RELATION BETWEEN VLF PHASE DEVIATIONS AND SOLAR X-RAY FLUXES DURING SOLAR FLARES

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Abstract. Sudden phase anomalies (SPA's) observed in the phase of GBR 16 kHz VLF signals during the years 1977 to 1983 have been analysed in the light of their associated solar X-ray fluxes in the 0.5–4 Å and 1–8 Å bands. An attempt has been made to investigate the solar zenith angle (χ) dependence of the integrated solar X-ray flux for producing SPA's. It is deduced from the observations for $\chi < 81°$ that the phase deviation increases linearly as a whole with increasing solar X-ray fluxes in these two bands. The threshold X-ray flux needed to produce a detectable SPA effect has been estimated to be 1.6×10^{-4} erg cm^{-2} s^{-1} and 1.8×10^{-3} erg cm^{-2} s^{-1} in the 0.5–4 Å and 1–8 Å bands, respectively. For both bands the average cross section for all atmospheric constituents at a height of 70 km is almost equal to the absorption cross section for the 3 Å X-ray emission.

1. Introduction

During the occurrence of most solar flares, the electron density in the ionosphere on the sunlit part of the earth is enhanced and ionization is usually produced below the normal D-region (Bracewell and Straker, 1949; Chilton *et al.*, 1963; Mitra, 1966; Kaufmann and Mendes, 1970). Although the normal D-region is thought to be formed through ionization caused by solar Lyman-α and cosmic rays (Nicolet and Aiken, 1960), the enhanced X-ray emission during solar flares over a wide spectral range produces the sudden and increased ionization at various levels in the earth's ionosphere (Deshpande *et al.*, 1972). The emission below 10 Å is important for producing enhanced ionization of the D-region (Friedman, 1962; Whitten and Popoff, 1961; Sengupta, 1971), which varies with the solar zenith angle (χ) in a way different from that valid for normal D-region ionization (Gough, 1974). This enhanced ionization in turn leads to sudden phase anomalies (SPA's) in the propagation of VLF signals. An SPA appears as an advance in the phase of the downcoming sky-wave, the effect of which is superimposed upon the regular diurnal variation of the relative phase of VLF signals, varying from a few minutes to a few hours (Mitra, 1974). These SPA's produced in the VLF propagation in the lower ionosphere during solar flares are more sensitive indicators of sudden ionospheric disturbances (SID's) than other SID effects, (e.g., SWF, SCNA, PCA, etc.). Correlation studies between observed SPA's at VLF signals and associated solar X-ray fluxes have been made extensively in the past (Mitra, 1974).

Chilton *et al.* (1963), Sengupta (1971) and Dubey *et al.* (1977) have shown that the observed changes in the VLF phase ($\Delta\phi$) are apparently related to $\log(\sec\chi)$ along the propagation path. A quantitative relationship between VLF phase devia-

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tions during SPA's and solar X-ray fluxes in the 1–8 Å band during solar flares has been investigated by Muraoka *et al.* (1977). Since no observed solar X-ray data were available for solar flares during the period of observations of SPA's, the solar X-ray fluxes were estimated by them on the basis of an empirical relation among $f_{\min}$, the lowest frequency for vertical ionospheric reflection, F_0, the solar X-ray flux in the 1–8 Å band and $\cos\chi$, given by Sato (1975), as:

$$f_{\min}\,(\mathrm{MHz}) = 10F_0^{1/4}\cos^{1/2}\chi,$$

where F_0 is in the unit of erg cm^{-2} s^{-1} and χ is the solar zenith angle at the location where $f_{\min}$ is observed. From theoretical consideration, Muraoka *et al.* (1977) have shown that an apparent linear relationship exists between the phase deviation $\Delta\phi$ observed at VLF and solar X-ray fluxes in the 1–8 Å band, as a function of sec $\chi_{\min}$, where $\chi_{\min}$ is the minimum value of χ over the propagation path at the instant of maximum $\Delta\phi$ observed. Although, Pant *et al.* (1983) have shown that a linear relation between $\Delta\phi$ and logarithm of X-ray burst peak intensities exists in the 0.5–4 Å and 1–8 Å bands, the data analysed by them does not show a noticeable dependence on χ below 82°.

In the present study we have investigated whether one should use the normalized phase deviations in the relation between the observed phase deviation and X-ray fluxes during solar flares. An attempt has also been made to investigate the solar zenith angle dependence of the integrated solar X-ray flux for producing SPA's. Threshold X-ray fluxes needed to produce a detectable SPA effect in the 0.5–4 Å and 1–8 Å bands, have also been estimated and discussed.

2. Observation and Analysis

The phase variations of phase stabilized VLF transmissions over a long propagation path were observed at this observatory (29.36° N, 79.45° E) by means of GBR 16 kHz VLF signals radiated from Rugby (U.K.) (52.36° N, 1.18° W). The equipment used for recording the relative phase of VLF signals is a dual channel precision timing system, manufactured by Electronics Engineering Company (EECO), U.S.A., which mainly consists of a 5 MHz quartz crystal oscillator, a clock control unit, a VLF receiver with a loop antenna and a strip chart recorder. A detailed description of the equipment and the stability of the oscillator have been given by Mahra (1976). The phase change on the chart recorder can be read with an accuracy of one μs, which corresponds to a change of 5.76° in the phase of 16 kHz VLF signals. A total of 111 SPA events were recorded during April 1977 to May 1983. Solar X-ray burst data were taken from the satellite GOES observations in the X-ray bands of 0.5–4 Å and 1–8 Å which are reported in the Solar Geophysical Data (NOAA, Boulder). The phase deviations ($\Delta\phi$), solar X-ray fluxes (F_0, in the 0.5–4 Å and 1–8 Å bands) and time of SPA observations in UT are presented in Table I.

TABLE I

Time of occurrence of SPA's, solar X-ray flux (F_0) and phase deviation ($\Delta\phi$)

Date	Time of SPA Observations (UT)			solar X-ray fluxes in bands ($\times 10^{-6}$ W m^{-2})		$\Delta\phi$ (°)
	Onset	Maximum	Ending	0.5–4 Å	1–8 Å	
1977						
14 Apr	0545	0600	0700	5.2	30.0	74.8
15 Apr	0830	0900	1000	0.56	4.5	46.0
25 June	1030	1100	1200	–	7.0	40.3
26 June	1000	1015	1200	3.7	18.0	74.8
27 June	0500	0530	0730	2.1	13.0	51.8
19 Sept	1000	1045	1400	52.0	300.0	195.8
1978						
08 Jan	0700	0745	1100	27.0	120.0	144.0
02 Feb	1130	1145	1300	-	18.0	80.6
15 Feb	0745	0800	0900	6.1	26.0	86.4
10 Mar	1045	1115	1200	2.1	14.0	63.3
08 May	1200	1245	1500	10.0	60.0	103.6
30 May	0715	0730	1000	8.7	54.0	97.9
31 May	1015	1100	1400	6.4	57.0	115.2
05 June	0730	0745	0845	1.0	9.5	57.6
07 July	0730	0745	0900	5.5	28.0	92.1
07 July	1130	1145	1300	6.9	32.0	109.4
09 July	1200	1245	1500	6.0	38.0	63.3
10 July	0800	0815	1100	180.0	810.0	184.3
23 Sep	0930	1015	1300	30.1	176.0	109.3
01 Oct	0700	0730	0900	17.6	90.3	74.8
15 Oct	0645	0645	0800	4.6	28.0	69.1
1979						
15 Jan	0715	0745	0900	6.9	47.7	69.1
25 Feb	0600	0714	0845	1.7	17.6	57.6
26 Feb	0730	0800	1000	0.9	9.5	51.8
29 Mar	0715	0745	0830	1.0	10.0	51.8
09 Apr*	1215	1245	1400	3.9	30.1	74.8
10 Apr	0630	0700	0800	1.0	10.1	69.1
14 Apr	0715	0745	0900	0.9	10.0	46.8
27 Apr	0630	0700	0900	60.2	176.0	195.8

TABLE I

Continued

Date	Time of SPA Observations (UT)			solar X-ray fluxes in bands ($\times 10^{-6}$ W m^{-2})		$\Delta\phi$ (°)
	Onset	Maximum	Ending	0.5–4 Å	1–8 Å	
1979 *Continued*						
29 Apr	0700	0730	1000	0.9	9.0	51.8
03 June	0815	0900	1100	3.0	47.7	97.9
04 June	0515	0600	1000	30.1	176.0	172.8
26 July	0930	1000	1200	0.7	8.4	40.3
01 Aug	1115	1130	1300	4.7	17.6	51.8
10 Aug	0900	0930	1100	1.7	10.0	86.4
20 Aug	0900	0930	1300	176.0	778.0	213.1
23 Aug*	1245	1315	1500	6.0	39.7	57.7
15 Sep	1015	1045	1200	17.6	90.3	138.2
05 Oct*	1130	1200	1500	30.1	95.4	74.8
06 Oct	0730	0745	0900	0.8	7.7	69.1
07 Oct	0730	0815	1000	0.8	6.9	46.0
17 Oct	0630	0715	0900	9.0	47.7	120.9
18 Oct	0900	0930	1200	3.0	17.6	80.6
19 Oct*	1200	1230	1330	-	17.6	46.0
20 Oct	0530	0545	0800	7.7	47.7	103.6
21 Oct*	1215	1230	1500	6.9	39.7	46.0
20 Dec	0600	0630	0900	47.7	100.0	92.1
20 Dec*	0900	0945	1100	4.7	30.1	57.6
1980						
08 Feb	0910	0915	1020	60.2	176.0	132.4
28 Mar	1000	-	-	1.7	10.0	63.0
05 Apr	0545	0610	0700	0.9	17.6	74.8
07 Apr	0530	0600	0700	17.6	95.4	132.4
02 June	0720	0730	0820	4.7	39.7	92.1
28 June	0800	0815	0900	3.0	17.6	57.6
28 June	1115	1130	1200	1.7	17.6	46.0
17 July	0600	0615	0720	6.0	54.4	63.3
22 Aug	0530	0530	0620	1.7	9.5	51.8
22 Aug	0830	0845	1020	1.0	9.0	51.8
09 Oct*	1120	1145	1300	30.1	95.4	86.4
20 Nov	0830	0900	1000	7.7	47.7	138.2
21 Nov	0800	-	-	1.7	10.0	57.6
21 Nov	1000	-	-	3.0	17.6	69.1

TABLE I
Continued

Date	Time of SPA Observations (UT)			solar X-ray fluxes in bands ($\times 10^{-6}$ W m^{-2})		$\Delta\phi$ (°)
	Onset	Maximum	Ending	0.5–4 Å	1–8 Å	
1981						
09 Feb	0620	0630	0715	1.7	10.0	97.9
23 Mar	1040	1050	1120	4.7	30.1	80.6
03 Apr	0920	1015	1200	10.0	90.3	103.6
10 Apr	1100	1130	1300	30.1	100.0	149.7
13 May	-	1130	-	47.7	176.0	178.5
24 June	0630	0645	0730	3.0	17.6	57.6
11 Aug	0745	0800	0845	9.0	60.2	74.8
13 Aug	0800	0815	0900	17.7	60.2	97.9
16 Aug	0615	0630	0710	3.0	10.0	97.7
11 Nov	0820	0830	1000	0.7	7.7	63.3
13 Dec	1030	1040	1100	1 7	1o 0	134 5
1982						
18 Feb	0900	0910	1030	3.0	17.6	57.6
20 Feb	0915	0950	1120	6.0	47.7	132.4
31 Mar	0615	0630	0700	6.0	47.7	74.8
31 Mar	0800	0830	0920	8.4	60.2	80.6
04 June*	0300	0315	0420	39.7	100.0	86.4
12 June	0500	0515	0700	95.4	397.0	167.0
20 June	0640	0645	0800	1.7	10.0	40.3
20 June*	1200	1215	1300	4.7	30.1	46.8
21 June	1120	1140	1300	1.7	17.6	46.8
22 June	0540	0550	0800	6.0	39.7	57.6
23 June	1020	1030	1200	6.5	30.1	74.8
23 June	1200	1220	1300	3.0	17.6	80.6
24 June	0520	0545	0630	4.7	30.1	86.4
26 June	0920	0940	1040	1.0	10.0	51.8
27 June	1020	1030	1115	4.7	30.1	69.1
12 July	0900	1000	1300	176.0	845.0	161.2
14 July	1000	1050	1120	4.7	30.1	69.1
15 July	0920	0950	1020	3.0	17.6	51.8
17 July	1020	1030	1230	90.3	477.0	178.5
01 Sep	0745	0800	1000	6.0	47.7	92.1
05 Sep	1000	1015	1100	8.4	47.7	80.6
06 Sep	0810	0830	0900	9.0	47.7	74.8
09 Sep	0930	0940	1020	3.0	17.6	40.3
09 Sep*	1040	1050	1120	3.0	30.1	40.3
09 Sep*	1130	1145	-	60.2	100.0	155.5

TABLE I
Continued

Date	Time of SPA Observations (UT)			solar X-ray fluxes in bands ($\times 10^{-6}$ W m^{-2})		$\Delta\phi$ (°)
	Onset	Maximum	Ending	0.5–4 Å	1–8 Å	
1982 *Continued*						
10 Sep	0830	0845	0930	0.8	6.9	34.5
13 Sep	0800	0815	0900	10.0	69.8	120.9
17 Sep	1000	1015	1100	3.0	10.0	34.5
18 Sep	0820	0830	0945	60.2	100.0	138.2
11 Dec*	0445	0450	-	30.1	90.3	80.6
1983						
17 Mar	0900	0915	1000	6.0	30.1	115.2
22 Apr	0900	0930	1000	1.0	10.0	46.8
30 Apr	0745	815	0930	6.0	47.7	115.5
07 May	1040	1100	1130	1.7	10.0	63.3
11 May*	0400	0415	0520	6.9	30.1	97.9
12 May*	0300	0310	-	17.6	100.0	57.6
12 May	1340	1400	-	9.5	69.8	74.8
15 May	0840	0900	1100	90.3	387.9	201.6

* Data for which $\chi > 81°$, over the entire propagation path.

Only those SPA events were considered for which the associated X-ray burst peak intensities have been measured by satellite GOES. An example of the complex SPA event recorded by VLF receiver and time-profiles of the corresponding days, X-ray fluxes measurements in 0.5–4 Å and 1–8 Å bands has been reproduced on the same time scale in Figure 1. Since, the period considered here corresponds to a high level of solar activity of the 21st solar cycle, the solar X-ray fluxes measurements by satellite GOES, manifest quite complex flux time-profiles for X-rays. Therefore, the corresponding day-time phase variation records were equally complex during this period. Hence, we took only those SPA's which have their onset time coincidences with those in X-ray flux time-profiles and also got reflected in both channels of the VLF receiver. Here, channel-A has been used for detecting SPA's. Timewise, channel-B is lagging behind by about 17 minutes as compared to channel-A (Figure 1). The values of χ at the instants of maximum $\Delta\phi$ observed for SPA's were calculated at the midpoints of twenty sections of equally divided path from Rugby (U.K.) to Naini Tal.

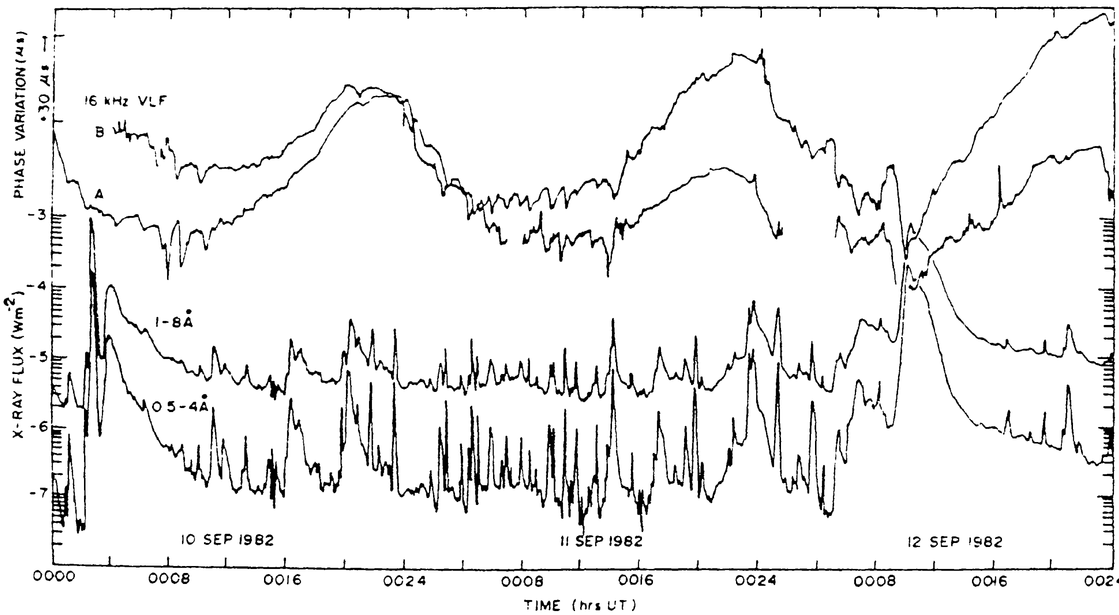

Fig. 1. Comparison between phase variations of GBR (16 kHz) VLF signals received at the observatory (Naini Tal) and associated solar X-ray fluxes in the 0.5–4 Å and 1–8 Å bands, as recorded by the satellite GOES.

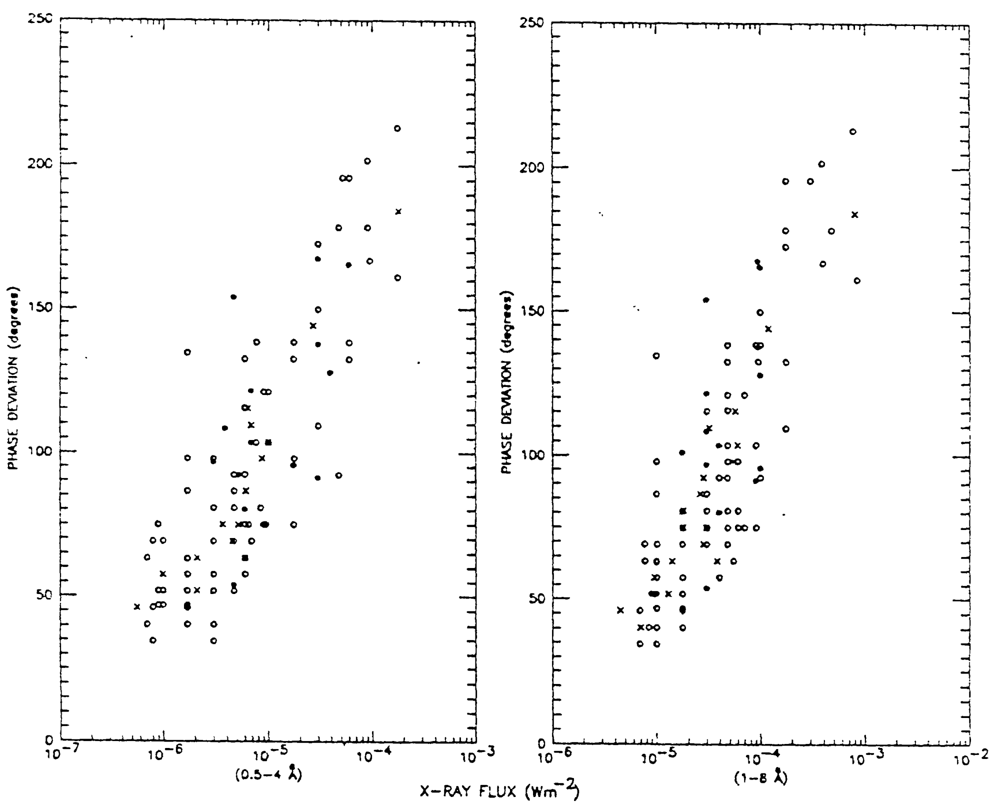

Fig. 2. Relationship between maximum phase deviation in SPA events and associated solar X-ray fluxes in the 0.5–4 Å and 1–8 Å bands for GBR (16 kHz) VLF signals received at Naini Tal. Open circles represent the unnormalized phase deviations plotted against log F_0 values for $\chi < 81°$ over the entire path of propagation, while the filled circles denote the points of normalized phase deviations ($\Delta\phi \sec \chi_{\min}$), plotted against log F_0 values for $\chi > 81°$. The data used in the earlier investigation by Pant *et al.* (1983) have been plotted as crosses.

3. Results and Discussions

A plot of maximum $\Delta\phi$ versus logarithm of peak solar X-ray fluxes, ($\log F_0$), in 0.5–4 Å and 1–8 Å bands is shown in Figure 2. Open circles denote the points of unnormalized phase deviations (i.e., $\Delta\phi$), plotted against $\log F_0$ values for $\chi < 81°$ over the entire propagation path. The filled circles represent the normalized phase deviations (i.e., $\Delta\phi \sec \chi_{\text{min}}$), plotted against $\log F_0$ values for $\chi > 81°$. The data used in the earlier investigation by Pant *et al.* (1983) have been plotted as crosses ($\times$) and it is evident from Figure 2 that these are distributed over the same area as covered by the scatter area of points obtained in the present analysis. The study of diurnal phase variations of 16 kHz VLF signals have shown an excellent correlation between the observed and the calculated phase variations (Pant and Mahra, 1980). These theoretically calculated diurnal phase variations were obtained by considering the phase variations in VLF signals as a function of χ, along the path of VLF propagation (Ijima *et al.*, 1968). An excellent correlation was found by Kaufmann and Barros (1969) between SPA's importance and the logarithm of X-ray burst peak intensities in the 0–3 Å, 0–8 Å and 8–20 Å bands.

These results show that for producing the observed SPA, the degree of ionization versus sec χ profile produced by the X-rays is different from the quiet time ionization versus sec χ profile. If we assume that the solar X-ray flux for $\chi < 81°$ is directed at all angles and at all times of the day then to a first approximation the average value of sec χ becomes unity, and the relation given by Muraoka *et al.* (1977) can then be expressed as:

$$\log F_\infty = 0.43 A \rho_0 P^{-1} \Delta\phi + \log F_c, \tag{1}$$

where

$$P = 360 \frac{d}{\lambda_w} \left(\frac{1}{2a} + \frac{\lambda_w^2}{16h^3} \right).$$

Here, F_∞ is the X-ray flux at the top of the atmosphere, A is the average absorption cross section of the X-ray emission for all atmospheric constituents, ρ is the number density of atmospheric particles at a datum level h_0, F_c is the threshold X-ray flux for an SPA event, λ_w is the wavelength of the VLF wave, d is the distance between the transmitter and the receiver, a is the radius of the earth and h is the reflection height of the VLF wave at a quiet time.

The relation between $\Delta\phi$ and $\log F_0$, obtained from the least squares solution of the data for which $\chi < 81°$ for the entire propagation path from GBR (Rugby) to Naini Tal is found as:

$$\log F_0(0.5\text{–}4\ \text{Å}) = 1.67 \times 10^{-2} \Delta\phi - 6.79 \tag{2}$$

and

$$\log F_0(1\text{–}8\ \text{Å}) = 1.39 \times 10^{-2} \Delta\phi - 5.73. \tag{3}$$

From relations (1), (2) and (3) we find that the threshold X-ray flux (F_c) needed to produce a detectable SPA effect is 1.6×10^{-7} W m^{-2} and 1.8×10^{-6} W m^{-2} in 0.5–4 Å and 1–8 Å bands respectively. The value of F_c in the 1–8 Å band is in good agreement with the values obtained by Kreplin *et al.* (1962) and Muraoka *et al.* (1977). Relations expressed by (2) and (3) hold for $\chi < 81°$. For larger values of χ (i.e., $\chi > 81°$) the condition stated above is quite uncertain as evident from Figure 2. The discrepancy in the observed and the theoretical relation can be understood on the basis of different studies made in the spectral distribution of measured X-ray fluxes and observed $\Delta\phi$ versus reflection height change in the D-region during solar flares (Sengupta, 1971; Deshpande *et al.*, 1972). The expression given by Muraoka *et al.* (1977) may be true for a short propagation path but as the path becomes longer, one has to bear in mind that the single value of χ cannot hold for the entire path length.

From relations (1), (2) and (3) we also infer that the value of the factor $0.43A\rho_0P^{-1}$ is 0.0167 and 0.0139 for X-ray bands 0.5–4 Å and 1–8 Å, respectively. Substituting the values of $\lambda_w = 18.758$ km, $d = 6854$ km, $a = 6371$ km and $\rho_0 = 2 \times 10^{15}$ cm^{-3} at 70 km (Champion, 1975), we obtained the value of the average cross section A for all atmospheric constituents as 3.6×10^{-21} cm^2 and 3.1×10^{-21} cm^2 for 0.5–4 Å and 1–8 Å bands, respectively. The value of A in the 1–8Å band is almost equal to that obtained by Muraoka *et al.* (1977). These values of average absorption cross section are almost equal to the absorption cross section for 3 Å X-ray emission (Friedman, 1962).

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