ON THE RELATIONSHIPS BETWEEN SFE (CROCHET) AND SOLAR X-RAY AND MICROWAVE BURSTS

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Abstract. Geomagnetic crochets (sfe) observed at Kodaikanal over the period 1966–71 have been studied in relation to solar X-ray bursts observed by NRL satellite (SOLRAD-9) in the 0.5–3 Å, 1–8 Å and 8–20 Å bands and radio bursts observed in the frequency range 1000–17000 MHz. The amplitude of sfe is linearly correlated with the peak intensities of X-ray bursts in the 1–8 Å and 8–20 Å bands. The single frequency correlation of sfe with radio bursts is a flat maximum in the frequency range 2000–3750 MHz. Following the spectral classification of AFCRL for microwave bursts, it is noticed that sfe are mostly associated with the 'A' type burst spectra and are very poorly correlated with bursts with the 'G', 'C' and 'M' type spectra. These features differ from those of other SID's reported earlier.

1. Introduction

The sudden perturbations in geomagnetic elements concurrent with the eruption of a solar flare designated as sfe (crochet) is a well known geophysical event and constitutes one of the sudden ionospheric disturbances (SID's). Earlier investigations made at different latitudes showed that the occurrence of sfe is a maximum around local noon and its amplitude has a local time variation similar to that of *Sq* (McNish 1937; Newton, 1948; Nagata, 1952; Subrahmanyam, 1964). It is pointed out that the sfe is not due to a mere augmentation of the normal *Sq* field and that the current flowing layer responsible for sfe is below the normal dynamo current flowing region (Volland and Taubenheim, 1958; Veldkamp and Van Sabben, 1960). An interpretation in terms of X-ray flux enhancement in the band 1–20 Å was made by Ohshio (1964) from a detailed consideration of sfe observed during I.G.Y. on a world-wide basis. A similar conclusion has been reached by Pintér (1967) who inferred that the region of enhanced conductivity responsible for sfe lies either in the D-region or the boundary between the D and E regions.

It is generally accepted that energetic electrons resulting from the eruption of a solar flare are responsible for solar microwave bursts and enhancements of ultraviolet (UV) and X-ray emission (Kundu, 1965). It is established that enhancements of X-ray flux at wavelengths less than 20 Å produces excess ionization in the lower ionosphere mainly below 100 km (Chubb *et al.*, 1957; Friedman, 1964). This excess ionization is responsible for the SID's of SWF, SCNA, SEA, SPA and SES. Although the normal D-region owes its existence to Lα radiation, its behaviour under disturbed conditions is better explained by X-ray enhancements during solar flares (Nicolet and Aikin, 1960; Reid, 1964). Statistical studies made earlier have established the association between SID's (except sfe) and the various characteristics of solar X-ray and

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microwave bursts (Castelli and Strauss, 1967; Kaufmann and Barros, 1969; Deshpande *et al.*, 1972; Sastri and Subrahmanyam, 1974).

In view of the prevailing consensus that sfe is due to enhanced conductivity in the region below the normal electrojet due to X-ray enhancement at wavelengths below 20 Å, it is felt desirable to investigate the relationships between the characteristics of sfe and solar X-ray and microwave bursts. Such an attempt has been made using our magnetic data over a six-year period from 1966–71, the results of which comprise the following sections of this communication.

2. Sources and Treatment of Data

As mentioned, sfe's observed at our station alone have been used in this study and only those sfe that have been observed during daylight hours have been taken into consideration. Each sfe is described by two parameters. One is an index of the amplitude of sfe denoted by $|m|_r$ and defined as:

$$|m|_r = h_3 - (h_1 + h_2)/2 \tag{1}$$

where h_1, h_2 and h_3 are the values of the horizontal component of magnetic field at the start, end and maximum (or minimum) of sfe. The other is an index of quiet day solar variation $Sq(H)$ denoted by M_t and computed for the days when sfe was observed by taking the difference between mean value of H field at the beginning and end of sfe and the mean H field at the preceding and succeeding midnight hours.

Data on solar X-ray bursts has been taken from the ionization chamber experiments aboard the SOLRAD-9 (Explorer-37) satellite in the wavelength bands 0.5–3 Å, 1–8 Å, and 8–20 Å and regularly published by ESSA in monthly bulletins of *Solar-Geophysical Data* (Lit. 1). To study the association between sfe and X-ray flares, data over a three-year period from 1969 to 1971 is used and a total of 38 simultaneous events have been noticed which constitute the material. The Hardening ratio defined as the ratio of peak flux in the 0.5–3 Å and 1–8 Å bands is evaluated to indicate the relative proportion of X-ray energy below 3 Å. It is to be recalled here that the published X-ray flux levels are based on gray body solar emission spectra and assume a constant solar temperature for the solar source region. In this preliminary approach to the problem, we have used the published X-ray flux values only. Data on solar microwave bursts has been taken from the single frequency observations at 1000, 2000, 3750 and 9400 MHz made by the Research Institute of Astrophysics, Nagoya University, Japan and at 17000 MHz made by Tokyo Astronomical Observatory, Japan. These are regularly published in the *IAU Quarterly Bulletin on Solar Activity* (Lit. 2). The burst spectra are evaluated using the observations of Nagoya University alone (frequency coverage 1000–9400 MHz) and the spectral classification of AFCRL (Castelli and Aarons, 1968) is followed. It is to be mentioned that the Japanese observations have been taken as they give the best possible coverage to our sfe events among the existing sources of radio burst data. The coverage of Nagoya University is from 23 to 06 UT in the 1st and 4th quarter and from 22 to 07 UT in the 2nd

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and 3rd quarter of the year and that of Tokyo Astronomical Observatory is from 00 to 06 UT in the 1st and 4th quarter and from 23 to 07 UT in the 2nd and 3rd quarter of the year. We feel that our selection of the Japanese radio burst data is justified for the following reason. The occurrence of sfe is known to be a maximum around noon and is more or less symmetrical around the maximum. Since the Japanese observations cover the period up to the maximum, whatever features are noticed for the period up to noon time must also represent the latter half of the day. The association between sfe and radio bursts is studied for a five-year period from 1966–70 during which a total of 72 sfe have been noticed.

3. Results

3.1. X-RAY BURSTS

A scrutiny of peak flux levels in the three bands 0.5–3 Å, 1–8 Å and 8–20 Å for X-ray bursts that produced sfe showed the striking feature that in 30 out of a total of 38 events studied, the peak flux level in the 0.5–3 Å band consistently rose to the value of $120–130 \times 10^{-5}$ erg cm^{-2} s^{-1} (very close to the upper limit of the dynamic range of the NRL experiment). In Figure 1 is shown the peak flux in the 0.5–3 Å band and the Hardening ratio for the events studied. It can be seen that the occurrence of sfe is more dependent on the flux in the 0.5–3 Å band than on the relative

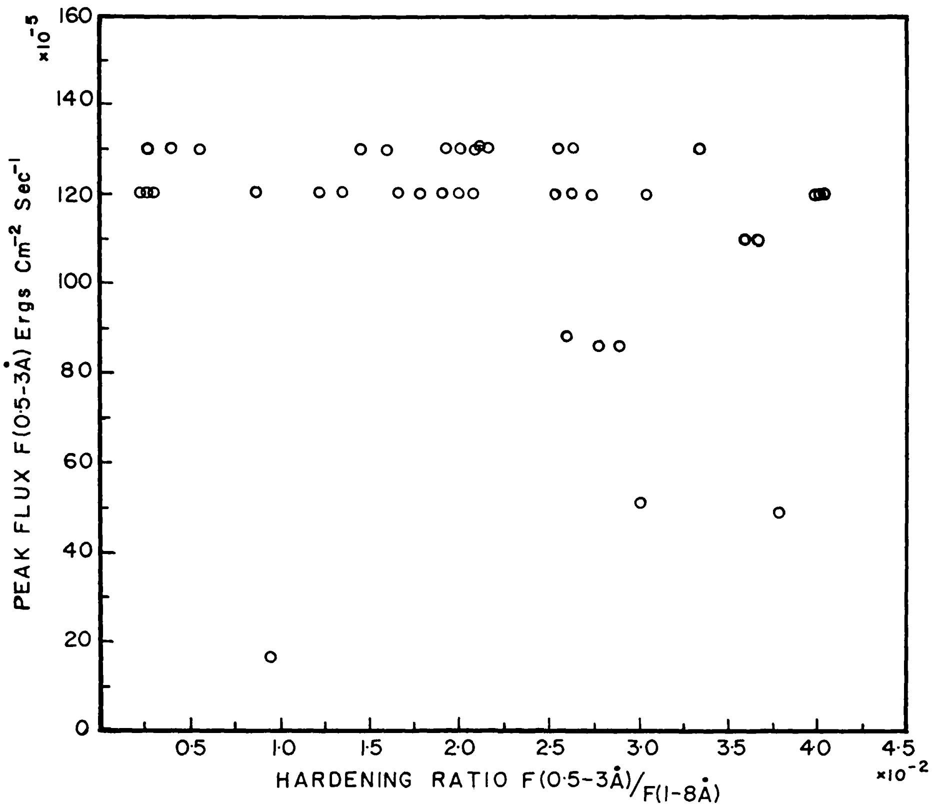

Fig. 1. Scatter plot of the peak X-ray flux in the 0.5–3 Å band and hardening ratio for the flare events that produced sfe.

hardening of the spectrum in the bands 0.5–3 Å and 1–8 Å. Kaufman and Barros (1969) reported the threshold flux in the 0.5–3 Å band for the occurrence of SPA as 4.3×10^{-5} erg cm^{-2} s^{-1} while Deshpande *et al.* (1972) gave a value of $(1-3) \times 10^{-5}$ erg cm^{-2} s^{-1} for SID's in general. These values are significantly smaller compared to that of sfe. A similar feature is also noticed for the flux levels in the 1–8 Å and 8–20 Å bands. This leads to the general observation that very large X-ray enhancements are necessary to produce sfe and this accounts for the relatively low frequency of occurrence of sfe compared to other SID's whose origin is due to enhanced ionization below 100 km: SWF, SCNA, SEA, SES and SPA.

The dependence of sfe amplitude on X-ray flux enhancement is studied by evaluating the ratio $|m|/Mt$, as $|m|$ is known to have local time variation similar to that of *Sq* field. Further, the data is divided into time blocks 09–11, 11–13, 13–15, 15–17 hours (75 E.M.T.) as the ratio $|m|/Mt$ varies with Mt and hence with local time (Subrahmanyam, 1964). In Figure 2 and 3 are shown the variation of $|m|/Mt$ with the peak flux in the bands 1–8 Å and 8–20 Å. It is evident that there is a positive linear correlation between the amplitude of sfe and X-ray flux enhancements. Correlation coefficients evaluated are significant at a level $P > 0.01$ (except in one case when it is > 0.02). Earlier Kaufman and Barros (1969) reported an exponential increase of

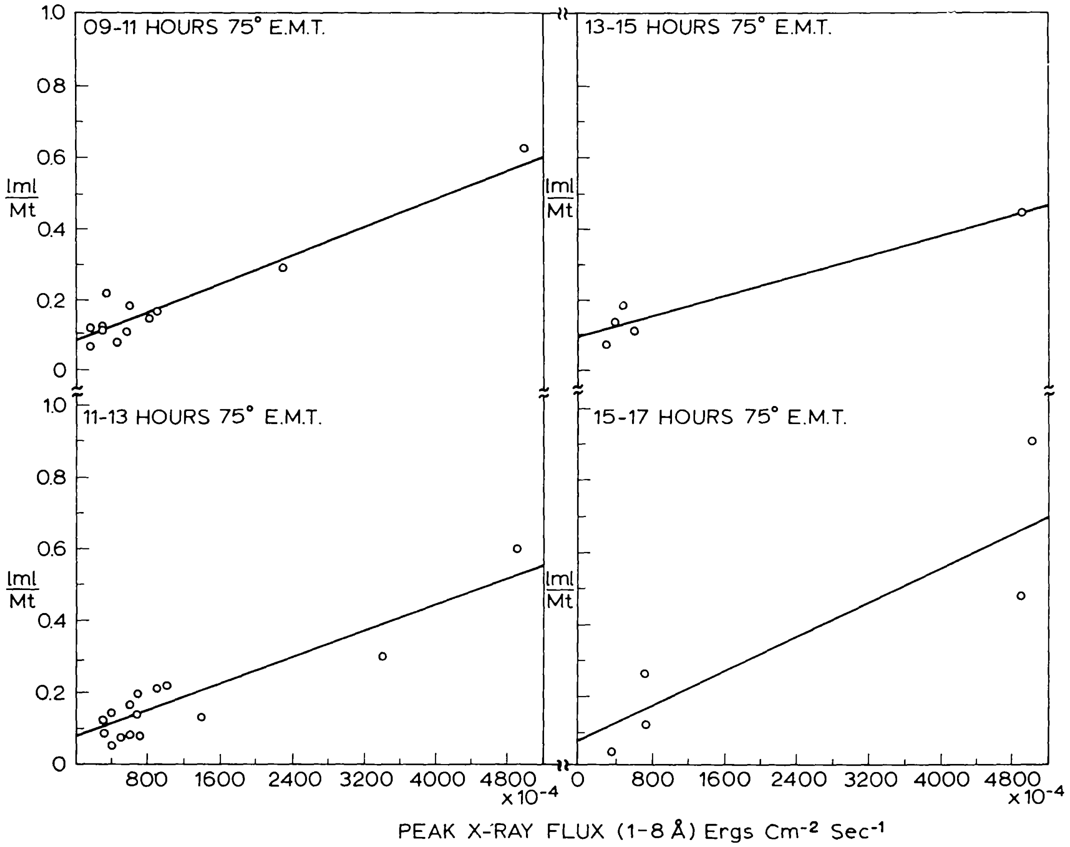

Fig. 2. Scatter plots showing the parameter $|m|/Mt$ of sfe as a function of the corresponding X-ray burst peak flux in the 1–8 Å band.

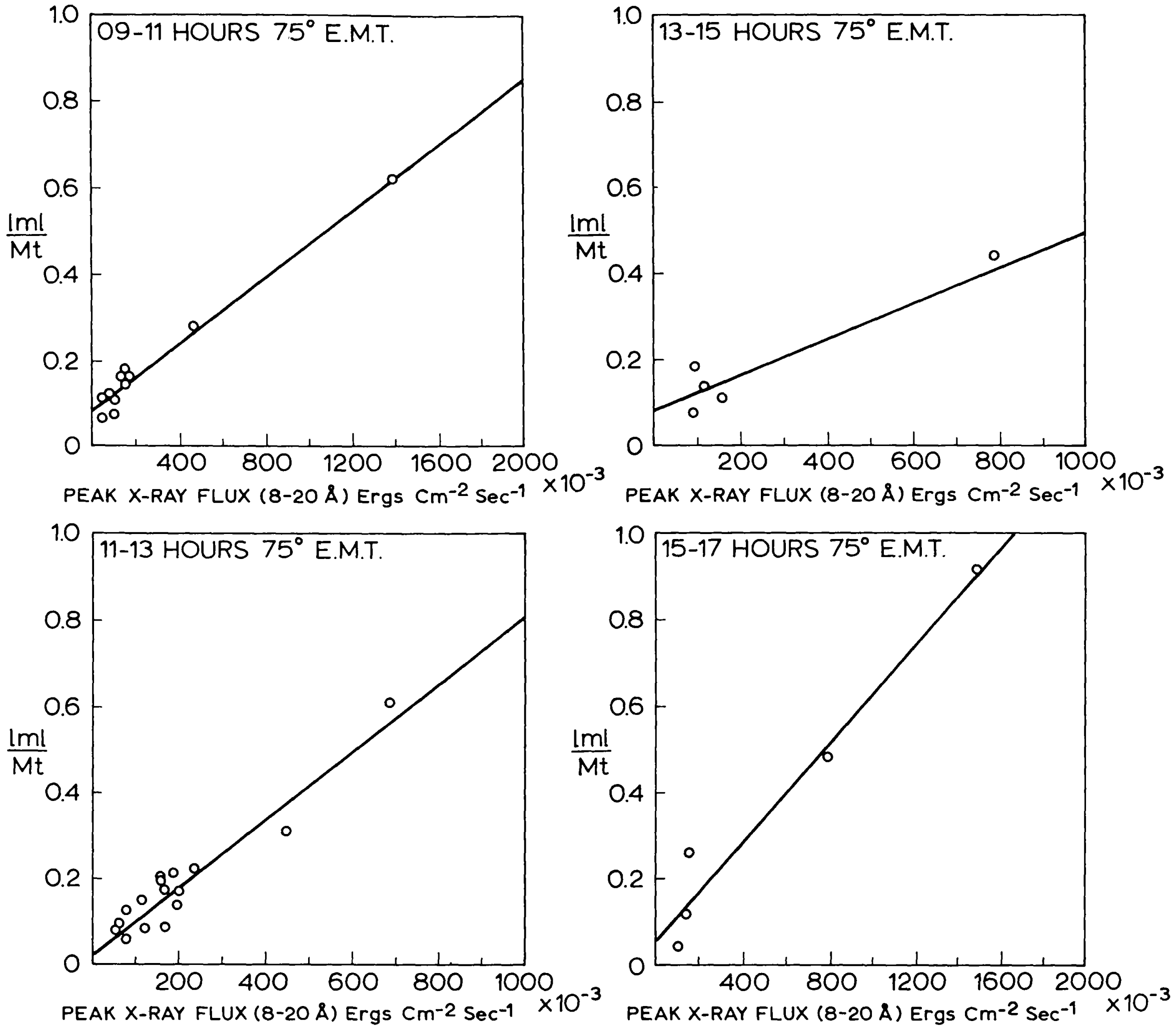

Fig. 3. Scatter plots showing the parameter $|m|/Mt$ of sfe as a function of the corresponding X-ray burst, peak flux in the 8–20 Å band.

SPA importance with peak flux in the three bands 0.5–3 Å; 1–8 Å and 8–20 Å. Similarly Deshpande *et al.* (1972) noticed an exponential increase of SCNA size with flux enhancement in the 1–8 Å band. It follows that the nature of the dependence of the size of SPA and SCNA on X-ray flux enhancement differs from that of sfe.

The relaxation time defined as the time difference between the maximum of the ionizing radiation and the maximum of SID effect (sfe in the present study) has been evaluated with reference to the X-ray flux maximum in the bands: 0.5–3 Å, 1–8 Å and 8–20 Å and the results are presented in Table I. The simplified expression for relaxation time is given by

$$\tau_{\text{eff}} = \frac{1}{2\alpha_{\text{eff}} N_m}, \tag{2}$$

where α_{eff} is the recombination coefficient and N_m is the maximum electron density at the level of flare induced ionization.

TABLE I

Relaxation time of sfe with respect to X-ray bursts in three bands

SID effect	Relaxation time in minutes Satellite and X-ray observation bands (Å)		
	SOLRAD-9 0.5–3	SOLRAD-9 1–8	SOLRAD-9 8–20
sfe	+2.1 (38)	+4.0 (38)	+1.4 (38)

Note: Figures in brackets indicate the number of events studied.

It is often noticed that the maximum of sfe occurs before that of the integrated flux in the three bands. As may be seen from Table I, the relaxation time of sfe with respect to soft X-rays is 1.5–4.0 min on the average. This gives $(\alpha_{\text{eff}}N)$ values around $(21–55) \times 10^{-4}\ \text{s}^{-1}$.

3.2. MICROWAVE BURSTS

The percentage correlation of sfe with solar radio bursts monitored at the spot frequencies: 1000, 2000, 3750, 9400 and 17000 MHz is shown in Figure 4. Error bars are provided using the expression

$$(\%\ \text{corr.} + \%\ \text{error}) = \frac{n \pm \sqrt{n}}{N} \times 100, \tag{3}$$

where n is the number of correlated events and N is the total number of sfe events.

It is evident that the correlation is a flat maximum in the frequency range 2000–

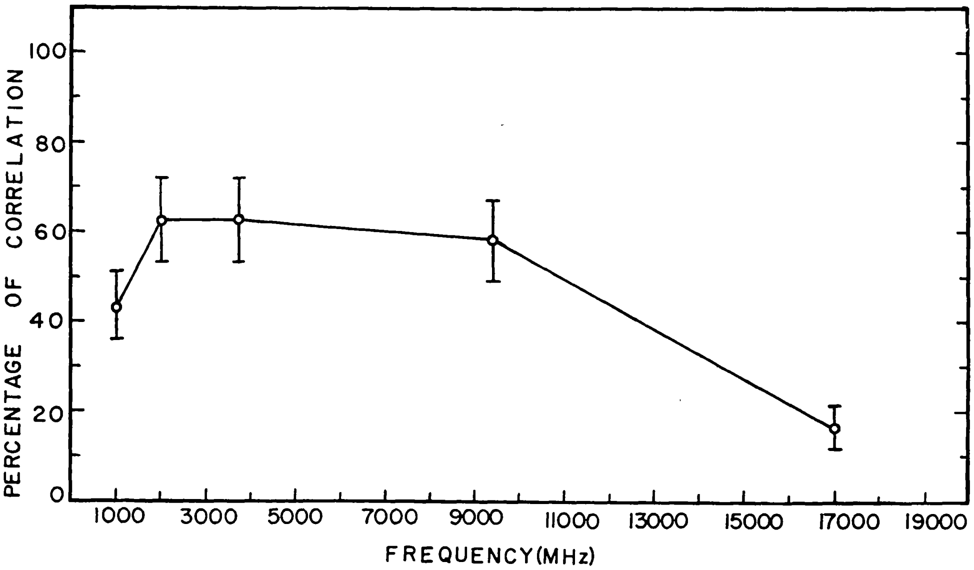

Fig. 4. Percentage of sfe events accompanied by solar radio bursts as a function of the monitoring frequency of the bursts.

3750 MHz and decreases on either side of this range. This feature is in deviation to the earlier work wherein the association between SID's of D-region origin and radio bursts is noticed to increase monotonically with the monitoring frequency (Castelli and Strauss, 1967; Sastri and Subrahmanyam, 1974). In Table II are presented the details of the association of sfe with different types of burst spectra. It is found that sfe is mostly associated with 'A' type burst spectra (wherein the peak flux increases with frequency and the peak flux variation with frequency is of 'U' type) and is poorly correlated with G (wherein the peak flux decreases with frequency), C (wherein the peak flux variation with frequency is a maximum in the frequency range covered) and M (wherein the peak flux variation with frequency is zigzag) type burst spectra. The lack of correlation between SID's (including SFD) and class 'G' radio bursts is more or less an established result of earlier work (Castelli and Strauss, 1967; Strauss *et al.*, 1969; Sastri and Subrahmanyam, 1974). However all SID's whose origin is due to enhanced ionization below 100 km (excluding sfe) are noticed to have high and more or less equal association with C and M type burst spectra (Sastri and Subrahmanyam, 1974). This is also in contradiction with the result of the present study for sfe.

TABLE II

Association between sfe and microwave burst spectra of different types

Total number of sfe for which burst spectra are available	Correlated bursts spectra of different types			
	A	C	G	M
45	38	5	1	1

As an attempt to understand the discrepancies in the association of sfe with microwave bursts compared to other SID's, we have studied the association of our sfe events with other SID's using published data (Lit. 1) and the results are presented in Table III. It can be seen that sfe is highly associated with SWF and SPA (≈83%) and to a lesser extent with SCNA, SEA and SES (≈57–64%). The reverse situation, however, is not found to be true. The difference in the nature of the association of sfe with radio bursts at spot frequencies, compared to that of other SID's may be

TABLE III

Association of sfe with other SID's

Total number of sfe	Simultaneous occurrence of other SID's (number of cases)				
	SWF	SPA	SES	SEA	SCNA
92	76	77	59	56	52

understood, on a qualitative basis, in terms of the facts that the other SID's are relatively more sensitive to X-ray flares compared to sfe and the association between X-ray flares and microwave bursts increases with the frequency of monitoring (Sen Gupta 1973).

4. Summary

To summarize, the following are the results obtained from the present study.

(1) Relatively large X-ray flux enhancements are noticed to be necessary for the occurrence of sfe compared to other SID's of D-region origin), and its occurrence is not critically dependent on the hardening of the X-ray spectrum in the 0.5–3 Å and 1–8 Å bands.

(2) The amplitude of sfe is positively correlated with the X-ray flux enhancements in the 1–8 Å and 8–20 Å bands. This is in contrast to the behaviour of SPA and SCNA whose size is noticed to increase exponentially with the flux enhancement.

(3) The relaxation time of sfe with respect of soft X-ray flares is about (1.5–4.0 min.) which indicates the values of $(\alpha_{\text{eff}}N)$ as $(21\text{–}55) \times 10^{-4}\ \text{s}^{-1}$.

(4) The correlation between sfe and microwave bursts is a flat maximum in the frequency range 2000–3750 MHz and sfe is mostly associated with class 'A' burst spectra and shows poor association with 'G', 'C' and 'M' type burst spectra. These features differ from those of other SID's (SWF, SCNA, SPA, SEA and SES) reported earlier.

The results of the present study on the association between sfe and X-ray flux enhancements provide supporting evidence to the consensus that sfe is due to enhanced ionization in the D-region due to flux enhancements at wavelengths less than 20 Å. Further work is necessary for a better understanding of the association of sfe characteristics on X-ray flux enhancements using the time histories of flux enhancements and taking into consideration the changes in the solar source temperature. Such an attempt is being made and will be reported later.

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