JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. A7, PAGES 14,075–14,086, JULY 1, 1997

Anomalous sudden commencement on March 24, 1991

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Abstract. An anomalous geomagnetic sudden commencement (SC) occurred on March 24, 1991. It is characterized by an exceptionally large and sharp impulse observed in its initial part along the noon meridian in middle and low latitudes. The analysis of the SC was made by using high time resolution digital data from the 210° Meridian Magnetometer Chain in the west Pacific, Sub-Auroral Magnetometer Network (SAMNET) in the United Kingdom and southern Scandinavia, the EISCAT Magnetometer Cross in northern Scandinavia and Svalbard, and Canopus in Canada together with other ground and satellite (GOES 6, GOES 7, CRRES, and GMS) data. The results of the analysis suggest that the pulse observed at lower-latitude ground stations was caused by the propagation of a strong magnetospheric compression of short duration (less than 1 min) which has never been observed before this event. The HF Doppler observation in Kyoto near local noon seems to be consistent with existence of the bipolar electric field associated with the propagating compressional magnetic pulse. The SAMNET stations and CRRES in the early morning also detected positive pulses which delays 30–50 s from the pulses in noon sector. Although the delay in the peak time of the pulse observed on the ground is consistent with ionospheric hydromagnetic wave propagation from the dayside to the nightside with finite speed, the initial onset time of the pulse on the ground was almost simultaneous everywhere suggesting the existence of an "almost instantaneous" propagation mode below the ionosphere.

1. Introduction

Several researchers have reported a new radiation belt in the inner magnetosphere which was created during a sudden commencement (SC) on March 24, 1991, and lasted more than a half year [*Vampola and Korth*, 1992; *Blake*, 1992; *Blake et al.*, 1992; *Shea et al.*, 1992; *Li et al.*, 1993; *Wygant et al.*, 1994]. It was observed by the CRRES satellite at $L = 2.6$ near the postmidnight equatorial plane as a so-called "drift echo" event. It is interpreted as a sudden injection or acceleration of charged particles localized in the longitudinal direction. *Li et al.* [1993] successfully simulated this event by particle acceleration due to a sharp compressional electromagnetic pulse launched from the magnetopause at 1500 LT in the very initial stage of the SC. The CRRES actually observed an 130 nT monopolar magnetic pulse and an associated bipolar electric pulse with a peak-to-peak amplitude of 80 mV/m. The duration of the pulse is about 2 min. Such a large and sharp pulse has never been observed before in this region of the magnetosphere. The SC itself might be produced by a coronal mass ejection (CME) driven interplanetary shock which was presumably related with a 3B optical flare at 2246 UT on March 22, 1991.

Since the analyses of this event have mostly been limited to particle data so far, it is necessary to study properties of the electromagnetic pulse observed by CRRES in more detail by analyzing other magnetic data. Although the CRRES observations and the simulation by *Li et al.* [1993] greatly contributed to understand this peculiar event, we have to recognize that the CRRES observations were made at one point in the magnetosphere. It is difficult therefore to discuss in detail about excitation and propagation of the observed pulse. Analyses of SCs made so far [see *Araki*, 1994] show that a simple compression of the magnetosphere causes a complex global distribution of amplitude and waveform of SC. The main positive H component increase of SCs is often preceded by a positive or negative impulse of short duration. This preceding impulse can be much larger than the main impulse in high latitudes. It is considered to be caused by a secondary induced ionospheric current of polar origin and is not directly related with the magnetospheric compression. We have to check therefore whether the pulse observed by CRRES was directly caused by the compression of the magnetosphere and was propagated from dayside to nightside by analyzing multipoints observations in space and on the ground.

If the pulse is the direct effect of magnetospheric compression, we have to explore the corresponding structure in the solar wind dynamic pressure. The postulated pressure pulse should have a large amplitude and a short duration which have never been detected in the solar wind. We have to consider how the pulse was formed and maintained in the solar wind, because such a sharp and large pulse would steepen and decay rapidly.

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Paper number 96JA03637.
0148-0227/97/96JA-03637$09.00

One problem in analyzing the geomagnetic data on the ground is that the temporal variation during the SC is so rapid that both the ordinary photorecording normal-run magnetograms and the standard 1-min digital data from routine observatories are almost of no use. Therefore we have to derive the maximum information from higher time resolution digital data collected from limited areas. The results of this effort are reported in this paper.

2. Background Model

We consider that three different physical processes occur in the system composed of the magnetosphere, the ionosphere, and the conducting Earth when the magnetosphere is compressed by an sudden increase of the solar wind dynamic pressure [*Araki*, 1977, 1994]. The direct effect of the magnetopause current increase propagates down to the low- and middle-latitude ionosphere across the geomagnetic field as a compressional hydromagnetic wave and produces a stepwise increase of the geomagnetic H component on the ground. The amplitude is largest at the equator and decreases with increasing latitude. This field is denoted by DL, which means a disturbance dominant in low latitudes. A dusk-to-dawn electric field along the compressional hydromagnetic (HM) wave front propagating in the dayside magnetosphere is transmitted to the polar ionosphere by a transverse HM wave converted from the compressional mode wave [*Tamao*, 1964a]. This electric field induces a twin vortex ionospheric current system [*Tamao*, 1964b] which produces a sharp pulse called the preliminary impulse (PI). This disturbance field is denoted DP_{pi} field (DP means the disturbance field of polar origin). The twin vortex current system for the DP_{pi} field was first proposed by *Nagata and Abe* [1955] as the equivalent current system, modified by *Araki et al.* [1985] and detected as an actual current by the MAGSAT observation [*Araki et al.*, 1984].

If the increased dynamic pressure is continuously kept up behind the interplanetary shock, the magnetospheric convection has to adjust itself to a new compressed state of the magnetosphere. As a result, the dawn-to-dusk convection electric field is enhanced. It is also transmitted along geomagnetic lines of force to the polar ionosphere to produce a twin vortices ionospheric current system with a sense opposite to that of the DP_{pi} field. This current system produces the main impulse (MI) of polar origin on the ground which is called DP_{mi} field. Thus the disturbance field of an SC is decomposed into three subfields:

$$D_{\mathrm{sc}} = DL + DP_{\mathrm{pi}} + DP_{\mathrm{mi}}.$$

An SC often triggers pulsations (P_{sc}) at higher latitudes. In this case a local disturbance field denoted as D_{Psc} is added to the right-hand side. The field of the SC in high latitudes may also be modified by a substorm [*Iyemori and Tsunomura*, 1983; *Le et al.*, 1993] and particle precipitation [*Brown*, 1973].

The cross-field propagation of the magnetospheric compressional effect to low latitudes by a compressional HM wave and field-aligned transmission of dusk-dawn electric field to the polar ionosphere by a transverse HM wave are fundamental mechanisms which should always be taken into account when we consider the compression and expansion of the magnetosphere. If the compression is localized on one side (dawnside or duskside) of the magnetosphere, the appearance of twin vortices will be limited to that side. If a transient local compression moves along one side of the magnetosphere, moving twin vortices will be observed in the polar ionosphere. This idea was used in the interpretation of the traveling magnetospheric convection vortices [*Glassmeier*, 1992]. An analysis shows that a geomagnetic disturbance during a magnetospheric expansion can also be decomposed into the DL, DP_{pi}, and DP_{mi} field with opposite sense [*Araki and Nagano*, 1988].

3. Results of Analysis

Table 1 is a list of the ground stations which are used in this analysis. The sampling interval of the digital observations is given in the last column. Location of the magnetometer networks and satellites is shown in Figure 1.

3.1. Noon Sector

3.1.1. Kakioka: A very sharp and large amplitude pulse appears at the initial part of the SC in each component (Figure 2a). The H component amplitude of this pulse is 202 nT at Kakioka (KAK) and 234 nT at Memambetsu (MMB, 34.8°N) north of KAK. We checked amplitude of SCs that occurred at Kakioka between 1957 and 1994 and found that the amplitude of the pulse is largest. The second and third largest SC occurred on July 8, 1991, and April 30, 1960, and the H component amplitude at KAK was 146 and 124 nT, respectively. Thus the initial pulse of the SC under consideration is about 1.4 times larger than the second largest SC. Seventeen SCs with amplitude larger than 50 nT were observed at KAK for 12 years after 1983 when the digital observation started. Ten minute plots of them are shown in Figure 2b. Figure 2b shows the SC under consideration is anomalous not only in amplitude but also in waveform. The H component of usual SCs increases initially in several minutes and stays steady around a higher level. In the event on March 24, 1991, on the other hand, the H component rapidly increases to the peak value (202 nT) within 1 min, decreased once to the level lower than the initial level and then increased gradually to the second peak in a few minutes. The H component amplitude of this second peak is 77 nT and large enough as a peak value of an SC. As was mentioned in the Introduction, a positive H component pulse sometimes precedes the main impulse [see *Kikuchi and Araki*, 1985], but it is smaller than the following main pulse in low- and middle-latitude stations.

3.1.2. The 210° Meridian Chain. Figure 3 plots the H and the D component of 1 s sampled values observed along the 210° Meridian Magnetometer Chain [*Yumoto et al.*, 1992, 1996] around local noon. Plots of 1 min values at Honolulu (geomagnetic latitude = 20.5°) are inserted in the middle panel. We note the following characteristics:

Item a1: The SC appears symmetrically in the H component and antisymmetrically in the D component in the northern and the southern hemispheres.

Item a2: The H component pulse is positive and becomes sharper at higher-latitude stations. The duration of the pulse is 60–80 s in the lower-latitude stations.

Item a3: The peak in the H component pulse appears delayed at the lower-latitude stations.

Item a4: In the D component a sharp pulse with a duration of 10–20 s is superposed on a broader pulse with opposite sense. The latter has a duration similar to the H component pulse (60–80 s).

Item a5: The sense of the D component variation is westward for the sharp pulse and eastward for the broader pulse in

Table 1. Stations Used in This Analysis

Station Name	Abbreviation	Geographic		Geomagnetic		Sampling Interval
		Latitude	Longitude	Latitude	Longitude	
		Svalbard				
New Alesund	NYA	78.92	11.95	75.31	131.24	10 s
Hopen	HOP	76.50	25.00	71.60	132.45	10 s
Bjornoyja	BJN	74.50	19.20	70.94	125.07	10 s
		EISCAT Magnetometer Cross				
Soroya	SOR	70.54	22.22	67.3	107.9	20 s
Kilpisjarvi	KIL	69.02	20.79	66.0	105.6	20 s
Alta	ALT	69.86	22.96	66.6	107.8	20 s
Kevo	KEV	69.76	27.01	66.2	110.6	20 s
Kautokeino	KAU	69.02	23.05	65.8	107.2	20 s
Muoni	MUO	68.02	23.53	64.7	106.7	20 s
Pello	PEL	66.90	24.08	63.6	106.0	20 s
		SAMNET				
Faroes	FAR	62.05	352.98	60.77	78.12	5 s
Glenmore	GML	57.16	356.32	54.94	77.99	5 s
York	YOR	53.16	358.95	50.99	78.57	5 s
Nordli	NOR	64.37	13.36	61.28	95.28	5 s
Kvistaberg	KVI	59.50	17.63	55.83	95.95	5 s
Oulu	OUL	65.10	25.85	61.30	105.56	5 s
Nurmijarvi	NUR	60.51	24.66	56.59	102.17	5 s
		CANOPUS				
Fort McMurray	FMM	56.7	248.8	63.2	315.3	5 s
		210° Meridian Chain				
Moshiri	MSR	44.37	142.27	37.76	212.96	1 s
Kagoshima	KAG	31.48	130.72	25.23	201.99	1 s
Chichijima	CBI	27.15	142.30	20.65	212.74	1 s
Weipa	WEP	−12.68	141.88	−23.06	214.07	1 s
Birdsbille	BSV	−25.83	139.33	−37.08	212.86	1 s
Adelaide	ADE	−34.67	138.65	−46.72	213.34	1 s
		Others				
Memambetsu	MMB	43.90	144.20	34.75	210.46	1 s
Beijing	BJI	40.06	116.18	29.26	186.40	6 s
Kakioka	KAK	36.23	140.18	26.77	207.99	1 s
Honolulu	HON	21.32	202.00	21.51	268.84	1 min

the northern hemisphere. It is reversed in the southern hemisphere.

Item a6: The amplitude of the *D* component variations is larger at higher latitudes for both sharp pulse and broader pulse.

Item a7: The peak of the sharp *D* component pulse appears almost simultaneously at all stations.

Item a8: The level of the quasi-steady state 2–3 min after the onset of the SC (shaded portion) is higher at lower lati-

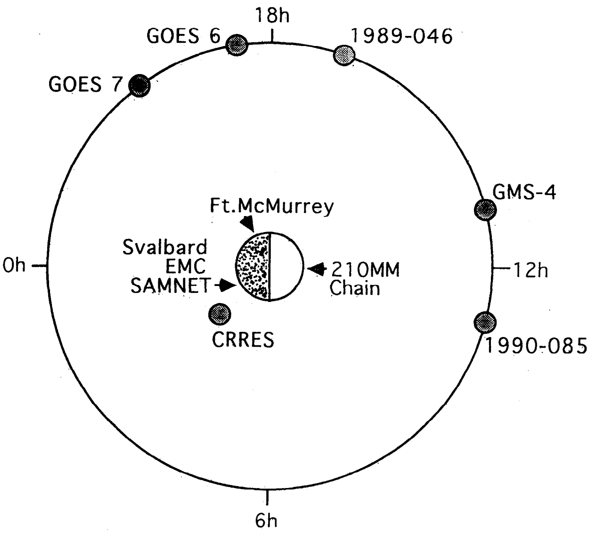

Figure 1. Equatorial projection of location of satellites and magnetometer networks on the ground used in this analysis.

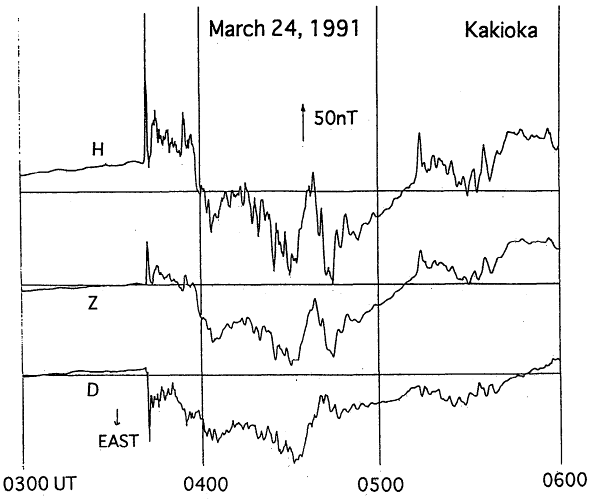

Figure 2a. Sudden commencement (SC) observed at Kakioka (geomagnetic latitude = 26.6°N), Japan on March 24, 1991.

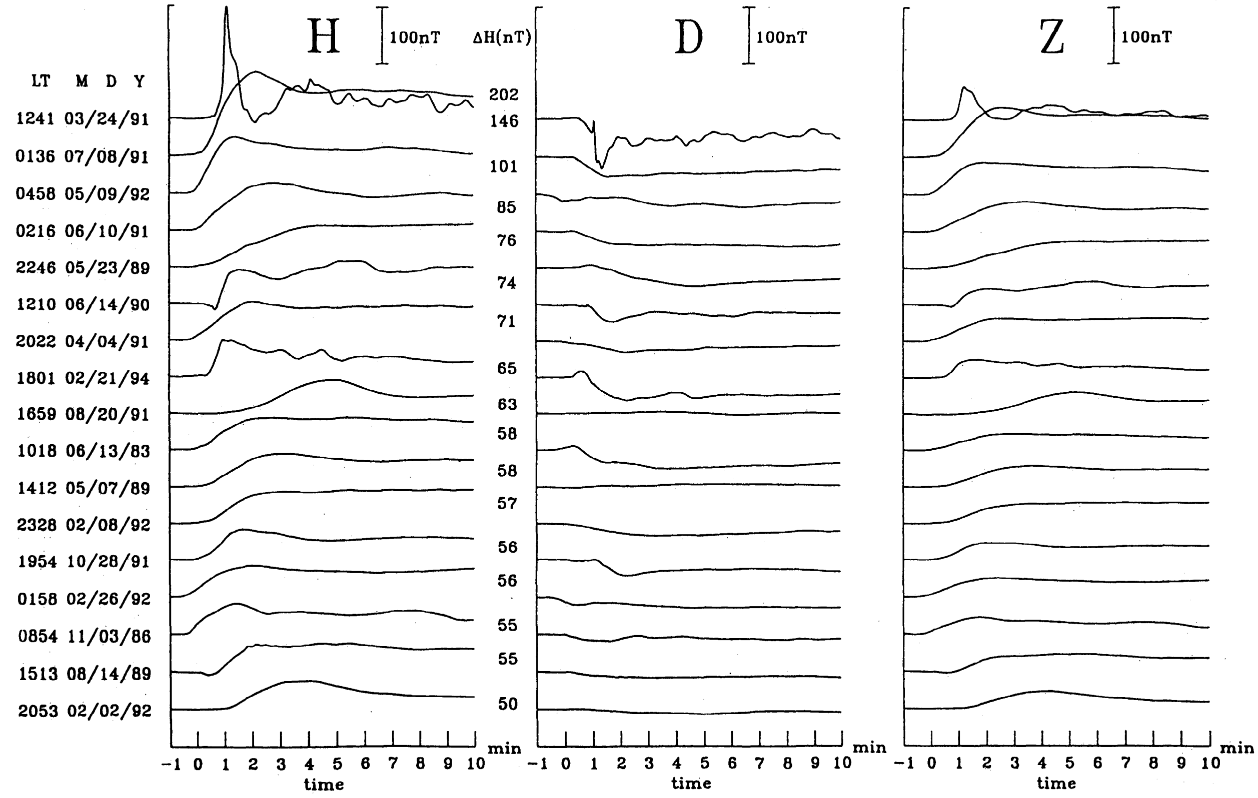

Figure 2b. Seventeen largest SCs observed at Kakioka between 1983 and 1994.

tudes for the *H* component (the peak value was 95 nT at CBI and 77 nT at KAK at about 0345:13 UT) and at higher latitudes for the *D* component. The *D* component deflection is eastward in the northern hemisphere and westward in the southern hemisphere.

Item a9: A pulsation appears predominantly in the *H* component at the higher-latitude stations. The period is almost the same (about 22 s) at the conjugate stations, MSR (geomagnetic latitude = 37.8°N) in the northern hemisphere and at BSV (−37.1°S) in the southern hemisphere. The pulsation almost disappears at the lower-latitude stations KAG (25.2°N), CBI (20.7°N), and WEP (−23.1°S).

3.1.3. Honolulu, Beijing, GMS, and HF Doppler: The following items refer to observations made on the ground and on the geosynchronous orbit.

Item a10: One minute values at Honolulu do not provide much information about the fine structure of the pulse, but the *H* component showed the two large peak values of 96 nT at 0343 UT and 88 nT at 0346 UT.

Item a11: Six second sampled values at Beijing Observatory (29.1°N) (not shown here) show a similar time variation to that at MMB.

Item a12: The geosynchronous meteorological satellite GMS at 140°E longitude (1300 LT) observed a sudden increase of high-energy ions at 0340:50 (Nagai, private communication, 1995). If it indicated the onset time of the SC at the geosynchronous orbit and if the SC was propagated along the Sun-Earth line to KAK around noon, the average propagation speed is estimated as 810 km/s from difference in the onset time.

Item a13: The HF Doppler observation (Figure 4) at Kyoto (geomagnetic latitude = 24.6°N), Japan, shows a clear frequency shift of the JJY standard radio signal (8 MHz) transmitted from Nazaki about 390 km northeast of Kyoto. A sharp positive pulse and a broader negative pulse in the frequency shift successively appear in accordance with the increase and decrease of the *H* component pulse at KAK.

3.2. Early Morning Sector

Data from the Sub-Auroral Magnetometer Network (SAMNET) [*Yeomen et al.*, 1990], the EISCAT Magnetometer Cross (EMC) [*Luhr et al.*, 1984] and from three stations in Svalbard are plotted together with data obtained by the CRRES satellite in Figures 5a and 5b. These observations in the European sector were made in the early morning hours (0200–0400 LT). What we read from Figures 5a and 5b is summarized as follows.

3.2.1. SAMNET and CRRES: Observations at seven SAMNET stations and the satellite CRRES are summarized as follows.

Item b1: There are no detectable simultaneous pulses at the time of the initial pulse observed in the noon sector.

Item b2: The peak of the first pulse of the *H* component appears 30–50 s later, and the duration is longer than the *H* component pulses observed in the noon sector. The time difference between the lowest-latitude station YOR in the SAMNET and CBI of the 210° Chain is 30–40 s.

Item b3: The peak time of the first *H* component pulse is delayed from east to west (NUR → KVI → GML, and OUL → NOR → FAR), suggesting a propagation from the dayside to the nightside.

Item b4: The amplitude of the first *H* pulse is slightly less than 400 nT at the middle- and lower-latitude stations (NUR, KVI GML, and YOR) and equal to or larger than 400 nT at higher-latitude stations (OUL, NOR, and FAR).

Item b5: The increase of the *H* component pulse at the three higher-latitude stations (FAR, NOR, and OUL) seems to be delayed from that of the four lower-latitude stations and also of the EISCAT Magnetometer Cross stations at higher latitudes.

Item b6: A pulsation appears after the first pulse. The period is about 115 s at middle latitudes (NUR, KVI, and GML) and 130 s at higher latitudes (OUL, NOR, and FAR).

Item b7: The maximum peak-to-peak amplitude of the pulsation is estimated to about 1200 nT at OUL although the lower peak is not known due to saturation. The amplitude is larger at the eastern stations nearer to the sunlit hemisphere (OUL and NUR) than the western stations (FAR and GML) at a similar latitude. The *H* component pulsation almost disappears at the lowest-latitude station YOR.

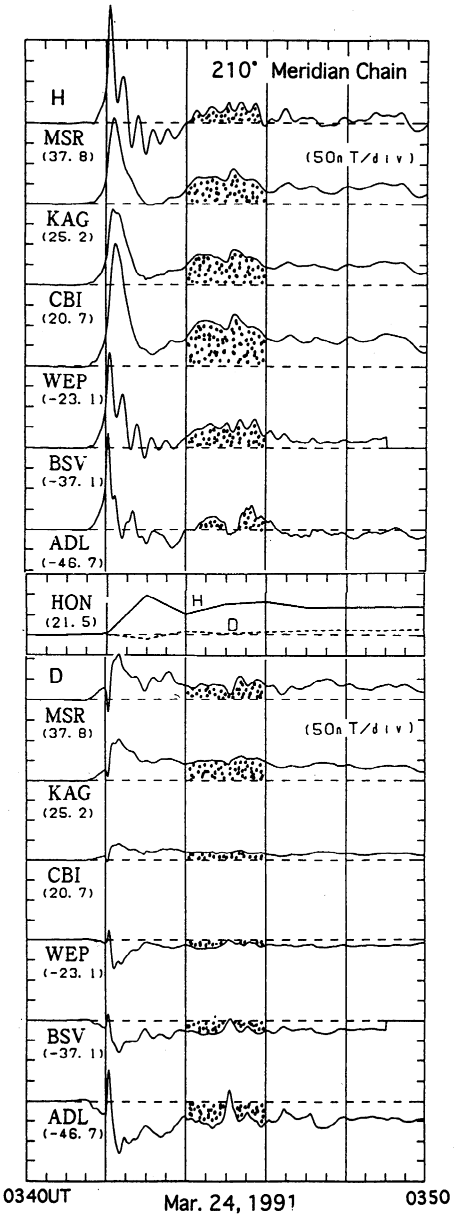

Figure 3. The SC observed around noon at six stations along the 210° Meridian Magnetometer Chain (1 s values) and Honolulu (1 min values). Geomagnetic latitude of each station is indicated in the parenthesis.

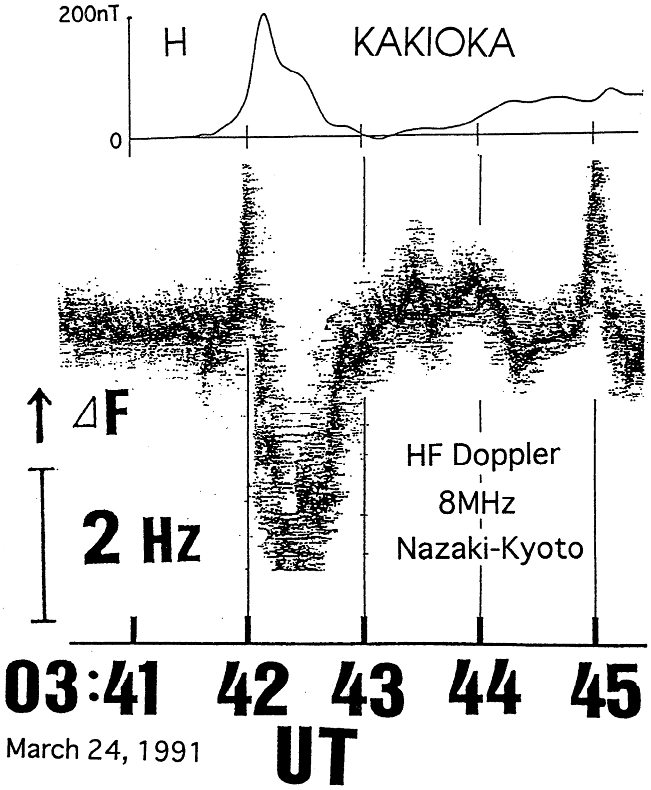

Figure 4. The HF Doppler frequency shift observed at Kyoto (geomagnetic latitude = 24.6°N), Japan during the SC. The HF radio signal is transmitted from Nazaki about 390 km northeast of Kyoto. The top panel shows the *H*-component at Kakioka (geomagnetic latitude = 26.6°).

Item b8: The satellite CRRES which was in its inbound path at 2.5 LT and $L = 2.6$ (8700 km altitude) near the equatorial plane (−12.0° geomagnetic latitude) observed a positive *H* component pulse with about 130 nT amplitude at approximately the same time as the first pulse in the SAMNET. The waveform (Figure 5a, bottom) is most similar to that at YOR, the lowest-latitude station of SAMNET in similar longitude. Charged particle observations are described in the references cited in the Introduction.

3.2.2. EISCAT Magnetometer Cross (EMC): Geomagnetic variations at the six stations along the EISCAT Magnetometer Cross (Figure 5b, bottom) show the characteristics below.

Item b9: After a smaller increase of the *X* component it decreased at all the stations. Both the first increase and the second decrease are larger at higher-latitude stations (SOR, ALT, KIL, and KEV) and are very small at the lowest-latitude station PEL.

Item b10: Pulsations appears at all stations. It is difficult to determine the accurate period of the pulsation because of the low time resolution (20 s), but it ranges between 120 and 160 s.

Item b11: The pulsation appeared more clearly in the *Y* component which oscillated almost coherently at all seven stations. The *Y* component amplitude is largest at ALT.

Item b12: The maximum peak-to-peak amplitude of the initial portion of the pulsation at PEL is more than 1500 nT for the *X* component and more than 900 nT for the *Y* component.

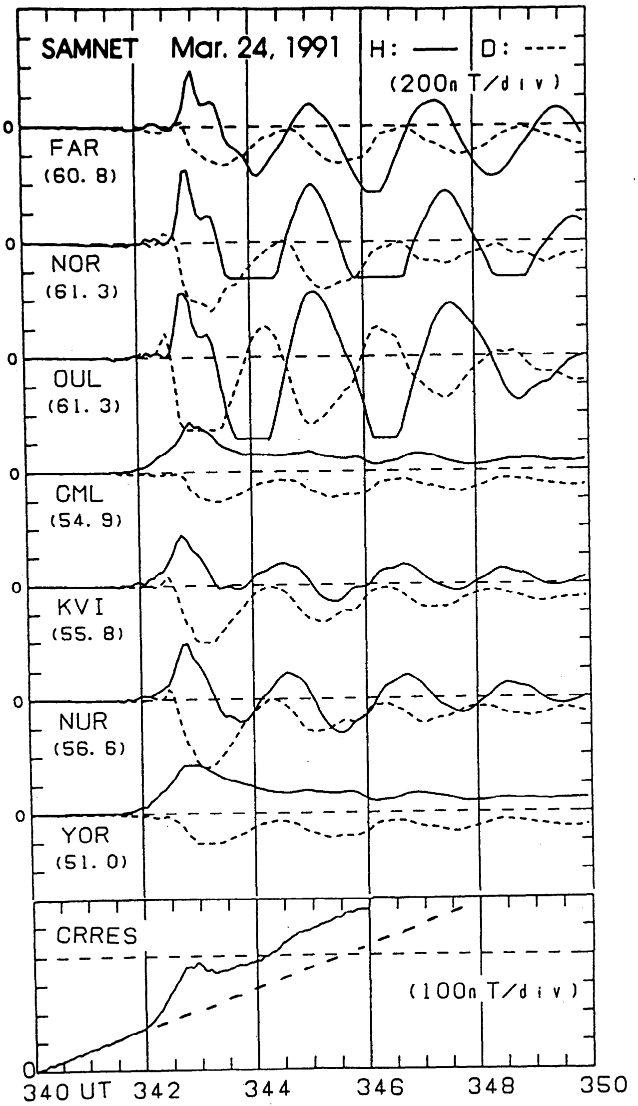

Figure 5a. The SC observed in the SAMNET and by the CRRES satellite in early morning hour. Geomagnetic latitude of ground stations is indicated in parenthesis.

3.2.3. Svalbard: The SC at the three geomagnetic stations in Svalbard is plotted in Figure 5b (top) from which we notice the following two characteristics.

Item b13: The X component variation consists of a first smaller positive pulse and a second larger negative pulse followed by a broader positive pulse.

Item b14: The pulsation appears in both X and Y component, but the amplitude is much smaller than that at EMC.

3.3. Evening Sector

3.3.1. GOES 6 and 7: The geosynchronous satellites GOES 6 and 7 detected the SC in the evening (1840 and 2032 MLT, respectively, see Figure 6). Here we mention two items below.

Item c1: The geosynchronous satellites GOES 6 and 7 detected the SC in the evening (1840 and 2032 MLT, respectively, Figure 6). The onset time was identified as 0341:36 UT at GOES 6 and 0341:53 UT at GOES 7 by Zwickl and Sauer [*Blake*, 1992]. It is important to note that the time associated with each of the uniform 3.06 s samples from GOES can be offset from universal time by approximately 2 s.

Item c2: The onset at GOES 6 is almost simultaneous with the ground SC signature in the noon sector. The disturbance is dominantly in the H_p component parallel to the Earth's rotation axis (maximum amplitude is about 65 nT) at GOES 6 and in the earthward H_e component (120 nT) at GOES 7. However, it should be noted that as a result of the filters in the GOES magnetometers, there can be underestimates or overestimates of the measurements, depending on the component and direction of signal change. These difficulties occur during offset changes in the H_p component and gain changes in the H_e and H_n components and for a few following points, especially when there are large variations in the magnetic field. An examination of the raw data for this event shows that there were several instances where this situation occurred and the true amplitude of the disturbances seen at GOES may have been different from that in Figure 5.

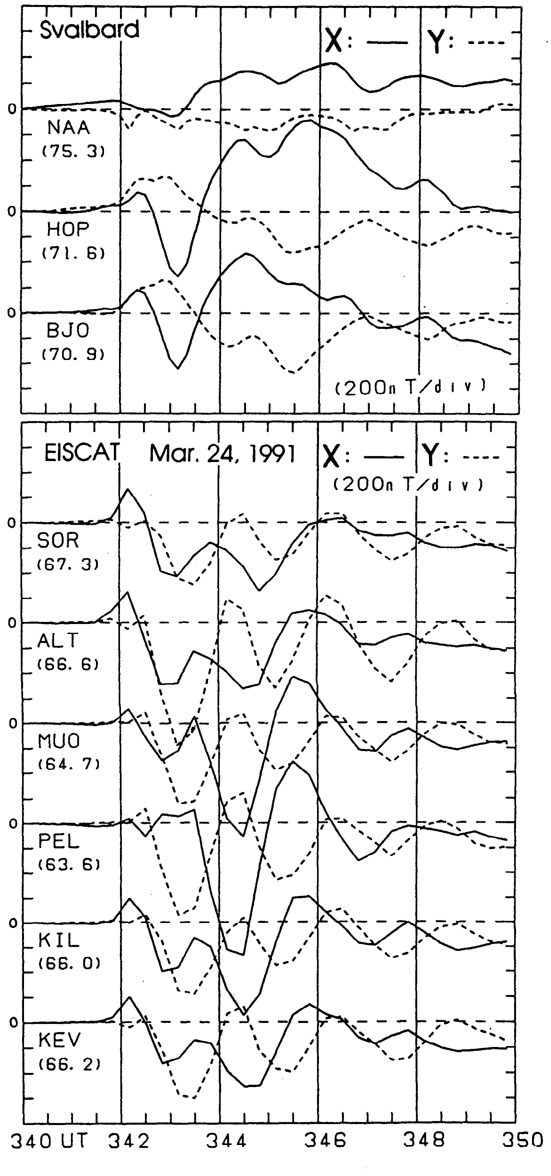

Figure 5b. The SC observed in the EISCAT Magnetometer Cross and Svalbard in early morning hour. Geomagnetic latitude is indicated in parenthesis.

3.3.2. CANOPUS: Figure 6 (bottom) shows the SC observed at Fort McMurray (geomagnetic latitude: 63.2°N) of the CANOPUS Array [*Samson et al.*, 1991].

Item c3: The X component at this station shows a large positive pulse with an amplitude of nearly 1130 nT after two negative pulses. This appearance of successive pulses at auroral latitudes in the evening sector roughly corresponds to the pulses with similar duration in the early morning hours.

3.4. Onset Time

The H component of the 210° meridian chain near noon and SAMNET in the early morning side are plotted together on amplified scale in Figure 7. What we should note here is that the onset of the SC at each station is almost simultaneous (around 0341:30 UT) within the time accuracy of the measurement (1 s for the 210° chain and 5 s for SAMNET), while the peak of the following impulse is delayed by 30–40 s from the dayside to the early morning as shown by horizontal bars. Figure 6 (bottom) also shows that the SC at Fort McMurray (5 s sampling) started around 0341:30 UT. Figure 8 shows global distribution of the onset time and peak time of the pulse. It also shows peak time of the sharp D component pulse observed in the dayside (item a7 in section 3.1.2).

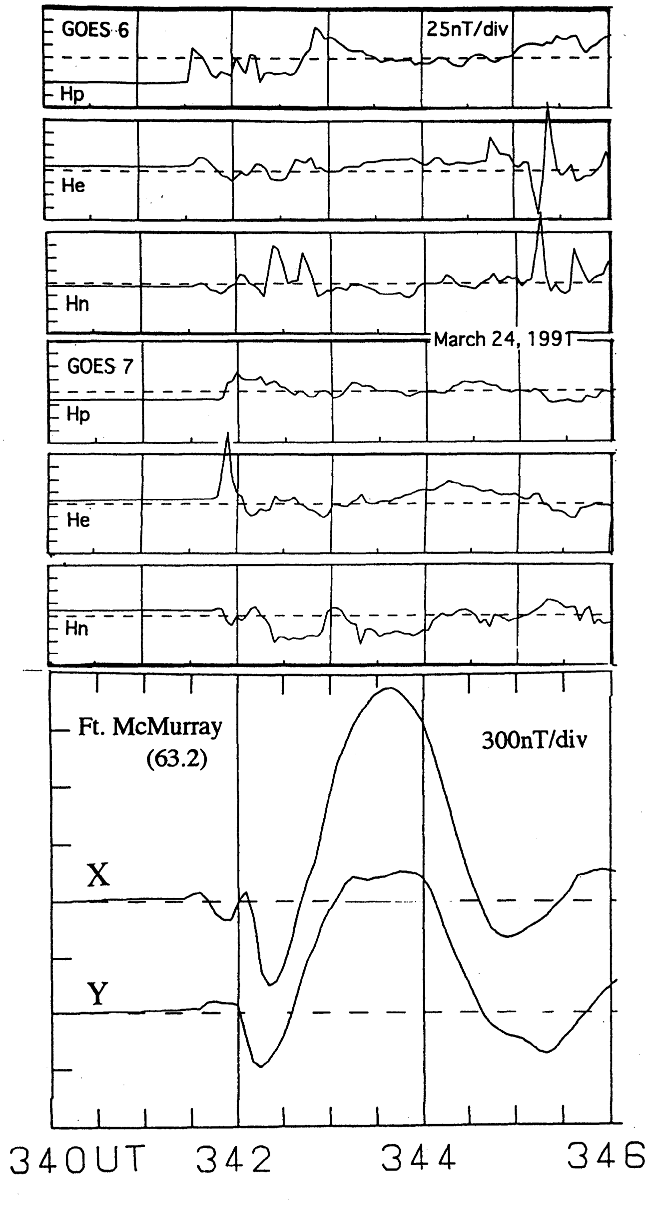

Figure 6. The SC observed by the geosynchronous satellites GOES 6 and 7 and Fort McMurray (geomagnetic latitude = 63.5°), Canada in the evening hour.

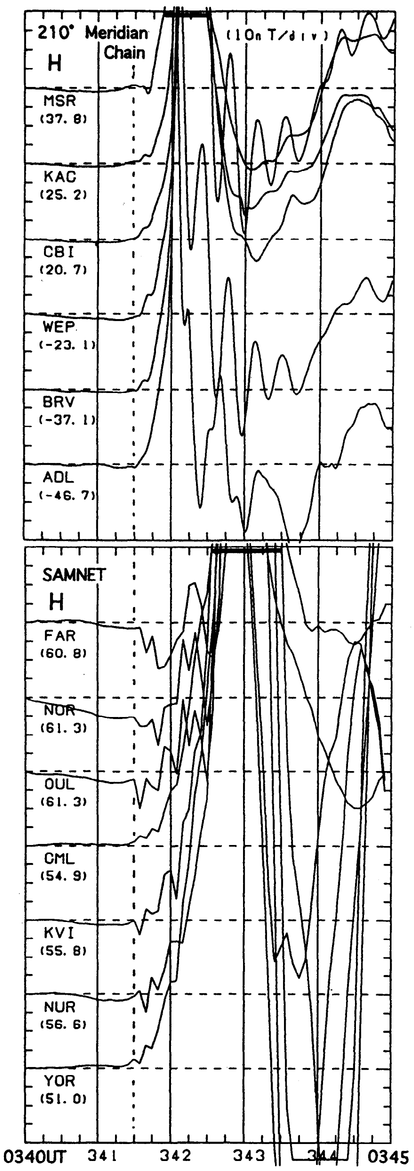

Figure 7. Simultaneous plots of the H component from noon (210° meridian chain) and early morning (SAMNET) on amplified scale.

4. Interpretation and Discussions

Since the large pulse appearing in the initial part (first 60–80 s) of the SC on the dayside is truly anomalous both in amplitude and waveform, interpretation of it seemed to be impossible at first. After checking all the data collected, however, we found that the pulse might be interpreted in the framework of the mechanism described in section 2.

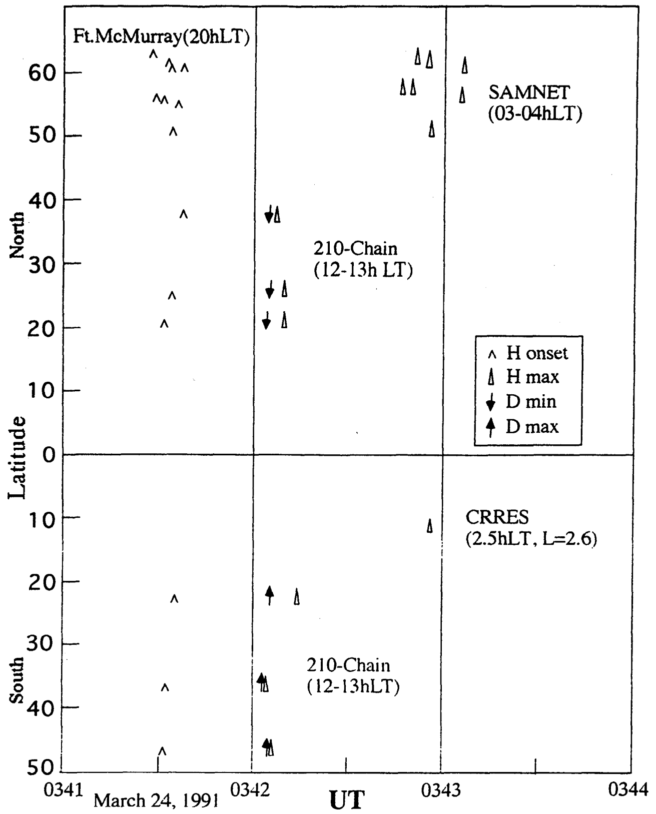

Figure 8. Distribution of the onset time (H_{onset}) and peak time ($H_{\max}$) of the pulse under consideration. Peak time of the sharp D component pulse ($D_{\min}$ and $D_{\max}$) is also plotted.

4.1. Noon Sector

The most important feature to interpret the SC under consideration is hidden in the D component profile along the 210° Meridian Chain around noon (Figure 3). As was mentioned in item (a4) of the previous section, the sharp D component pulse with 10–20 s duration is superposed on the broader (60–80 s) pulse with opposite sense. This means that there were at least two different kinds of variations. The clear increase of amplitude of the sharp pulse with latitude (item a6) suggests that it was caused by an ionospheric current induced in the polar region (that is, it is Dp field). The simultaneity of the peak of the sharp D pulse at each station (item a7 and Figure 8) indicates that it was propagated toward low latitudes almost instantaneously. The broader pulse is discussed later.

The H component distribution is more puzzling. The positive pulse which has duration of 60–80 s in low latitudes becomes sharper and larger at higher latitudes, and the peak time is delayed at lower latitudes (items a2 and a3). The easiest way to understand this latitudinal distribution is to interpret it as a superposition of two pulses of different origin with the same positive sense in both northern and southern hemisphere; one is broader (60–80 s duration) monopolar pulse which is dominant at low latitudes (thus we can call it DL field) and the other is sharper (10–20 s duration) bipolar pulse which is larger at high latitudes (DP field). The latter should have the same polar origin as the D component sharp pulse, and the peak time of both components should coincide with each other. The peak of the broader DL pulse appears later and so the peak of the resultant H component pulse is delayed in the lower-latitude stations where the DL pulse is larger than the DP pulse. The peak time of the resultant pulse of the H and D component almost coincides at higher latitudes because the sharper DP pulse is dominant there.

Figure 9 shows decomposition of the H and the D component pulse observed at KAK into two components (DP and DL field). Waveform (double-peak structure) of the D component is well explained by assuming bipolar form for the DP pulse.

The HF Doppler observation previously described in item a13 is most simply interpreted in terms of vertical motion of the ionosphere if the positive broader pulse under consideration is a compressional pulse propagated from the dayside magnetosphere. The positive magnetic monopolar pulse is accompanied by a bipolar (westward and then eastward) electric field in the dayside ionosphere (see Figure 10) and the $\mathbf{E} \times \mathbf{B}$ drift produces vertical (downward and then upward) motion of the ionospheric plasma and consequently positive and then negative Doppler shift through change of the reflection height [*Rishbeth and Garriot*, 1964].

The geomagnetic variation due to the magnetopause current (DL field) should be approximately parallel to the Earth's dipole axis. Thus a D component variation may also be produced by the magnetopause current if the direction of the local static geomagnetic field on the ground deviates from the geomagnetic dipole north [*Fukushima*, 1966]. The sense of the variation should be eastward if the deviation is westward and westward if it is eastward.

The sense of the D component variations of both the broader pulse (with 60–80 s duration) and the quasi-steady state level along the 210° meridian chain described in the items a5 and a8 are consistent with this consideration because declination along the chain is westward in the north of the equator and eastward in the south and increases in magnitude away from the equator (see a contour map of the geomagnetic declination). Thus we consider that the broader D pulse is the DL field produced by the magnetopause current. The sense of the sharper pulse (with 10–20 s duration) superposed on the broader pulse is opposite to the broader pulse and cannot be explained by the DL field.

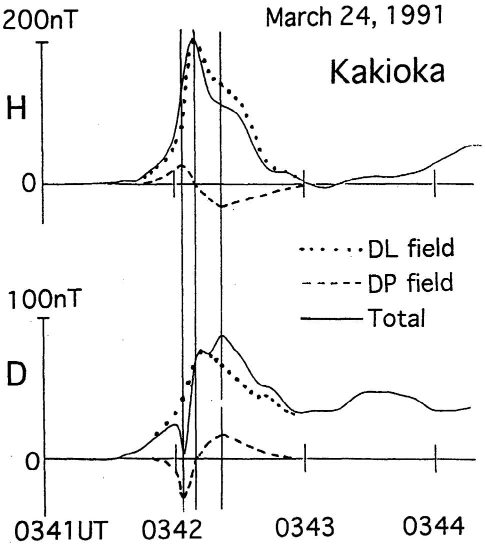

Figure 9. Decomposition of the pulse observed at Kakioka (solid line) into two subfields, DL (dotted line) and DP field (dashed line).

4.2. Early Morning

The features of the early morning data described in items (b1)–(b3) are most easily interpreted by considering that the broader H component pulse observed in the noon meridian propagated to the nightside to produce the delayed first H component pulse at SAMNET. In this interpretation the first positive H component pulse observed at the lower-latitude stations of SAMNET is essentially the DL field due to the magnetopause current and the waveform and amplitude might be modified by a contamination of the DP field of ionospheric origin at higher-latitude stations. The rise and the peak of the H component observed by the CRRES satellite approximately coincide with those of the H component variations at YOR, the lowest-latitude station of SAMNET. There was no preceding pulse at CRRES corresponding to the first positive pulse observed at EMC. This also suggests that the first pulse at EMC was not of magnetospheric origin but produced by an ionospheric current of polar origin.

Thus we can say that the SC observed in the early morning can also be decomposed into a field of polar origin (DP field) and a field dominant in low latitudes (DL field). We consider that the DP field might be related to the sharp DP pulse on the noonside and that the H component observed at CRRES and the lowest-latitude station of SAMNET, YOR, roughly expresses the DL field. Time delays of the H component peaks mentioned in item b3 indicate propagation of the compressional pulse from the dayside to the nightside.

As was mentioned in the Introduction, CRRES observed a drift echo event of magnetospheric high-energy particles. *Li et al.* [1993] simulated this event assuming a particle acceleration due to an electric field associated with the compressional magnetic pulse. Their results show that the best agreement between the simulation and the observation was obtained when the magnetic pulse starts propagating from the magnetopause at 1500 LT which was first concluded from the arrival times of the first newly accelerated electrons and protons observed at CRRES [*Blake et al.*, 1992].

Considering a possible decomposition of the SC field both along the 210° chain and SAMNET into the DP and the DL field and the successful result of the computer simulation of the drift echo event described above, it will be reasonable to assume that the broader pulse (DL field) with 60–80 s duration propagated from the dayside (210° chain) to the early morningside (SAMNET). The time difference between the peaks of the SC observed at the lower-latitude stations of both regions (CBI and YOR) is 30–40 s which corresponds to ionospheric propagation velocity of 370–490 km/s.

4.3. Evening Sector

The time difference (17 s) between the onset at GOES 6 and GOES 7 in the evening corresponds to 1090 km/s propagation velocity in the Sun-Earth direction. It would be a little bit slower if the wavefront propagated from the afternoonside of the magnetosphere as was proposed by *Blake et al.* [1992] and *Li et al.* [1993]. The X component variation at Fort McMurray (geomagnetic latitude = 64.1°N) in the auroral zone begins with two negative pulses followed by a large positive pulse (Fig. 6). The onset is almost simultaneous with that at GOES 6 at 1900 LT. The large pulse has no counterpart at GOES 6 and 7 but seems to correspond to the big negative pulse in the X and Y component at EMC suggesting its ionospheric origin. The two smaller negative pulses might correspond to the DP pulse at noon and early morning.

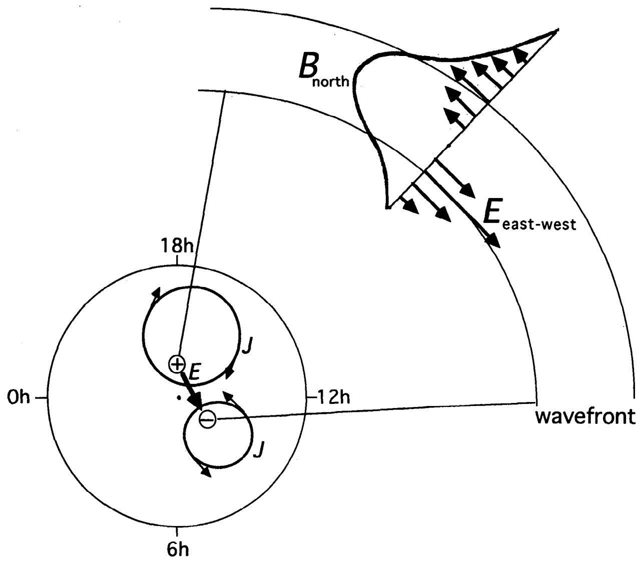

Figure 10. Illustration of propagation of the sharp compressional pulse in the afternoon magnetosphere and ionospheric current vortices due to the electric field projected from the wavefront.

4.4. Variation of the Solar Wind Dynamic Pressure and the *DL* Field

In the discussion of the 210° meridian chain data, we interpreted the sharp and the broad H component pulse in terms of the DP and the DL field, respectively. This means that the latter is directly produced by the solar wind dynamic pressure (Pd) variation. Figure 11 shows propagation of the DL pulse from the dayside magnetosphere to nightside. Thompson [*Blake*, 1992] reported that the geosynchronous satellites, 1990-085 at 1100 LT and 1989-046 at 1700 LT (see Figure 1), were outside the magnetopause for the periods 0341:24–0341:55 and 0341:23–0341:34, respectively. This suggests that the magnetopause was strongly compressed for several tens of seconds. If we assume that the maximum compression occurred at 0341:40 (middle of the magnetopause crossing period observed by 1990-085 near noon and that it produced the peak of the H component pulse at CBI around 0342:20, the propagation velocity is calculated to about 870 km/s. This is reasonably comparable to the propagation velocity of 810 km/s determined from the difference of the onset time of the high-energy particle increase at the GMS satellite and the ground station, KAK, near noon.

Further, the quasi-steady state level of the H component 2–3 min after the onset of the SC increases with decreasing latitude as was mentioned in the item a8. This is consistent with the latitudinal dependence of the magnetic field due to the magnetopause current. Therefore the time variation of Pd associated with the shock should resemble that of the H component observed at the lower latitude stations of the 210° meridian chain (CBI, KAG, and WEP). Although the rise of the broader DL pulse of the H component observed at the lower-latitude stations of the 210° meridian chain is more gradual compared with the sharper DP pulse at the higher-latitude stations, it is still very sharp if it is compared with ordinary SCs (see Figure 2b). The risetime of ordinary SCs ranges between 1 and 9 min with a peak occurrence frequency at 3–4 min [*Maeda et al.*, 1962], while the SC under consideration rises in about 50 s at

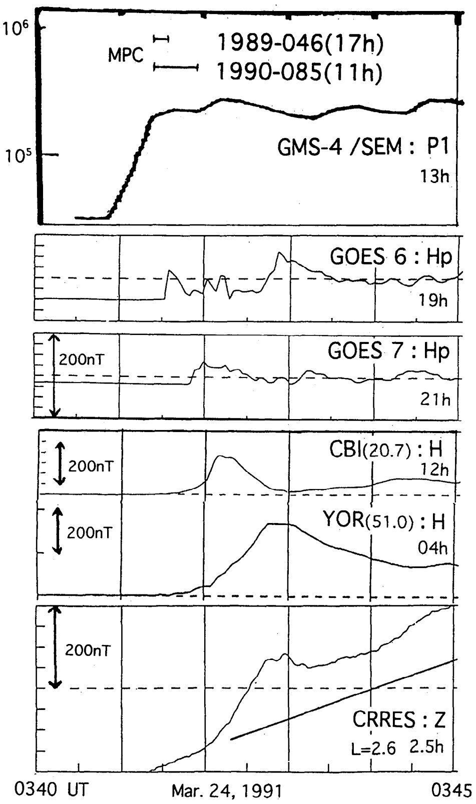

Figure 11. The SC observed by the geosynchronous satellites (GMS-4, GOES 6, and GOES 7), CRRES and on the ground (CBI and YOR). P1, high-energy proton observed by GMS-4; H_p, magnetic field parallel to the rotation axis of the Earth; H, the geomagnetic H component observed on the ground; z, H component observed by the CRRES satellite. Intervals of the magnetopause crossing (MPC) detected by the two geosynchronous satellites, 1989-046 and 1990-085 are shown by the horizontal bars. Geomagnetic latitude of CBI and York is indicated in parenthesis.

CBI if the second peak is taken as the peak of the *DL* pulse. This suggests that the magnetosphere was compressed unusually rapidly at the initial stage of the SC. Since the magnetospheric compression would be faster than that of the *DL* pulse observed on the ground, we speculate the duration of the pulse in the solar wind would be less than 50 s. Such a sharp and large pulse has never been observed in the interplanetary space.

4.5. *DP* Field

A westward and an eastward electric field are induced along the frontside and the rearside, respectively, of a monopolar compressional magnetic pulse propagated inward in the dayside magnetosphere. When the pulse under consideration here arrived in the early morningside, the bipolar electric field was actually detected by CRRES near the equatorial plane. The HF Doppler observation in the dayside (item a8) also suggests existence of the bipolar electric field in the low-latitude ionosphere as described in section 4.1.

When the compressional pulse was propagating in the equatorial magnetosphere, the associated electric field should be transmitted along magnetic lines of force to the polar ionosphere to produce twin vortex type ionospheric currents in a manner similar to the DP_{pi} field described previously [*Tamao*, 1964b; *Araki*, 1994]. The current will be enhanced by the high electrical conductivity of the dayside ionosphere and extend more to lower latitudes than on the nightside. Usually, the two centers of the twin vortices are located approximately symmetrically with respect to the noon meridian corresponding to the normal incidence of the interplanetary shock along the Sun-Earth line. If the shock is incident obliquely on the afternoonside of the magnetosphere as reported by *Blake et al.* [1992], the centers will rotate eastward around the north pole, and the current vortex on the morningside shifts toward noon. This situation is illustrated in Figure 10. The current direction of the morning vortex is counterclockwise (clockwise) in the northern hemisphere when the magnetospheric electric field is westward (eastward). The afternoon vortex becomes larger because of nonzero Hall conductivity and its nonuniformity in day-night direction.

Successive projections of an westward and an eastward electric field from the dayside magnetosphere will produce a counterclockwise and then a clockwise ionospheric current vortex and a bipolar magnetic pulse will be observed on the ground. The sense of the bipolar pulse will be same as the *DP* component shown in Figure 9 at the lower-latitude side of the morning vortex around noon; positive and then negative for the *H* component and negative and then positive for the *D* component.

It should be noted here that the solar X ray intensity was kept higher than the C class flare level throughout the day. It was nearly the M class flare level when the SC occurred. This might have contributed to enhance ionospheric currents through the enhanced conductivity of the lower ionosphere.

The width of the compressional wavefront of ordinary SCs propagating in the magnetosphere is usually much larger than the effective size of the magnetosphere. Therefore the magnetospheric electric field associated with the compressional wavefront is in one direction (dusk-to-dawn) over the whole effective magnetospheric size. The spatial distribution of the electric field in the magnetosphere and consequently the electric field projected into the polar ionosphere therefore is relatively simple except for the complexity caused by the wavefront deformation due to nonuniform distributions of the HM wave velocity and reflection at the plasmapause. On the other hand, the wavelength of the sharp compressional pulse under consideration should be smaller than the size of the dayside magnetosphere and so the westward and the eastward electric field coexist simultaneously in the dayside magnetospheric equatorial plane. Field aligned mapping of these electric fields to the polar ionosphere will produce more complex geomagnetic signatures with smaller scales on the ground. *Lysak and Lee* [1992] simulated the response of the dipole magnetosphere with a perfectly conducting ionosphere to an impulsive pressure pulse in the solar wind. Their results for an excitation by a transient impulse of 60 s duration show that several vortices appear at the ionospheric level and that the field line resonance appears at two latitudes. *Lysak and Song* [1994] improved the calculation by introducing the finite conductivity of the ionosphere. The observations in the EISCAT Magnetometer Cross and SAMNET should be further examined in the light of this kind of simulation study.

4.6. Instantaneous Propagation Mode of SC

As described above it seems to be reasonable to assume that the *DL* pulse observed in dayside was propagated to nightside. However, Figures 6, 7, and 8 showed that the onset of the pulse is almost simultaneous in dayside, morningside, and eveningside. This suggests that there is an almost instantaneous propagation mode from day to nightside although the main impulse is propagated with a finite HM wave velocity of several hundred kilometer per second.

Kikuchi and Araki [1979] discussed instantaneous propagation of an ionospheric electric field by the zeroth-order transverse magnetic (TM) mode in the Earth-ionosphere waveguide. *Ohnishi and Araki* [1992] showed that the rise of the SC caused on the ground by the interaction between a plane HM wave and the Earth-ionosphere system is almost simultaneous at all local times in the equatorial plane. Although effectiveness of the zeroth-order waveguide mode is questioned by *Pilipenko* [1990], the observation above could be accepted as an evidence for the existence of a propagation mode much faster than the HM wave propagation. Main wave energy is carried by HM wave in and above the ionosphere but the forerunner or onset is able to propagate almost instantaneously. The physical mechanism of this instantaneous propagation should be studied further. SCs with a sharp rise provide a good probe to explore this problem because of its well-defined onset time, if it is observed by magnetometers with high time resolution and high sensitivity.

5. Conclusion

The following summarizes the generation of the anomalous SC on March 24, 1991, based on the results of the data analysis described above and knowledge about SCs accumulated so far.

An interplanetary shock with an exceptionally steep and large pulse of momentum increase in the initial part of the wave front impacted the magnetosphere on the afternoonside and compressed it rapidly. The pulsed compression (positive magnetic pulse) propagated at an average velocity of 800–900 km/s through the dayside magnetosphere. The effect of compression started at the geosynchronous satellites GMS (at 12.8 LT) at 0340:50 and then reached GOES 6 (at 1840 LT) around 0341:36 and GOES 7 (2032 LT) at 0341:53. The magnetopause crossing was observed during 0341:24–0341:55 and 0241:23–0241:34 by the geosynchronous satellites 1990-085 at 1100 LT and 1989-046 at 1700 LT, respectively.

The compressional pulse produced an geomagnetic H component variation (DL pulse) with duration of 60–80 s at dayside low-latitude ground stations. The onset time of the magnetic pulse was 0341:34 UT at Kakioka, Japan. It was converted to an electromagnetic wave ducted in the space below the ionosphere and propagated to the nightside causing an almost simultaneous global onset of the DL pulse. The shielding current flowing in the ionosphere suppressed increase of the H component on the ground and the rise of the pulse became gradual on an expanded time scale. The initial rise was more gradual in the nightside than in the dayside, and the onset of the pulse seemed to be apparently delayed from that in the dayside.

The H component DL pulse reached its maximum amplitude around 0342:20 at the dayside low-latitude stations of the 210° chain near noon. It was propagated in the ionosphere to the nightside and the maximum amplitude was observed around 0342:40–0342:50 at the lower-latitude stations of SAMNET in the early morning sector (0500 LT). At 0343 UT the electric power line system was broken down over large parts of middle and south Sweden. Around 0341:58 the compression reached the CRRES satellite located at 2.6 R_E, 2.5 LT, and −12° latitude [see *Blake*, 1992].

A strong azimuthal bipolar electric field was induced along the wave front of the positive compressional magnetic pulse. The direction in the dayside magnetosphere was westward on the frontside of the pulse and eastward on the rearside. It was actually detected by the HF Doppler observation in low latitude near noon and by CRRES in the equatorial magnetosphere in early morning. The peak-to-peak amplitude at CRRES was 80 mV/m [*Wygant et al.*, 1994]. Charged particles accelerated by this electric field produced a drift echo event forming a radiation belt in the inner magnetosphere which lasted more than half a year. The radiation belt was detected also by Exos D (Akebono) (A. S. Yukimatsu et al., private communication, 1994).

The azimuthal bipolar electric field associated with the magnetic pulse propagating in the afternoon magnetopause was transmitted along field lines to the polar ionosphere and produced ionospheric current vortices which extended instantaneously to lower latitudes. They produced a sharp bipolar DP pulse in both H and D components. The ionospheric currents produced might be intensified in the dayside by the high conductivity in the lower ionosphere due to the enhanced level of solar X rays. A superposition of the DL and the DP pulse produced a complex waveform distribution of the resultant disturbance field.

The wavelength of the compressional pulse which is much shorter than the width of the compressional wave front of ordinary SCs might produce several smaller-scale current structures in the high-latitude ionosphere as was shown in the simulation by *Lysak and Lee* [1992] and *Lysak and Song* [1994]. The bipolar ionospheric electric field was transmitted also from high to lower latitudes in the nightside, but the lower ionospheric conductivity in this sector prevented the formation of the geomagnetic pulse seen in the dayside, and the effect of the ionospheric current was limited to relatively narrow region centered at auroral latitudes where the electric field was impressed.

The dynamic pressure of the solar wind after the steep large pulse described above increased as is expected for ordinary interplanetary shocks and produced the normal distribution of SC on the ground. The amplitude of the H component of the SC was approximately 88 nT (at 0346 UT) at Honolulu (21.5°N) and 73 nT (at 0345:13 UT) at Kakioka (26.8°N) which are fairly large for low-latitude stations. The compressional wave front excited field line resonance and a big oscillation appeared in the auroral zone especially on the dayside. The period depended on the latitude; 22 s at Memambetsu (geomagnetic latitude = 34.8°N), 120–140 s at SAMNET and 120–160 s at EISCAT Magnetometer CROSS.

The peculiarity of this SC was presumably produced by a large and steep positive pulse superposed on the very beginning of the leading edge of the interplanetary shock. The postulated large sharp pulse in front of the shock has never been observed in the interplanetary space before. If it were a narrow compressed pulse in the solar wind, it would not be able to last long because of high rate of dissipation so that it must have been formed near the Earth. If it is a corotating high-speed stream, the width should be very narrow and estimated as 1.2×10^4 km (approximately 2 R_E) for a 30 s duration pulse.

It was unfortunate that there was no solar wind observation during this extremely rare event. In addition, because of its rapid time variation, ordinary magnetograms and 1 min digital data from routine geomagnetic observatories could not be used for the more detailed analysis of the peculiar pulse on the ground. The results of the analysis therefore are rather speculative, but we nevertheless believe that the picture proposed here is most probable one.

Acknowledgments. We express our sincere thanks to all the members of the 210° MM Magnetic Observation Project for their ceaseless support.

The Editor thanks X. Li, O. Saka, and a third referee for their assistance in evaluating this paper.

References

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

Araki, T., A physical model of geomagnetic sudden commencement, in *Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves*, *Geophys. Monogr. Ser.*, vol. 81, edited by M. J. Engebretson, K. Takahashi, and M. Scholer, pp. 183–200, AGU, Washington, D. C., 1994.

Araki, T., and H. Nagano, Geomagnetic response to sudden expansions of the magnetosphere, *J. Geophys. Res.*, *93*, 3983–3988, 1988.

Araki, T., T. Iyemori, and T. Kamei, Sudden commencements observed by MAGSAT above the ionosphere, *J. Geomagn. Geoelectr.*, *36*, 507–520, 1984.

Araki, T., J. H. Allen, and Y. Araki, Extension of a polar ionospheric current to the nightside equator, *Planet. Space Sci.*, *33*, 11–16, 1985.

Blake, J., CRRES records creation of new radiation belt, STEP International, *2*(8), 1–5, 1992.

Blake, J., W. A. Kolasinski, R. W. Fillus, and E. G. Mullen, Injection of electrons and protons with energies of tens of Mev into $L < 3$ on 24 March 1991, *Geophys. Res. Lett.*, *19*, 821–824, 1992.

Brown, R. R., Sudden commencement and sudden impulse absorption events at high latitudes, *J. Geophys. Res.*, *78*, 5698–5702, 1973.

Fukushima, N., Declination change of s.c., its local-time and seasonal dependence at Kakioka Japan, *J. Geomagn. Geoelectr.*, *18*, 99–102, 1966.

Glassmeier, K.-H., Traveling magnetospheric convection twin-vortices: Observations and theory, *Ann. Geophys.*, *10*, 547–565, 1992.

Iyemori, T., and S. Tsunomura, Characteristics of the association between an SC and a substorm onset, *Mem. Natl. Inst. Polar Res.*, no. 26, 139–147, 1983.

Kikuchi, T., and T. Araki, Horizontal transmission of the polar electric field, *J. Atmos. Terr. Phys.*, *41*, 927–936, 1979.

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

Le, G., C. T. Russell, S. M. Petrinec, and M. Ginskey, Effect of sudden solar wind dynamic pressure changes at subauroral latitudes: Changes in magnetic field, *J. Geophys. Res.*, *98*, 3983–3990, 1993.

Li, X., I. Roth, M. Temerin, J. R. Wygant, M. K. Hudson, and J. B. Blake, Simulation of the prompt energization and transport of radiation belt particles during the March 24, 1991 SSC, *Geophys. Res. Lett.*, *20*, 1234–1235, 1993.

Luhr, H., S. Thuerey, and N. Kloecker, The EISCAT-magnetometer cross, *Geophys. Surv.*, *6*, 305–315, 1984.

Lysak, R. L., and D.-H. Lee, The response of the dipole magnetosphere to pressure pulse, *Geophys. Res. Lett.*, *19*, 937, 1992.

Lysak, R. L., and Y. Song, Generation of ULF waves by fluctuations in the magnetopause position, *Solar Wind Sources of Magnetospheric Ultra-Low Frequency Waves*, *Geophys. Monogr. Ser.*, vol. 81, edited by M. J. Engebretson, K. Takahashi, and M. Scholer, pp. 273–281, AGU, Washington, D. C., 1994.

Maeda, H., K. Sakurai, T. Ondoh, and M. Yamamoto, Solar terrestrial relationships during the IGY and IGC, *Ann. Geophys.*, *18*, 305–333, 1962.

Nagata, T., Distribution of SC* of magnetic storm, *Rep. Ionos. Res. Jpn.*, *6*, 13–30, 1952.

Nagata, T., and S. Abe, Notes on the distribution of SC* in high latitudes, *Rep. Ionos. Jpn.*, *9*, 33–44, 1955.

Ohnishi, H., and T. Araki, Two dimensional interaction between a plane hydromagnetic wave and the Earth-ionosphere system with curvature, *Ann. Geophys.*, *10*, 281–287, 1992.

Pilipenko, V. A., ULF waves on the ground and in space, *J. Atmos. Terr. Phys.*, *52*, 1193–1209, 1990.

Rishbeth, H., and O. K. Garriot, Relationship between simultaneous geomagnetic and ionospheric oscillations, *J. Res. Natl. Bur. Stand, Sect. D*, *68*, 339–343, 1964.

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

Samson, J. C., R. A. Greenwald, J. M. Ruohoniemi, T. J. Hughes, and D. D. Wallis, Magnetometer and radar observations of magnetospheric cavity modes in the Earth's magnetosphere, *Can. J. Phys.*, *6*, 929–937, 1991.

Shea, M. A., D. F. Smart, J. H. Allen, and D. C. Wilkinson, Spacecraft problems in association with episodes of intense solar activity and related terrestrial phenomena during March 1991, *IEEE Trans. Nucl. Sci.*, *39*, 1754–1760, 1992.

Tamao, T., The structure of three-dimensional hydromagnetic waves in a uniform cold plasma, *J. Geomagn. Geoelectr.*, *16*, 89–114, 1964a.

Tamao, T., Hydromagnetic interpretation of geomagnetic SSC*, *Rep. Ionos. Space Res. Jpn.*, *18*, 16–31, 1964b.

Vampola, A. L., and A. Korth, Electron drift echoes in the inner magnetosphere, *Geophys. Res. Lett.*, *19*, 625–628, 1992.

Wygant, J., F. Mozer, M. Temerin, J. Blake, N. Maynard, H. Singer, and M. Smiddy, Large amplitude electric and magnetic field signatures in the inner magnetosphere during injection of 15 Mev electron drift echoes, *Geophys. Res. Lett.*, *21*, 1739–1742, 1994.

Yeomen, T. K., D. K. Milling, and D. Orr, Pi2 pulsation polarization patterns on the U. K. Sub-Auroral Magnetometer Network (SAMNET), *Planet. Space Sci.*, *38*, 589–602, 1990.

Yukimatsu, A. S., M. Ejiri, S. Takagi, T. Terasawa, T. Kohno, and M. Makino, Structural variation of radiation belt associated with solar flare and SC event observed by radiation monitor (RDM) aboard Akebono (EXOS-D), in *Proceedings of Eighth International Symposium on Solar Terrestrial Physics*, p. 150, Sci. Comm. of Solar Terr. Phys., Sendai, Japan, 1994.

Yumoto, K., and the 210 (deg) MM Magnetic Observation Group, The STEP 210 (deg) magnetic meridian network project, *J. Geomagn. Geoelectr.*, *48*, 1297–1309, 1996.

Yumoto, K., et al., Globally coordinated magnetic observations along 210° magnetic meridian during STEP period, 1, Preliminary results of low latitude Pc 3's, *J. Geomagn. Geoelectr.*, *44*, 261–276, 1992.

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(Received September 12, 1994; revised July 31, 1996;
accepted November 15, 1996.)