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Solar Flare Effects on the Magnetic Variations

by

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Abstract

Magnetic variations caused by solar flare effects (sfe) are studied based on the magnetic data obtained at the Japanese stations, Memambetsu, Kakioka, Kanoya and Chichijima. It is clarified that the electric current system accompanied with the SFE event could be studied effectively using the data obtained at the Japanese stations. It is also found that short-period magnetic oscillations (magnetic pulsations) are sometimes associated with sfe.

1. Introduction

A sudden enhancement of X-ray is one of the most characteristic features of electromagnetic emissions during a solar flare event. It produces sudden ionization in the ionosphere, particularly in the lower region (ionospheric E- and D-layers) because of the great penetration power of X-ray. The sudden ionization in the ionosphere causes various disturbances such as sudden ionospheric disturbance (SID), short-wave fade-out (SWF), sudden cosmic-noise absorption (SCA) and others, and it causes the sudden enhancement of the electron density in the lower ionosphere. Therefore, it causes an increase of the electric conductivity in the ionospheric E- and D-layers. In association with the increase of the electric conductivity, there occurs a sudden enhancement of the ionospheric current over the sunlit hemisphere. Solar flare effects on the magnetic variation are recognized as impulsive changes, lasting about 30 min–1 hour, superposed on the Sq variation at low- and middle-latitudes. The distribution of magnetic vectors over the earth and the induced current system in the ionosphere have been studied by many researchers (Dellinger, 1937: Veldkamp and Sabben, 1960: Sabben, 1968: others). According to their results, the magnetic disturbances associated with sfe are interpreted as a temporary augmentation of the daily variation of the magnetic field (Sq), because the electric current system accompanied with sfe is similar to that of Sq. However, a careful investigation shows that there are several differences between the sfe current system and the Sq one. This is probably due to the fact that the solar radiation causing the sfe current produces ionization more effectively in the ionospheric D-layer, whereas the solar radiation causing the Sq current does in the ionospheric E-layer. Detailed studies of the sfe current system are left to be made in future because of lack of concurrent observations with the systematic station network at low- and middle-latitude, where a focus of the sfe current vortex is located.

Kato et al. (1959) reported that a characteristic type of magnetic pulsation with a period of about 1.5 min was frequently associated with sfe. However, detailed studies have also been left to be made in future because of lack of station networks at low- and middle latitude.

In order to study the magnetic variations at low- and middle-latitude in more detail, an automatic recording system of geomagnetic observations was installed at Chichijima in February 1973. Including Chichijima, a systematically-located station network was established at low- and middle-latitude as shown in Fig. 1. The station network consists of Memambetsu (MMB: 34.2° in geomagnetic latitude and 209.7° in geomagnetic longitude), Kakioka (KAK: 26.2°, 207.3°), Kanoya (KNY: 20.7°, 199.4°) and Chichijima (CBI: 17.4°, 210.2°). As shown in Fig. 1, MMB, KAK

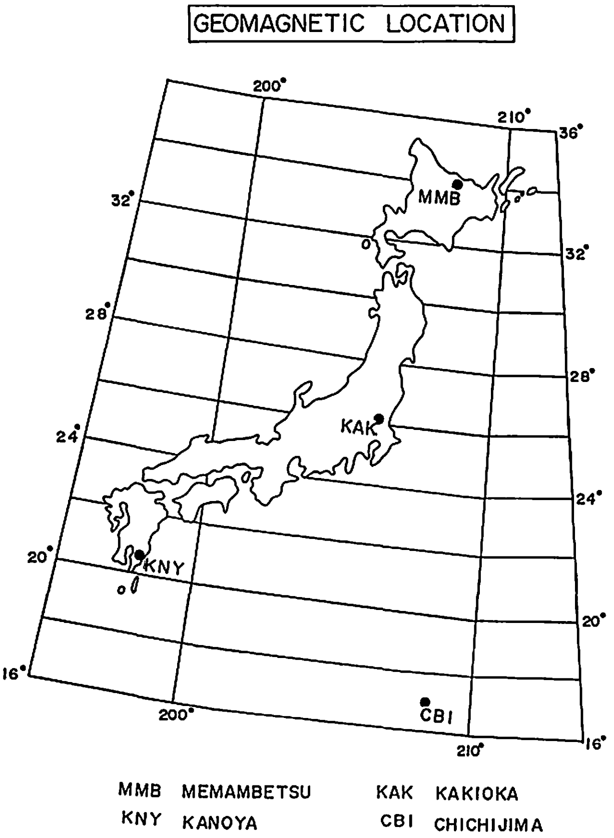

Fig. 1. Geomagnetic location of the Japanese stations used in the present study.

and CBI are located almost along the same magnetic meridian. Latitudinal effects will be studied effectively based on the data obtained at the three stations. Magnetic variations obtained at KNY is very useful for a study of longitudinal effects, since KNY is located about 10° west from that meridian.

In the present paper, sfe events will be studied based on the data obtained at the four Japanese stations shown in Fig. 1. Local time of these stations is 9 hours in advance of universal time. 179 sfe events have been identified at those stations during the period from February 1973 to May 1984. In the next section, electric-current flow patterns associated with sfe will be studied. Then, characteristic of magnetic pulsations associated with sfe will be studied in the section 3. The observational results will be discussed from a geophysical point of view in the last section.

2. Current system of magnetic variations associated with SFE

Figs. 2a and 2b show typical examples of magnetic disturbances associated with the storm sudden commencement (SSC) and bay, respectively. As shown in Fig. 2a, magnetic variations associated with SSC were observed at the four stations with very similar forms. In the figure, the onset of SSC is estimated at about 1243 UT on April 18, 1984. Simultaneously with the onset, sudden increase in H-component is

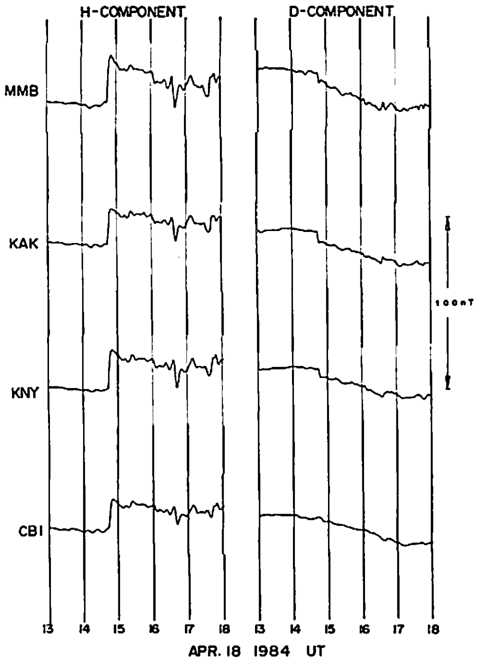

Fig. 2a. Magnetic variations associated with SSC at the Japanese stations shown in Fig. 1.

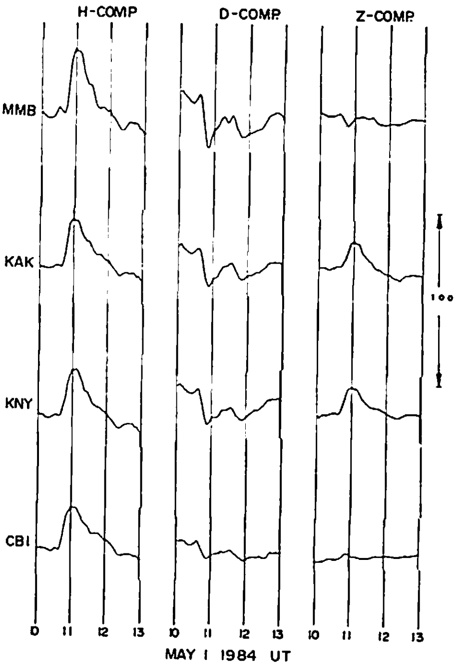

Fig. 2b. Magnetic variations associated with bay at the stations shown in Fig. 1.

seen at each station. Such similarity is also seen in the successive fluctuations following SSC during 16-18 UT in Fig. 2a. Those similar variations suggest that the source region of SSC is located far from the four stations whose relative distances are about 1,000 km. In fact, the source of SSC is expected to be located at the magnetopause (Mead, 1964: Olson and Pfitzer, 1979). Namely, the source region of SSC is located with a distance of 50,000-70,000 km from Japan.

Forms of the magnetic variations associated with bay disturbances are also similar to each other at the four stations as shown in Fig. 2b, where both the H- and D-components change in association with bay disturbance. Both the components showed similar variations at the four stations. Such similarity also suggests that the

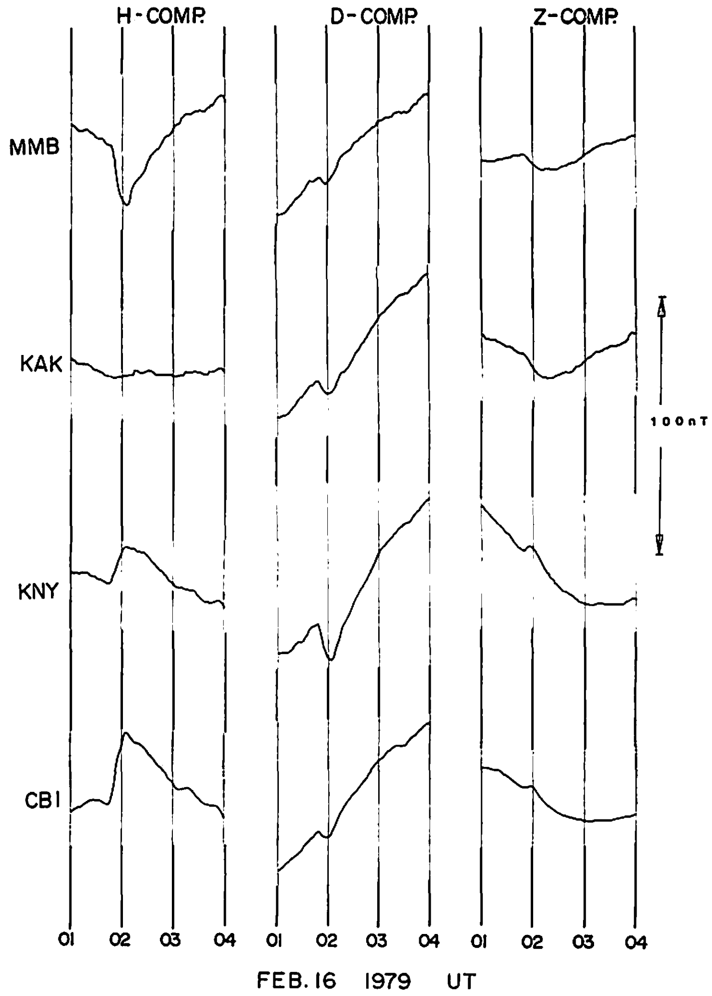

Fig. 3a. Magnetic variations associated with sfe at the Japanese stations shown in Fig. 1.

source region of bay disturbances would be located far from the four stations. McPherron et al. (1973) suggested that bay disturbances observed at low- and middle-latitude were due to the field-aligned current which connects between the cross-tail current in the magnetosphere and the auroral electrojet in the polar ionosphere. That model has been confirmed by the satellite-ground coordinated study (Singer et al. 1983). Namely, the source region of bay is located with a distance of 40,000-50,000 km from Japan.

Behaviors of magnetic variations associated with sfe at low and middle-latitude show conspicuous differences from these associated with SSC and bay. Fig. 3a shows magnetic variations associated with sfe simultaneously observed at the four stations. The onset of sfe on February 16, 1979 is estimated at 0146 UT. Simultaneously with the onset, decrease in H-component by 22 nT is registered at MMB as shown in Fig. 3a. On the other hand, magnetic variations associated with sfe is not so clearly in H-component at KAK. On the contrary to the decrease in H-component at MMB, increases in H-component are registered at KNY and CBI as shown in Fig. 3a by

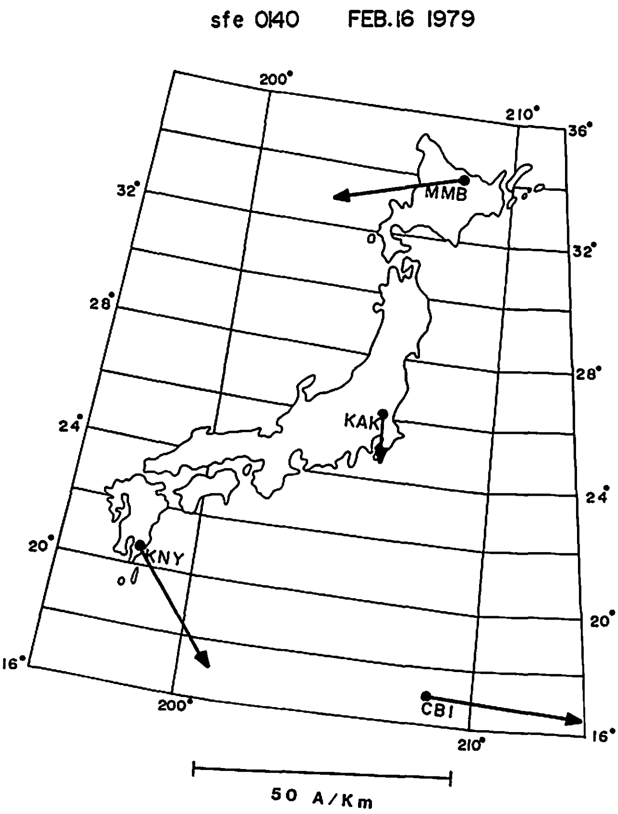

Fig. 3b. Horizontal current vectors in the ionosphere to produce the horizontal magnetic variation associated with sfe on February 16, 1979.

15 nT and 17 nT. In the variations of D-component, the sfe associated variation is largest at KNY, which is located at the lower latitude than MMB and KAK. Any similarity can not be seen in magnetic variations associated with sfe obtained at the four stations. The result seems to suggest that the source region of sfe is located near the Japanese stations whose relative distances are about 1,000 km. Namely, the source region of sfe is located in the lower ionosphere of low- and middle-latitude. Fig. 3b shows the horizontal electric currents in the ionosphere (arrow) which are necessary to produce the magnetic disturbances associated with sfe shown in Fig. 3a. The calculation of the current has been carried out for the period when the sfe event showed the greatest development. The relationship between the current density, I, in A/km and the magnitude of the magnetic disturbances, H, in nT is given by,

$$I=0.6\frac{H}{0.2\pi} \qquad (1)$$

where the factor of 0.6 corresponds to the induced current in the earth (Chapman and Bartels, 1940). Roughly speaking, the electric current pattern in Fig. 3b is

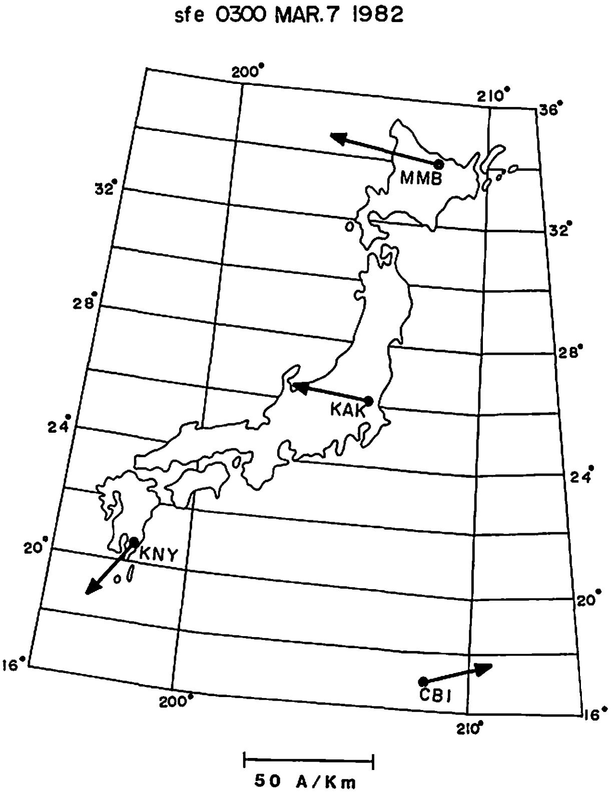

Fig. 4. Horizontal currnet vectors in the ionosphere to produce the horizontal magnetic variation associated with sfe on March 7, 1982.

similar to that of the daily magnetic variation (Sq), and it suggests that a focus of the sfe vortex would be located in a region which is in the east of KAK. That assumption is supported by the following two reasons. The one is that the sfe event shown in Figs. 3a and 3b occurred at the pre-noon hours (~1040 LT) so that the subsolar line (the meridian on the focus of the sfe vortex) is expected to be located in the east of the four stations during that sfe event. The other reason is that the current vector at KAK points almost to the south, which is a typical pattern obtained at a station located just in the west of a focus of a current vortex (Shiraki et al., 1980).

If the subsolar line is located on the Japanese station, a meridian on a focus of the sfe current vortex might be located nearly on the Japanese stations. Such assumption will be supported by the results shown in Fig. 4, where the sfe event occurred around noon (03h UT) on March 7, 1982. The current vectors at MMB and KAK are nearly in the westward direction. It suggests that MMB and KAK were located at the higher latitude and at almost same longitude of the focus during the sfe event.

The current vector at CBI is nearly in the eastward direction. It suggests that

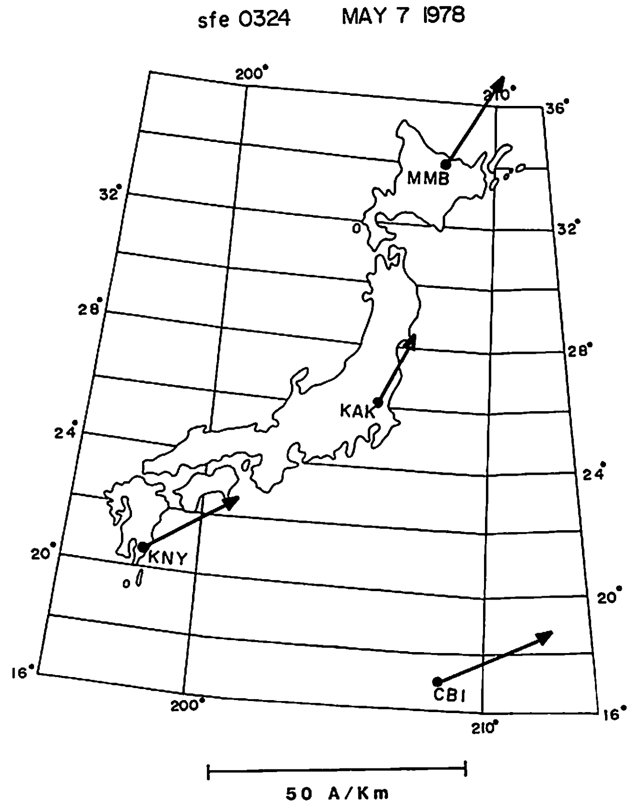

Fig. 5. Horizontal current vectors in the ionosphere to produce the horizontal magnetic variation associated with sfe on May 7, 1978.

CBI is located at the lower latitude and at almost same longitude of the focus. The current vector at KNY shows that KNY is located in the west of the focus. The results shown in Fig. 4 indicate that the focus of the sfe current vortex is located in area surrounded by KAK, KNY and CBI.

Fig. 5 shows the current patterns associated with the sfe event which occurred at the post-noon hours. In that sfe event, it is suggested that the focus of the sfe current vortex is located in a region to the west of the four stations.

In the present section, it is clarified that the electric current system accompanied with sfe can be effectively studied using the data obtained at the Japanese stations, MMB, KAK, KNY and CBI. The results will be further discussed in the last section.

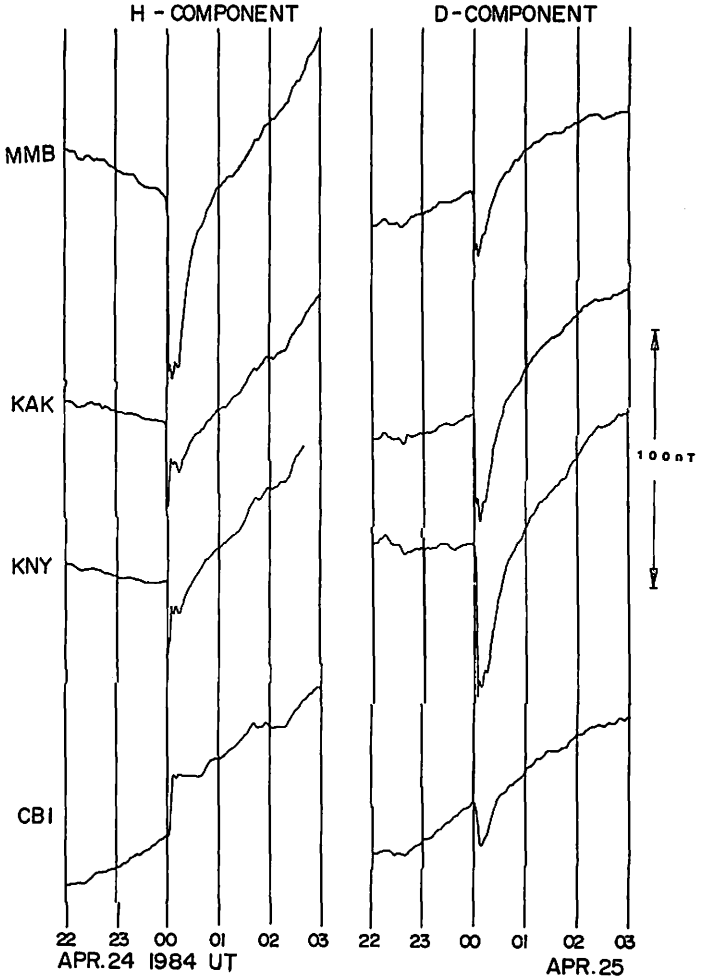

Fig. 6a. Magnetic variations observed at the Japanese stations associated with the sfe event which occurred on April 24, 1984.

3. Short-period magnetic oscillations associated with SFE

Fig. 6a shows magnetic variations associated with the sfe event which started at about 2359 UT on April 24, 1984. Simultaneously with the onset of sfe, sudden changes in both the magnetic H- and D-component were registered at the Japanese stations. A careful investigation of Fig. 6a shows existence of superposed short-period magnetic oscillation, especially in the beginning part of the sfe event. The short-period oscillation is seen more clearly in the induction magnetograms shown in Fig. 6b. Kato et al. (1959) named such magnetic oscillation as Psfe. Spectral analysis method is adopted, and the calculated results are presented in Fig. 6c. According to them, it is clarified that the period of the oscillation is about 70 sec (0.015 Hz). Although the period of 70 sec is considerably longer than the period of the magnetic pulsations observed at low- and middle-latitude, waveforms shown in Fig. 6b seem to be sinusoidal. It suggests that Psfe is caused by the hydromagnetic standing oscillations of the magnetic field lines anchored at low- and middle-latitude on the ground.

According to Kato et al. (1959), more than 90% of the sfe events accompanied Psfe. However, the present study does not support it. Fig. 7 shows both the occurrence frequency of sfe and that of Psfe. During the period from February 1973 to May 1984, 179 sfe events were observed. Among them, only 32 sfe events accom-

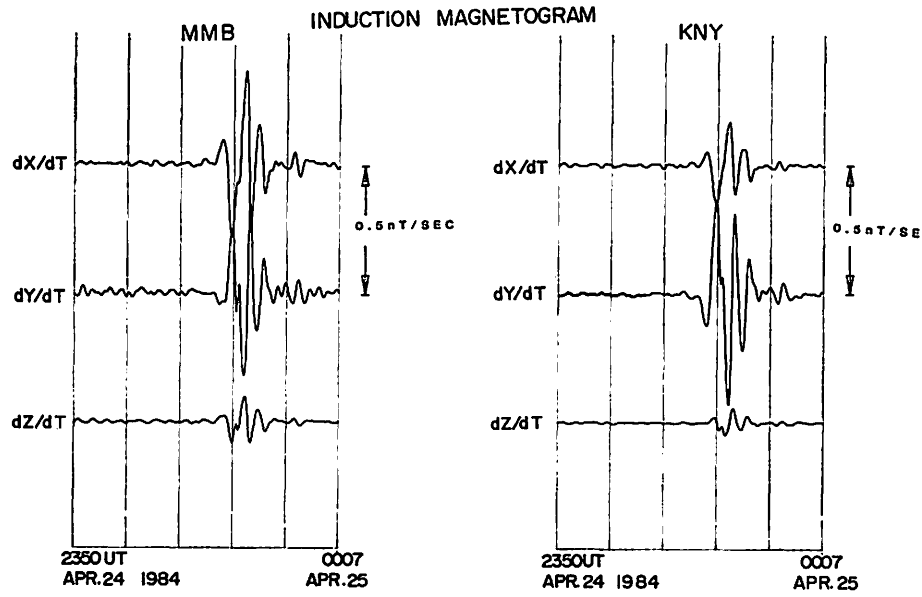

Fig. 6b. Induction magnetograms at MMB and KNY obtained during the sfe event shown in Fig. 6a.

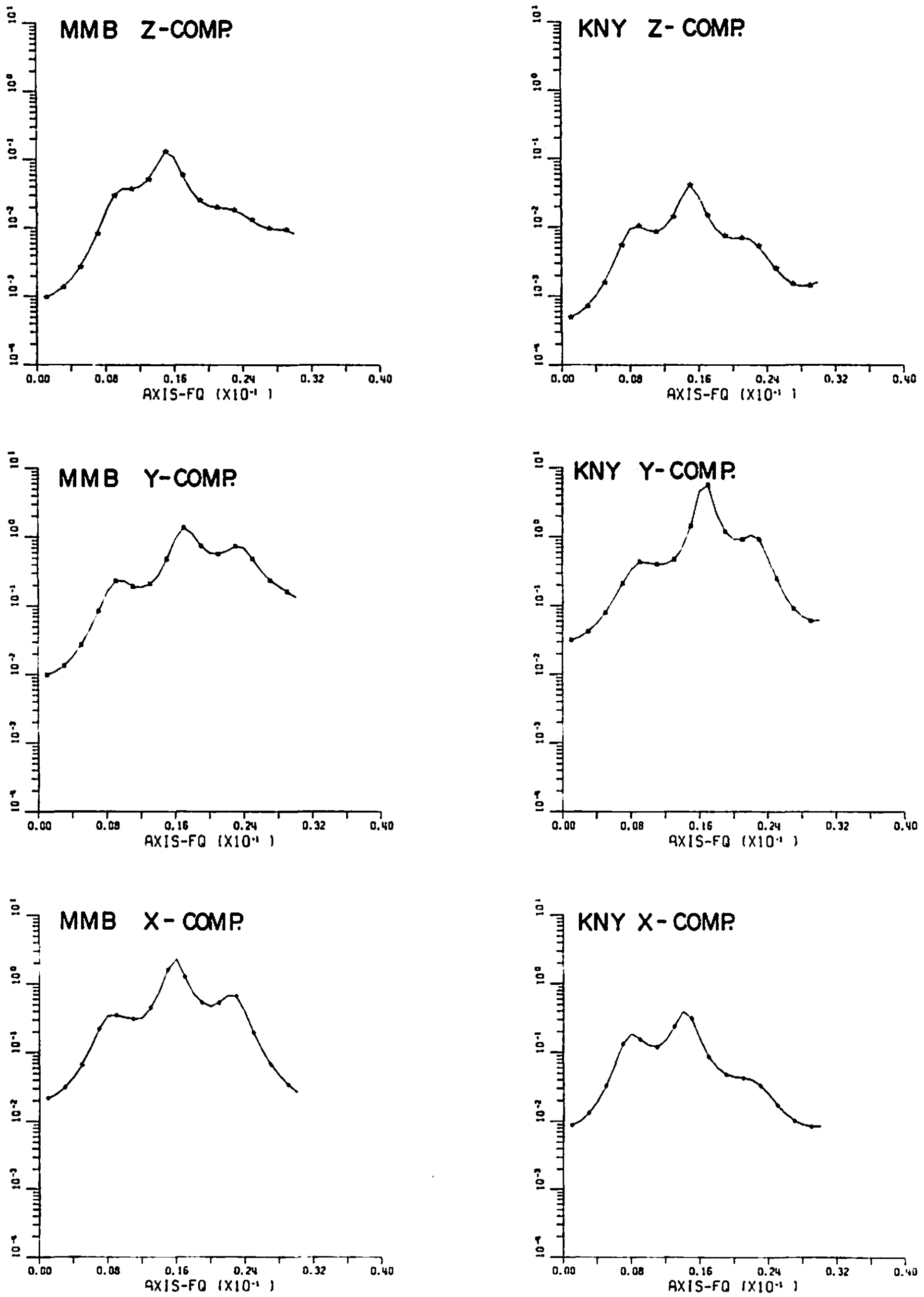

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Fig. 6c. Spectra for the magnetic oscillation associated with sfe shown in Fig. 6b.

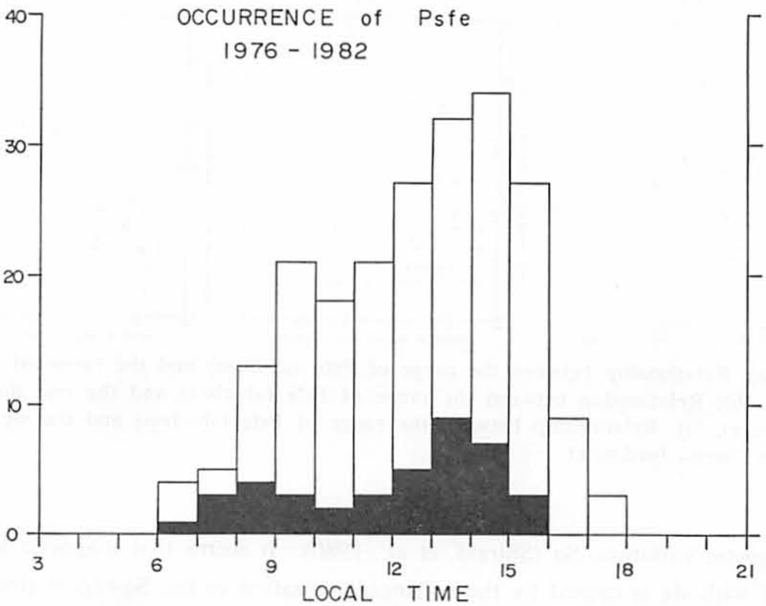

Fig. 7. Occurrences of sfe and Psfe as a function of local time.

panied Psfe. Namely, only 19% of the sfe events accompanied Psfe. Kato et al. (1959) analyzed only 10 sfe events during 1957–1959. So, it seems that they analyzed only very large sfe events. This is because sensitivity of the magnetometer was not well enough to investigate a small sfe event in that time. At the present time, we could investigate a very small sfe events as well as a large one. So, we could study which condition is more effective to excite Psfe. In order to clarify the condition, the amplitude of Psfe was analyzed in terms of magnitude of sfe, rise time of sfe, and steepness of sfe which is derived from dividing amplitude of sfe by rise time of sfe. The results are summarized in Figs. 8a, 8b and 8c. In the figures, it is clarified that amplitude of Psfe is very well correlated with steepness of sfe, namely, increasing rate of sfe. The condition which excites Psfe effectively is how fast the sfe event develops (nT/min). The result suggests that sudden increase in the ionospheric conductivity is one of the important conditions to excite the Psfe oscillation. This problem will be discussed in the next section.

4. Discussion

In the result of the present study, it has been clarified that we could estimate a location of a focus of the sfe current vortex using the current pattern derived from the data obtained at the four Japanese stations as shown in Figs. 2–5. Roughly speaking, the electric current pattern of sfe is similar to the current system of the

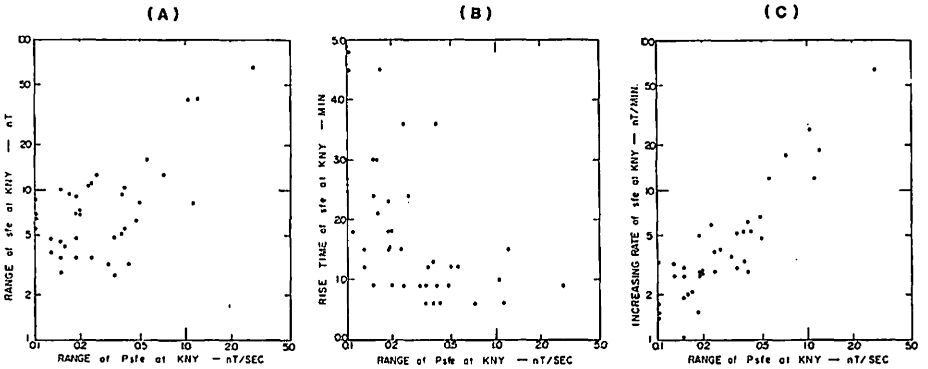

Fig. 8. (a): Relationship between the range of Psfe (abscissa) and the range of sfe (ordinate). (b): Relationship between the range of Psfe (abscissa) and the rise time of sfe (ordinate). (c): Relationship between the range of Psfe (abscissa) and the steepness of sfe –nT/min– (ordinate).

daily magnetic variation, Sq (Shiraki, et al., 1980). It seems that magnetic variations associated with sfe is caused by the enhanced ionization in the Sq-region (ionospheric E-layer), and the disturbance vectors of the variations point to the same directions as the vectors of the normal Sq variations. The current vectors shown in Figs. 3a, 4 and 5 were calculated on the assumption that the sfe current flow in the ionospheric E-layer of about 100 km height.

However, it should be noted that the most characteristic feature associated with a solar flare is an enhancement of X-ray, and X-ray causes an enhancement of ionization more effectively in the ionospheric D-layer (60–80 km high) than in the ionospheric E-layer (100 km high). X-ray with wavelengths of 1–2Å seem to be the most effective for ionization at the height of about 65 km. In fact, rocket measurements obtained during the sfe event gave evidences that X-ray penetrated below 80 km (Veldkamp and Sabben, 1960). Considering the result, the sfe current seems to flow both in the ionospheric D-layer and in the ionospheric E-layer. The height where the current associated with sfe flows is unknown at the present stage. However, it is possible to estimate the height by using the data obtained at the Japanese station network. It has been clarified that we can study the sfe current vector effectively by using the data observed at MMB, KAK, KNY and CBI.

In the present paper, it has also been clarified that the magnetic variations associated with sfe are, sometimes, accompanied with the short-period magnetic oscillations (Psfe). The amplitude of Psfe is well correlated with the steepness of sfe (nT/min). Two models were proposed for the generation mechanism of Psfe. One is the hydromagnetic standing oscillation of the field lines and the other is the fluctuation of the ionospheric current during the sfe event (Kato et al., 1959: Saito, 1969).

A sudden enhancement of the ionospheric conductivity by the X-ray produces plasma discontinuity in the ionosphere to excite the hydromagnetic standing oscillation of the magnetic field lines which are anchored in the discontinuity region of the ionosphere. It would be useful to investigate the Psfe period as a result of the hydromagnetic standing oscillation. The period of the hydromagnetic standing oscillations depends on both the magnetic field configurations and the distribution of the plasma density in the magnetosphere. The period, T, is given by

$$T=2\int\frac{(\mu_0\rho)^{1/2}}{B} \qquad (2)$$

where μ_0 is the free space permeability, ρ the plasma density, B the geomagnetic field intensity and ds the element of the length along the field line. Several researchers calculated the period of the hydromagnetic standing oscillations under the various magnetic and plasma conditions (Kuwashima and Saito, 1981: Yumoto and Saito, 1983: Poulter et al., 1984). According to their results, the period of the hydromagnetic standing oscillations at the low- and middle-latitude are in a range of several to scores of seconds. The period of Psfe, 70–100 seconds (Fig. 6c for example), is too long to interpret Psfe as the hydromagnetic standing oscillations.

The Psfe event might also be excited by the fluctuations of the ionospheric currents which flow in the ionospheric E- or D-layer. As a cause of the fluctuation, we considered that the periodic variations of the input X-ray are associated with sfe. However, it had been very difficult to confirm an existence of the periodical variation of the X-ray intensity. Recently, Kikuchi (1984) has found the periodical variation of X-ray intensity during the sfe event on April 24, 1984, which is discussed in the present study in Figs. 6a–6c. According to his results, the period of the fluctuation of X-ray intensity is about 1 min. The period is similar to that of Psfe as shown in Fig. 6c. Concerning to the sfe event on April 24, 1984, the present analysis suggests that Psfe is generated by the periodic input of X-ray in association with the solar flare. Fig. 8 indicates that the amplitude of Psfe is well correlated with the steepness of sfe (nT/min). The evidences suggest that X-ray event which develops suddenly accompanies superposed fluctuations. That fluctuations cause Psfe by inducing the fluctuations on the sfe current in the ionosphere. Physical clarifications for those processes are left to be made in future.

5. Conclusions

It is clarified that the ionospheric current system associated with sfe is studied effectively by using the Japanese station network. The sfe event, sometimes, accompanies the magnetic oscillations with the period ranging 60–100 seconds. Those oscillations might be caused by the periodic variations of the input X-ray.

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References

Chapmans, S. and Bartels, J. (1940): Geomagnetism, I and II Oxford University Press, Oxford.

Dellinger, J. H. (1937): Sudden ionospheric disturbances, Terr. Magn. Atmos. Elect., **42**, 49–53.

Kato, T., Tamao, T. and Saito, T. (1959): Geomagnetic pulsation accompanying the intense solar flare, J. Geomagnet. Geoelec., **10**, 203–207.

Kikuchi, T. (1984): Private communication.

Kuwashima, M. and Saito T. (1981): Special characteristics of magnetic Pi2 pulsations in the auroral region and lower latitudes, J. Geophys. Res., **86**, 4686–4696.

McPherron, R. L., Augry, M. P., Russel, C. T. and Coleman, P. J. Jr. (1973): Satellite studies of magnetospheric storms on August 15, 1968, OGO 5 magnetic field observations, J. Geophys. Res., **78**, 3068–3078.

Mead, G. D. (1964): Deformation of the geomagnetic field by the solar wind, J. Geophys. Res., **69**, 1169–1179.

Olson, W. P. and Pfitzer, K. A. (1979): Quantitative modelling of magnetospheric processes (edited by Olson, W. P.), AGU monograph 1979.

Poulter, E. M., Allan, W., Bailey, G. T. and Moffett, R. J. (1984): On the diurnal period variation of mid-latitude ULF pulsations, Planet. Space Sci., **32**, 727–734.

Sabben, D. V. (1968): Solar flare effects and simultaneous magnetic daily variation, 1959-1961, J. Atmosph. Terr. Phys., **30**, 1641–1648.

Saito, T. (1969): Geomagnetic pulsations, Space Sci. Rev., **10**, 319–412.

Shiraki, M., Shitamichi, M. and Kawamura, M. (1980): Magnetic daily variations associated with disturbances of the middle atmosphere, Proceeding of the 1st MAP symposium, 286–290, (in Japanese).

Singer, H. J., Hughes, W. J., Fougere, P. F. and Knecht, D. J. (1983): The localization of Pi2 pulsations, Ground-Satellite observations, J. Geophys. Res., **88**, 7029–7036.

Veldkamp, J. and Sabben, D. V. (1960): On the current system of solar-flare effects, J. Atmosph. Terr. Phys., **18**, 192–202.

Yumoto, K. and Saito, T. (1983): Relation of compressional HM waves at GOES 2 to low-latitude Pc3 magnetic pulsations, J. Geophys. Res., **88**, 10041–10052.

sfeに伴う磁気擾乱

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女満別，柿岡，鹿屋，父島の地磁気資料を使ってsfeに伴う磁気擾乱の研究を行った。日本の4つの観測点での資料が，sfe電流系を研究する上できわめて有効であることがわかった。又sfe磁気擾乱には，地磁気脈動を伴う例のあることがわかった。