution of the number of the SC's examined is indicated in the upper panel. SC's were observed by the satellites more frequently in the afternoon side than in the morning side. As shown in the lower panel of Fig. 5, the occurrence rate of clear SC was about 93% in the day side (06–18 h LT) and, especially, 100% between 09 and 15 h LT. On the other hand, in the night side (18–06 h LT) about 65% was not-clear SC. For the clear SC's in the morning side (00–12 h LT) the rate of counterclockwise polarization was about 65% (about 48% was clear counterclockwise) and the rate of clockwise polarization was 0%. In the afternoon side (12–24 h LT) about 78% of clear SC's was clockwise (about 46% was clear

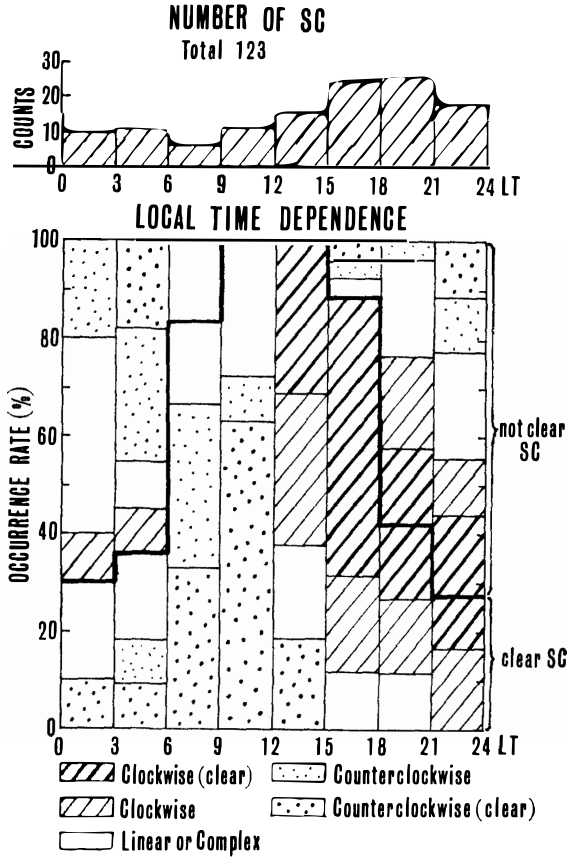

Fig. 5. Local time distribution of total 123 SC's (the upper panel) and occurrence rate for each type of SC polarization in the V-D plane (the lower panel). In the lower panel, not-clear and clear SC's are divided by a thick line.

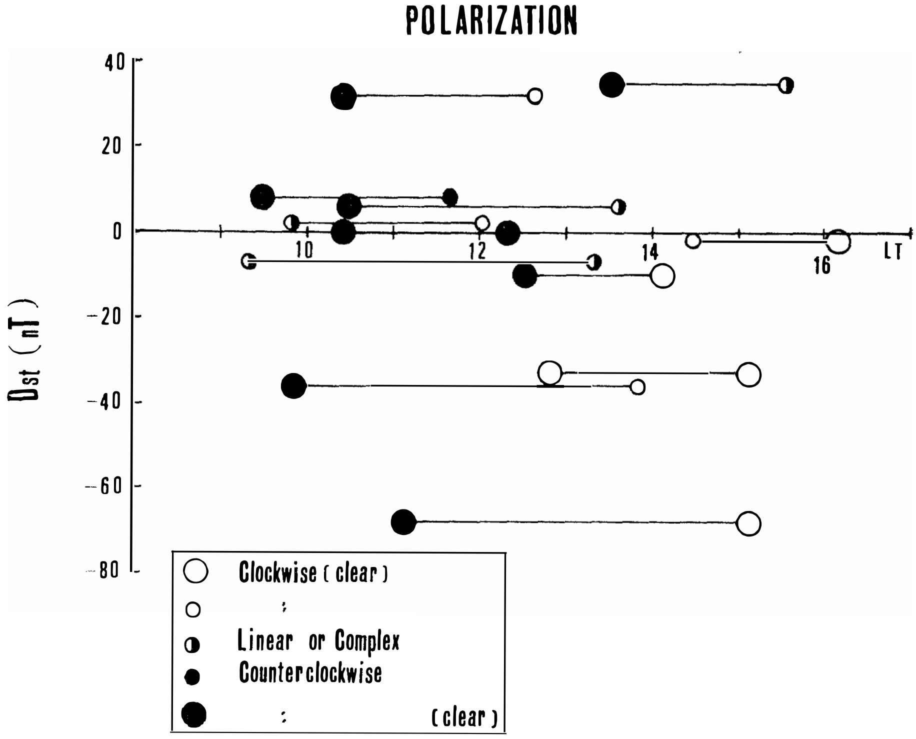

Fig. 6. Distribution of polarization in the ordinate of Dst index for twelve pairs of clear SC events simultaneously observed by GOES 2 and 3 during the interval 09 h to 16 h LT.

clockwise) and about 6% was counterclockwise. When the result for not-clear SC's was included, the rates of counterclockwise polarization in the morning side and clockwise polarization in the afternoon side were about 58 and 67%, respectively. The rate of clear polarization was higher in the day side (on the average about 55%) than in the night side (about 29%). Figure 6 shows twelve pairs of polarization for clear SC's simultaneously observed by GOES 2 and 3 during the interval 09 to 16 h LT. It can be seen from this figure that a polarization reversal occurred between 11 and 14 h LT.

3. Discussions

As shown in Figs. 5 and 6, the polarization in the *V–D* plane for SC's observed at geostationary orbit is counterclockwise in the morning side and clockwise in the afternoon side, when viewed along the field direction. The direction of SC vector rotates by 90° during passage through the ionosphere by the screening effect (NISHIDA, 1964), but the polarization sense remains unchangeable. Our result, therefore, agrees with the polarization rules derived from a statistical analysis of ground data by WILSON and SUGIURA (1961). Figure 7 shows a schematic picture describing the rotational

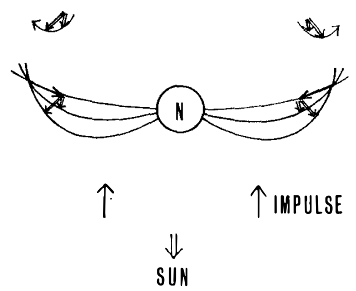

Fig. 7. Schematic picture describing the rotational sense of SC vector viewed from above the north pole in the morning and afternoon sides just above the geomagnetic equator. The sense becomes counterclockwise in the morning side and clockwise in the afternoon side, when viewed from the downward direction.

sense of SC vector in the morning and afternoon sides just above the geomagnetic equator during passage of a compressional impulse. Interaction between an interplanetary shock or discontinuity and the magnetosphere produces tailward bending of the magnetic field lines in the morning and afternoon sides of the outer magnetosphere. This bending causes time variation of the *V* and *D* components of the SC vector which is observed as polarization in the *V–D* plane. The rotational sense is clockwise in the morning side and counterclockwise in the afternoon side when viewed from above the north pole. When the rotation is projected along lines of force to the polar ionosphere, the rotational sense becomes counterclockwise in the morning side and clockwise in the afternoon side. The idea in Fig. 2 is essentially the same as that given by WILSON and SUGIURA (1961), but rotation angle of the SC vector itself will be less than 180°. The rotational angle of more than 360° frequently observed on the ground and at the geostationary orbit should be interpreted in terms of pulsations (Psc) triggered by SC's. ARAKI and ALLEN (1982) already noticed that polarization of SC's observed on the ground does not complete one rotation when Psc does not occur. KUWASHIMA *et al.* (1985) examined initial movement of the *D* component of Psc at geostationary orbit, and found that direction of the initial movement is east-

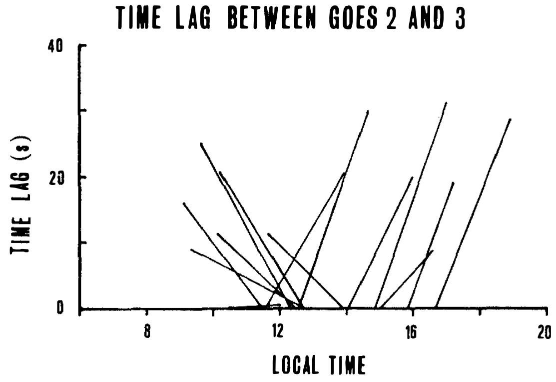

Fig. 8. Time lag between time at which a clear SC was observed by GOES 2 and that by GOES 3. Time at which either satellite observed first an SC is taken as a basis for lag.

ward in the morning and westward in the afternoon. This also shows that magnetic field lines bend tailward at the initial stage of an SC as shown in Fig. 7.

WILSON and SUGIURA (1961) showed that the demarcation line across which the rotational sense is reversed is located at 1000 and 2200 LT. Twelve pairs of polarization observed simultaneously by GOES 2 and 3 as shown in Fig. 6 indicate that the local time of the demarcation line varies between 11 and 14 h LT in the magnetosphere. This time span probably means that the shock fronts or discontinuities traveling in interplanetary space collide against the magnetosphere at different angles. Figure 8 shows time lag between onset time of clear SC's observed by GOES 2 and 3. This figure shows that local time when an SC is first observed at geostationary orbit varies in some time span depending upon the collision angle between the magnetosphere and the interplanetary shock or discontinuity. Among 19 SI and SC events which were examined by PATEL and CAHILL (1974), using Explorer 26 magnetic data in the magnetospheric region of L=3–6, 11 events showed linear polarization. This result is understandable if we take into consideration that the observation was made between 11 and 15 h LT.

The rate of not-clear SC was about 65% in the night side (18–06 h LT). KOKUBUN (1983) studied the local time dependence of SC amplitude at geostationary orbit and reported that the SC amplitude tends to become very small near midnight as compared with that on the ground. This may be caused by a partial ring current or a tail current. The decrease of the rate of clear polarization for night side SC's may be due to the influence of these currents or waves excited by them.

The existence of a latitudinal polarization reversal between 64° and 72°N in geomagnetic latitude was found by ARAKI and ALLEN (1982), using the North American IMS magnetometer data. WILSON and SUGIURA (1961) used data from stations in lower latitudes than College (64.9°N) at the time of the derivation of their polarization rules. The decrease in the percentage obeying their rules would be able to be seen if they used data from stations in higher latitudes. The magnetic field lines passing the geomagnetic latitudes 11.4°, 9.3° and 4.7°N at the synchronous altitude anchor at 67.6°, 67.4° and 67.2°N on the ground, respectively. Although these latitudes are in the reversal region on the ground, the polarization reversal in the magnetosphere could not be found from our data analysis. This suggests that the latitudinal reversal of SC polarization observed on the ground is caused by the ionosphere.

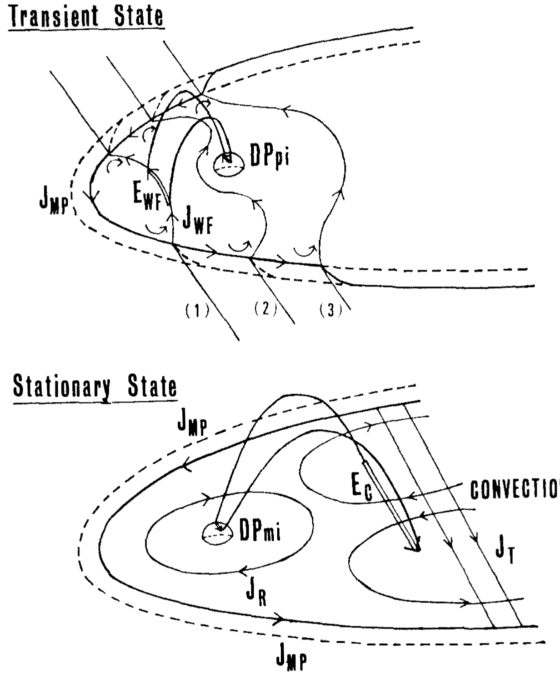

Fig. 9. Schematic picture describing SC current systems and electric fields on the equatorial plane in the magnetosphere and transmission of these fields to the northern polar ionosphere along geomagnetic field lines. The upper and lower panels are the transient and stationary states of SC disturbance. J_{MP}, J_{WF}, J_R and J_T denote the magnetopause current, wavefront current, ring current and tail current, respectively, E_{WF} and E_C represent the electric fields generated along the wavefront and the electric field caused by the enhanced convection, respectively, and DPpi and DPmi fields indicate preliminary and main impulses of SC disturbance of the polar origin, respectively. In the upper panel, (1), (2) and (3) represent the process of time when an interplanetary shock or discontinuity sweeps the magnetosphere, and semi circles with an arrow mean the rotation of SC vector as shown in Fig. 7.

The disturbance field of an SC, *Dsc*, on the ground was expressed by ARAKI (1977) as follows

$$Dsc = DPpi + DLmi + DPmi\,,$$

where *DP* and *DL* mean a disturbance of the polar origin and a disturbance dominant in low latitudes, respectively. Preliminary impulse and main impulse of an SC are represented by *pi* and *mi*, respectively. Figure 9 shows a schematic picture of SC current systems and electric fields on the equatorial plane in the magnetosphere. When an interplanetary shock or discontinuity collides against the magnetosphere, the dawn-to-dusk magnetopause current J_{MP} is enhanced and the magnetic field in the magnetosphere begins to increase. This increase propagates toward the earth as a compressional hydromagnetic wave. Along the wavefront the dusk-to-dawn polarization current J_{WF} flows to shield the increase of the magnetic field. When the earth is encircled by a current loop which consists of J_{MP} and J_{WF}, the H component begins to increase on the ground. This is the essential part of the *DLmi* field. Variations of the ring current J_R and the tail current J_T after passage of the compressional wavefront also contribute to the *DLmi* field at the stationary state. A dusk-to-dawn electric field E_{WF} along the wavefront is transmitted along the lines of force to the polar ionosphere and produces twin vortex type ionospheric currents. The *DPpi* field is the disturbance field due to these currents. After the tailward passage of the compressional wavefront, the magnetospheric convection is enhanced. The enhanced dawn-to-dusk electric field E_C is transmitted to the polar ionosphere along the geomagnetic field lines and produces twin vortex type ionospheric currents of which rotational sense is opposite to those for the *DPpi* field. These currents cause the *DPmi* field. The rotation of SC vector in the magnetosphere as explained in Fig. 7 may indicate a transitional situation before the *DPmi* field at the stationary state is built up. This transient field also is transmitted to the polar ionosphere as a transverse hydromagnetic wave. This is the *DPmi* field at the transient state. Total disturbance field consists of the superposition of these fields each of which varies rapidly in a few minutes. In high latitudes, effects of particle precipitation and Psc triggered by SC's are added and resultant time variation becomes very complex.

As one of candidates for the cause of the latitudinal reversal of SC polarization on the ground, we can consider horizontal movement of ionospheric current vortices as shown in Fig. 10. As described above, the polar electric field responsible for *DPpi* is directed from dusk to dawn. The ionospheric current vortices due to this electric field are counterclockwise in the morning side and clockwise in the afternoon side.

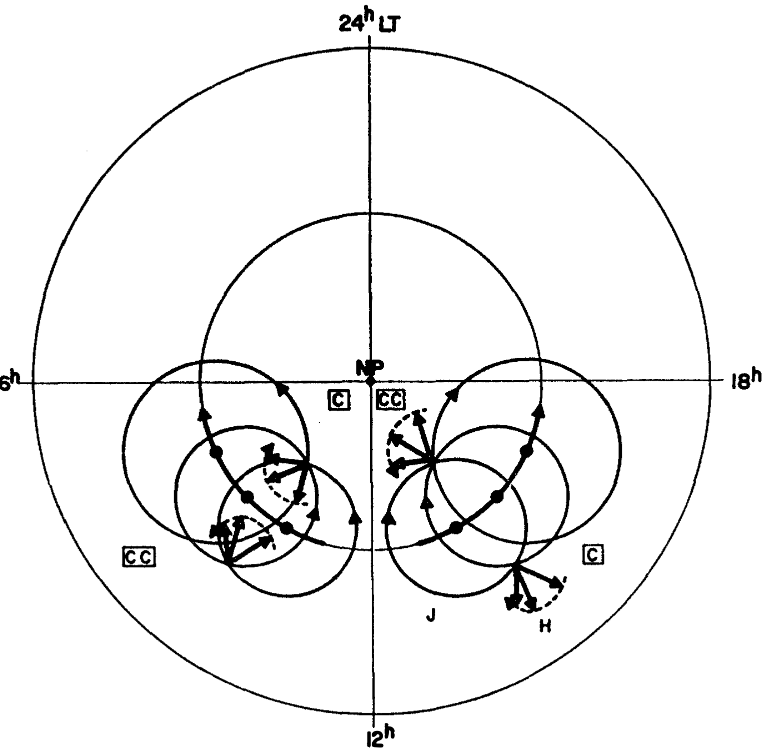

Fig. 10. A model for the latitudinal polarization reversal in high latitudes on the ground. C and CC represent clockwise and counterclockwise polarization. The rotational sense becomes opposite at each side of the locus of the center of a current vortex moving in the polar ionosphere.

The two vortices move from around noon to dawn- and dusk-side when the compressional wave front propagates earthward in the dayside magnetosphere, and magnetic field due to the current vortices changes its direction at a fixed point on the ground. As can be seen in Fig. 10, rotation of the horizontal vector is counterclockwise in the lower latitude side of the locus of the vortex center in the morning and clockwise in the higher latitude side. In the afternoon, the rotation is clockwise in the lower latitude side and counterclockwise in the higher latitude side. The rotation sense in the lower latitude side agrees with the polarization rules of WILSON and SUGIURA (1961). We may consider that this is the basic mechanism of SC polarization but it is sometimes modified by particle precipitation and/or Psc triggered by SC's.

Acknowledgments

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