Solar Microwave Radio Bursts in Relation to SXR Bursts.

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ABSTRACT

In this paper, some of the aspects of solar radio emission observed at frequencies 245, 410, 610, 1415, 2695, 4995, 8800, and 15400 MHz have been elucidated in relation to their associated soft x-ray (SXR) bursts. The present study reveals that there exists very poor correlation between the asymmetry of SXR bursts with asymmetry of radio bursts at the above mentioned frequencies. It is also observed that the coefficient of correlation is highest in between SXR bursts and radio bursts around (i) 2 GHz in respect of their durations, (ii) 5 GHz in respect of the asymmetry in duration of radio bursts and the duration of SXR bursts (negative correlation), (iii) 4 GHz in respect of the flux of radio bursts and the duration of SXR bursts, and (iv) 5 GHz in respect of the flux of the radio bursts and the flux of SXR bursts. All these results have been explained on the basis of the known mechanisms of radio and soft x-ray emissions.

(Keywords: solar radio emissions, soft x-ray, SXR, asymmetry)

INTRODUCTION

Different aspects of solar radio emission in different frequency bands had been explored by various researchers[1-4]. Nowadays, with the advent of various satellite missions like PIONEER, GOES, SOHO, YOHKOH etc., the Sun is being exploited in the x-ray wavelengths as well. As a consequence, a recent thrust has automatically come up to correlate these x-ray observations with those of solar radio emissions, particularly in the microwave band, so as to gain an insight into the unexplored facts about the x-ray and radio Sun. Simultaneous images of the flaring loop at multi-frequencies and solar soft x-ray images are used to model the magnetic structure of the loop and the energy distribution of the radiating electrons. It should be mentioned here that at microwaves the plasma emission mechanism plays an important role at frequencies below about 2 GHz, and above about 2 GHz, gyro synchrotron emission dominates. It is observed that at 15 GHz, the flare emission is optically thin and comes from the foot point of the flaring loop, while the 5 GHz emission is optically thick and its spatial maximum is close to the loop-top [5]. The changes in the appearance of the active region with frequency reflect the differing spectra of free-free emission and gyro resonance emission. The compact 8.4 GHZ source indicates the extent of 1000 G magnetic fields; the compact 5 GHz source indicates 600 G field; the excess emission in the range at 5 GHz indicates 450 G fields; and the excess flux at 1.5 GHz is interpreted as due to 130 G fields at the edge of an optically-thick free-free source [6].

Recently, it is observed that the distribution of times between solar flares (the flare waiting-time distribution) follows a power law for long waiting times. With the help of simultaneous soft x-ray data we get the information about the waiting-time distribution of flares is consistent with a time-dependent Poisson process. It is shown analytically that power law behavior of the waiting times originates in the exponential distribution of flaring rates [7]. The power-law fits to the differential (density) and cumulative distributions as a function of frequency, time and phase of the solar cycle [8]. The statistics of quiescent times between successive bursts of solar flares activity displays a power law distribution with exponent $\alpha \approx 2.4$, which can be an indication of underlying complex dynamics with long correlation times.

A shell model of MHD turbulence correctly can explain the observed distributions[9]. A comparative study of the time evolution of the emission measure derived from Bragg Crystal spectrometer (Fe XXV channel) and from soft x-ray telescope images for 27 limb flares well observed by YOHKOH has been made by [10] who confirms hot plasma is situated mainly inside the bright loop-top kernels, where it co-exists with cooler plasma. In the present paper we have made a comparative study between the solar microwave bursts and soft X-ray (SXR) bursts which coexist together in respect of their time of evolution, so as to get an understanding about their probable site in the solar atmosphere along with their respective source mechanisms.

DATA COLLECTION AND METHOD OF ANALYSIS

Radio bursts data observed at frequencies 245, 410, 610, 1415, 2695, 4995, 8800, and 15400 MHz by Sagamore Hill Radio Observatory are collected from Solar Geophysical Data bulletins published by U.S. Department of Commerce, the period of coverage being 1998-1999 which is the rising phase (pre-maximum phase) of the 23rd solar cycle. SXR data observed during the same period in the wavelength range 1 – 8 Å by the Geo-Stationary Environmental Satellites (GOES) have also been taken from the same data books. An event of a radio burst is said to be associated with the corresponding SXR burst, when they occurred within $\pm$ 5 minutes of their respective starting times. For the present study we have considered the different parameters regarding the solar radio bursts and SXR bursts, such as, starting time of a radio burst, the time in which a radio burst becomes maximum, the duration of a radio burst, the peak flux intensity of the radio burst, starting time of SXR bursts, the time in which the SXR burst becomes maximum, end time of the SXR burst, and intensity of the SXR bursts.

The asymmetry in duration of radio bursts is calculated for each of the events by applying the following formula:

$A_s = r/d$

where ‘r’ gives the rise time (the time interval between the maximum phase and the starting time of a radio burst) and ‘d’ represents the total duration of the respective burst. A smaller value of ‘A_s’ implies larger asymmetry and a larger value of ‘A_s’ gives rise to smaller asymmetry. In this connection it is to be noted that the asymmetry as defined here is quite different from the ‘impulsiveness’ which represents the growth rate of the energy input in flares as introduced by[11] . The other notations which have been used in the present analysis are also given below:

σ_d : correlation coefficient in between the duration of radio bursts and the duration of SXR bursts.

σ_a : correlation coefficient in between the asymmetry ‘A_s’ of radio bursts and the duration of SXR bursts.

σ_f : correlation coefficient in between the radio emission flux and the duration of SXR bursts.

σ_{ff} : correlation coefficient in between the radio emission flux and the flux of SXR bursts.

RESULTS

After associating each of the radio bursts with the respective SXR bursts, the asymmetry A_s as defined earlier is calculated for each of the cases. The procedure is repeated for each of the frequencies of observations of radio bursts. Next the scatter plots are done for different frequency radio bursts showing the variation of duration of SXR bursts against the duration of radio bursts. These results are shown in Figures 1(a) – 1(h).

Similar plots revealing the variation of the duration of SXR bursts with (i) the asymmetry in radio burst duration are presented by Figures 2(a) – 2(h); and (ii) that of the flux of radio bursts by Figures 3(a) – 3(h). The straight lines appearing in Figures 1 - 3 are nothing but some sort of least-square fit. In the next phase σ_d , σ_a , σ_f and σ_{ff} values are found out separately for the observing frequencies as stated in the present analysis.

Table 1 gives the correlation coefficients at different frequencies and Figures (4a – 4c) display the graphical representations of correlation coefficients in between duration of radio and SXR bursts, correlation coefficient in between radio flux & duration of SXR bursts, and correlation coefficient in between asymmetry in duration of radio bursts &duration of SXR bursts respectively with respect to frequencies of solar radio bursts.

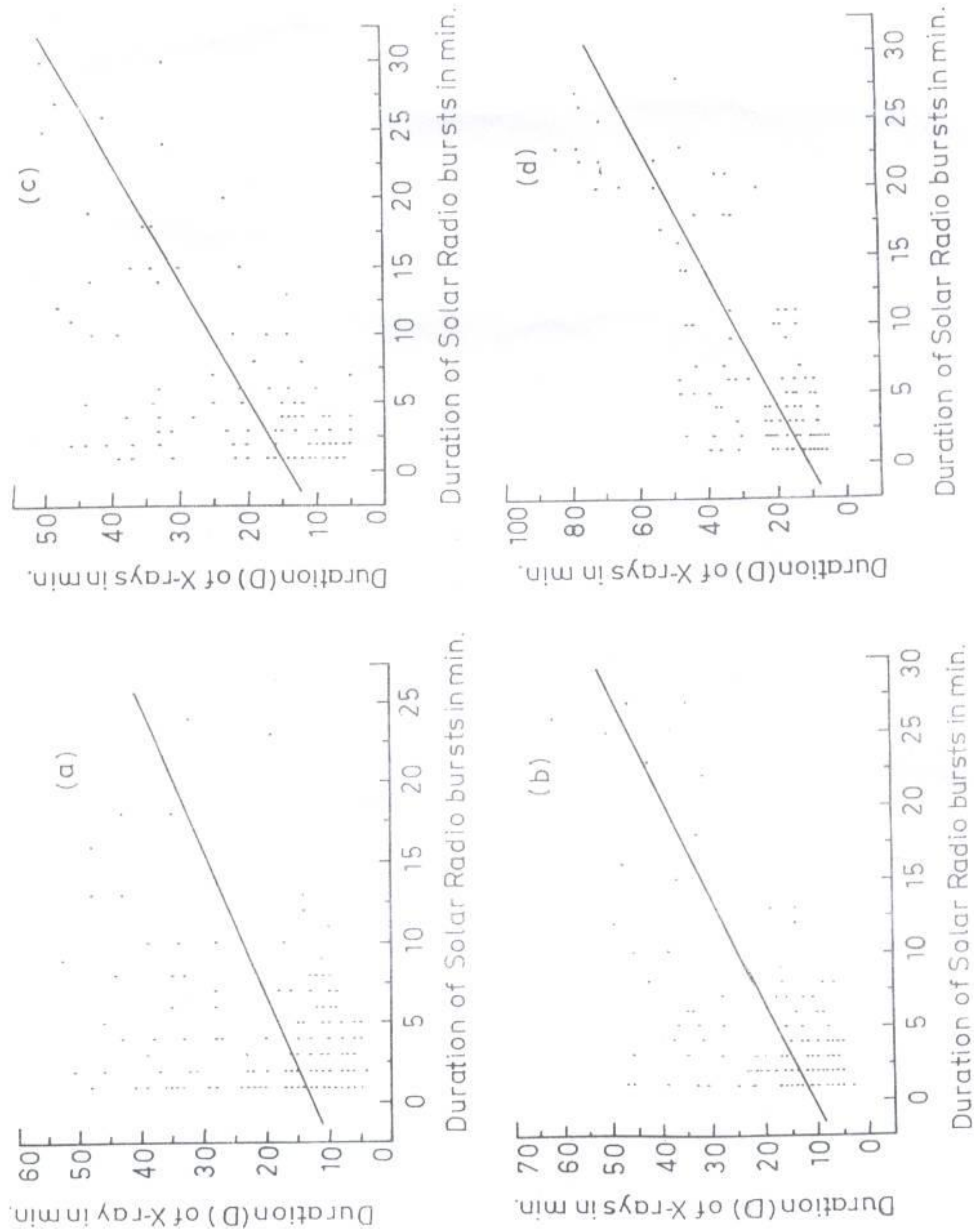

Figure 1a-1d

Figure 1: Scatter Plots of Duration of SXR bursts vs Duration of Radio Bursts at (a) 245, (b) 410, (c) 610, (d) 1415, (e) 2695, (f) 4995, (g) 8800, and (h) 15400 MHz.

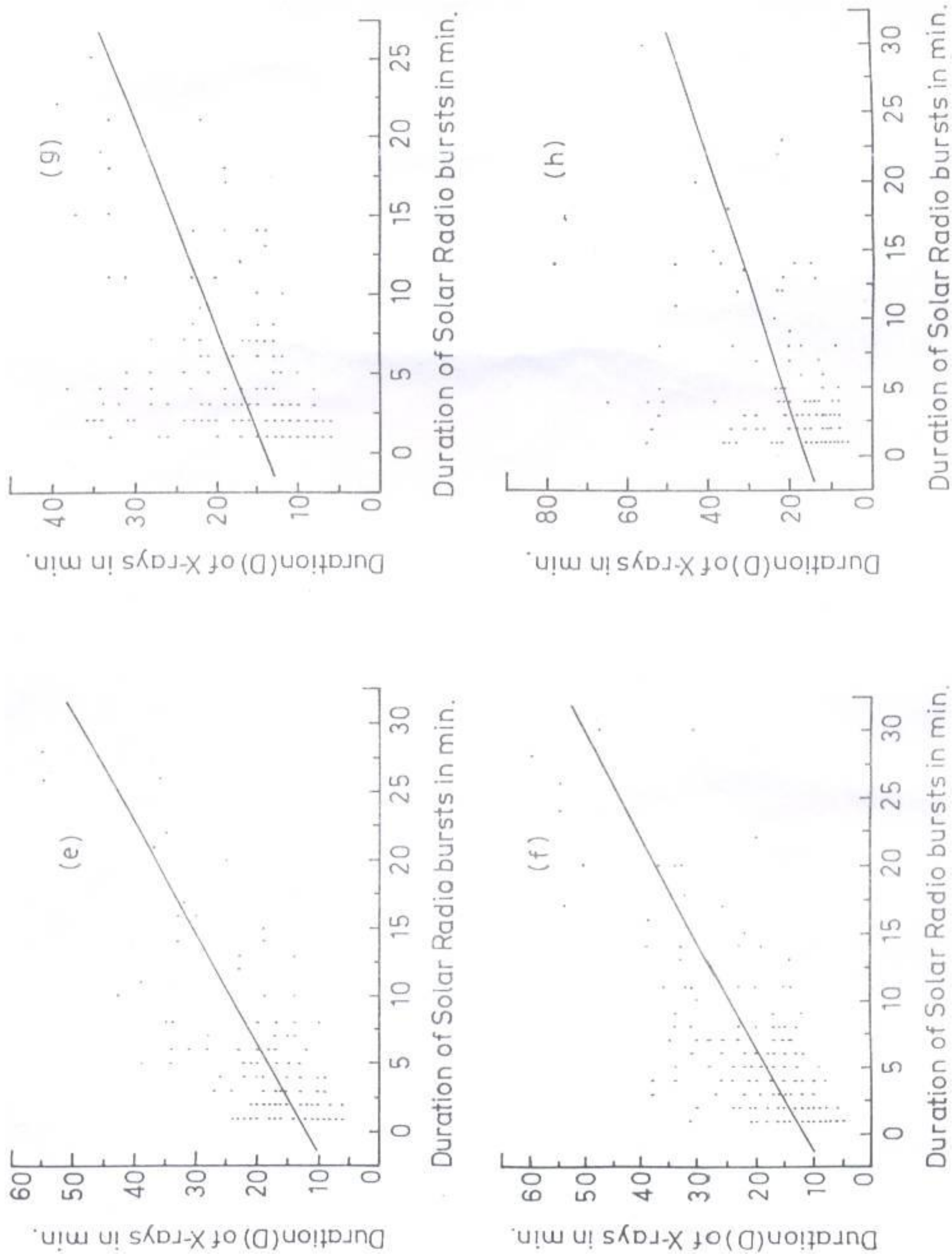

Figure 1e-1h

Figure 1 (continued): Scatter Plots of Duration of SXR bursts vs Duration of Radio Bursts at (a) 245, (b) 410, (c) 610, (d) 1415, (e) 2695, (f) 4995, (g) 8800, and (h) 15400 MHz.

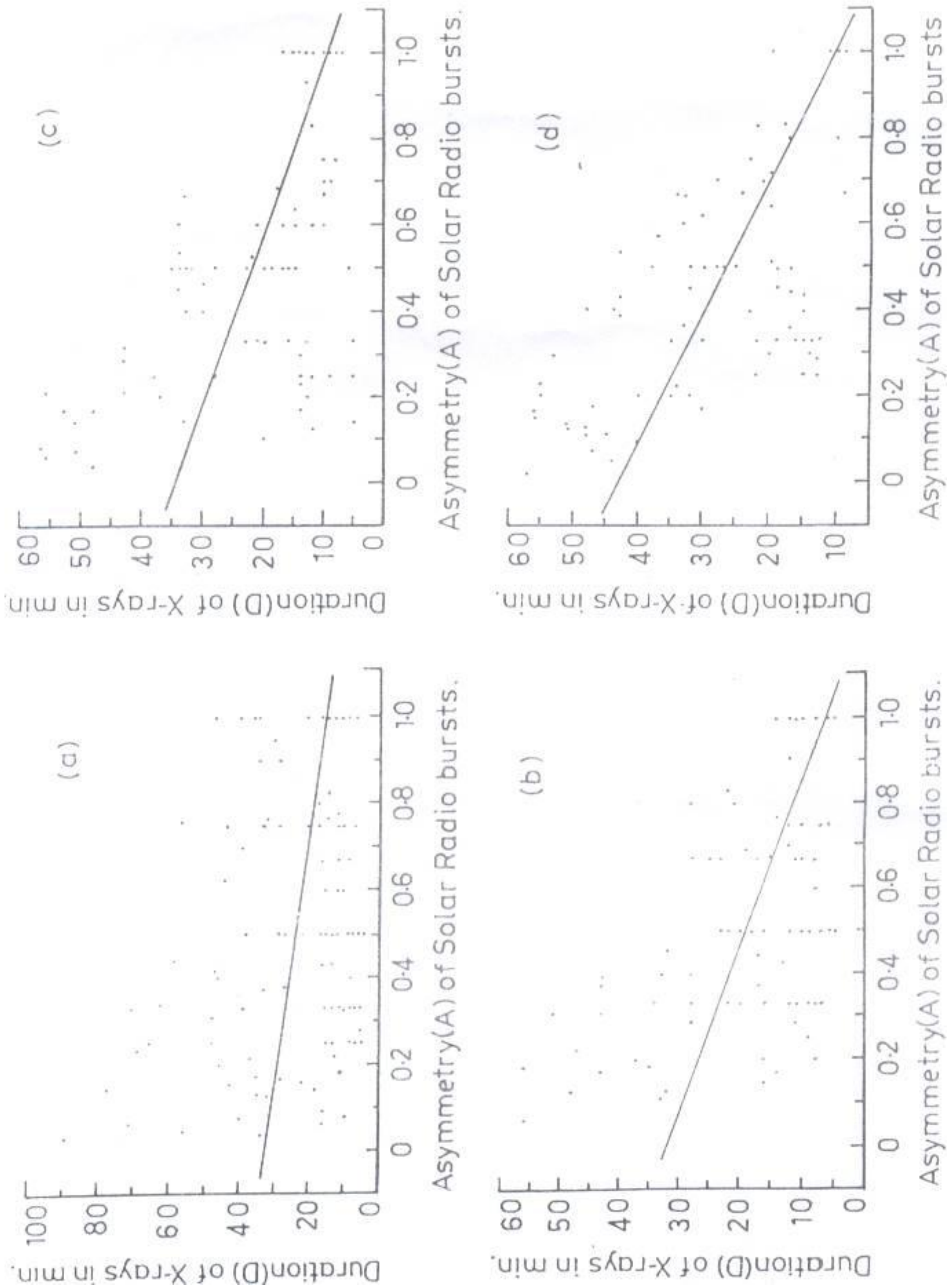

Figure 2a-2d

Figure 2: Scatter Plots of the Variation of the Duration of SXR Bursts with the Asymmetry of Radio Bursts at (a) 245, (b) 410, (c) 610, (d) 1415, (e) 2695, (f)4995, (g) 8800, and (h) 15400 MHz.

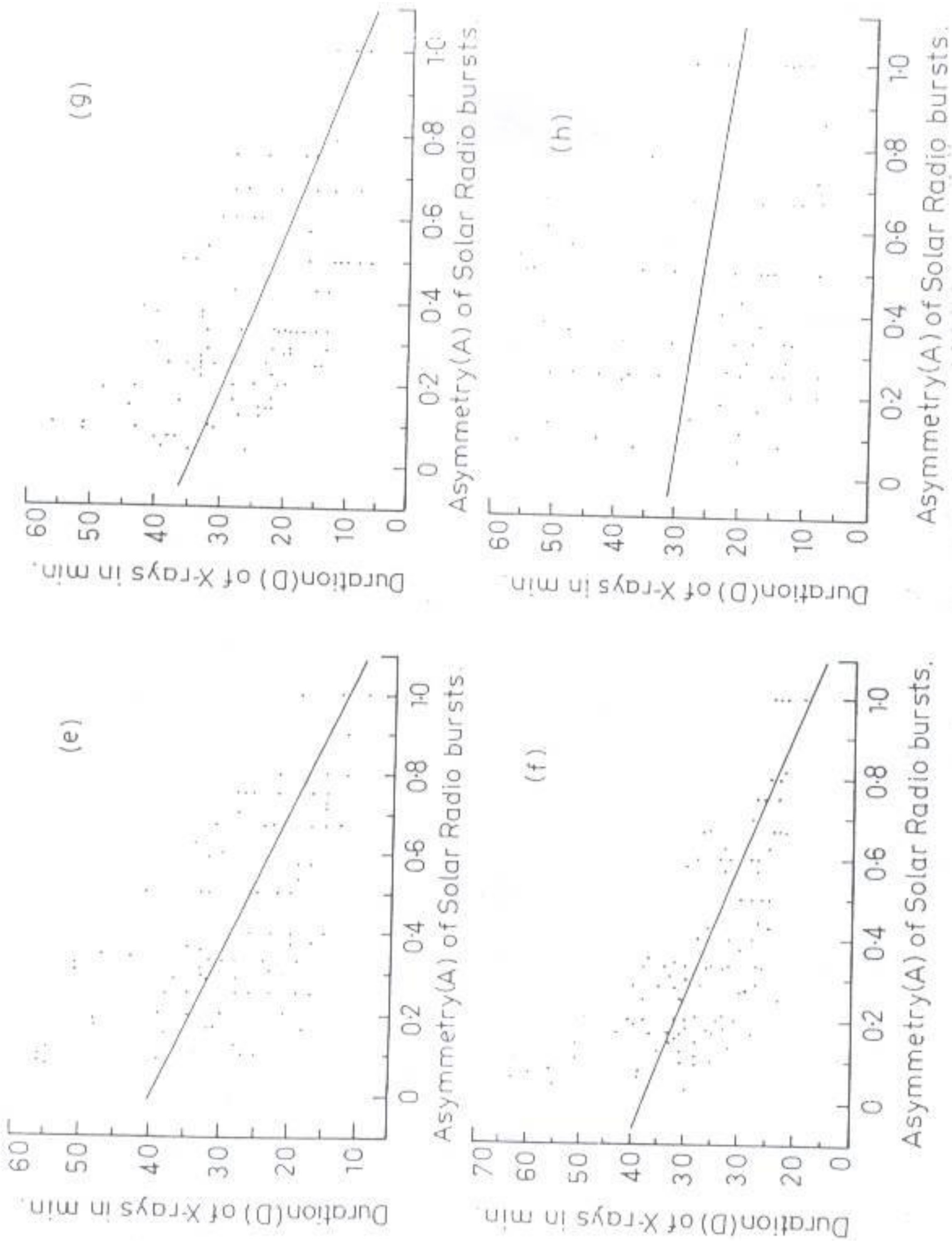

Figure 2e-2h

Figure 2 (continued): Scatter Plots of the Variation of the Duration of SXR Bursts with the Asymmetry of Radio Bursts at (a) 245, (b) 410, (c) 610, (d) 1415, (e) 2695, (f)4995, (g) 8800, and (h) 15400 MHz.

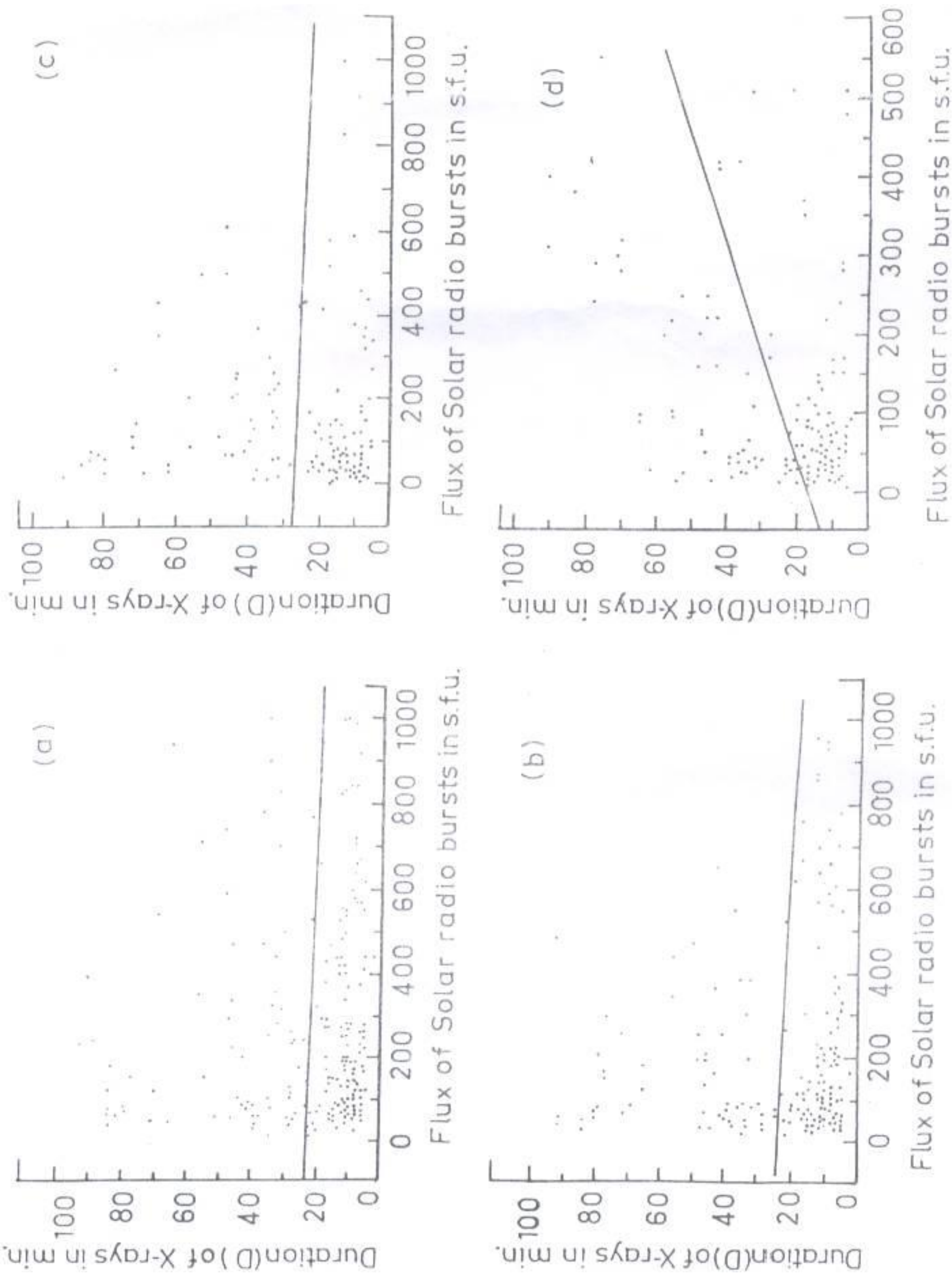

Figure 3a-3d

Figure 3: Scatter Diagram Showing the Variation of the Duration of SXR Bursts with the Flux of Radio Bursts Observed at (a) 245, (b) 410, (c) 610, (d) 1415, (e) 2695, (f) 4995, (g) 8800, and (h) 15400 MHz.

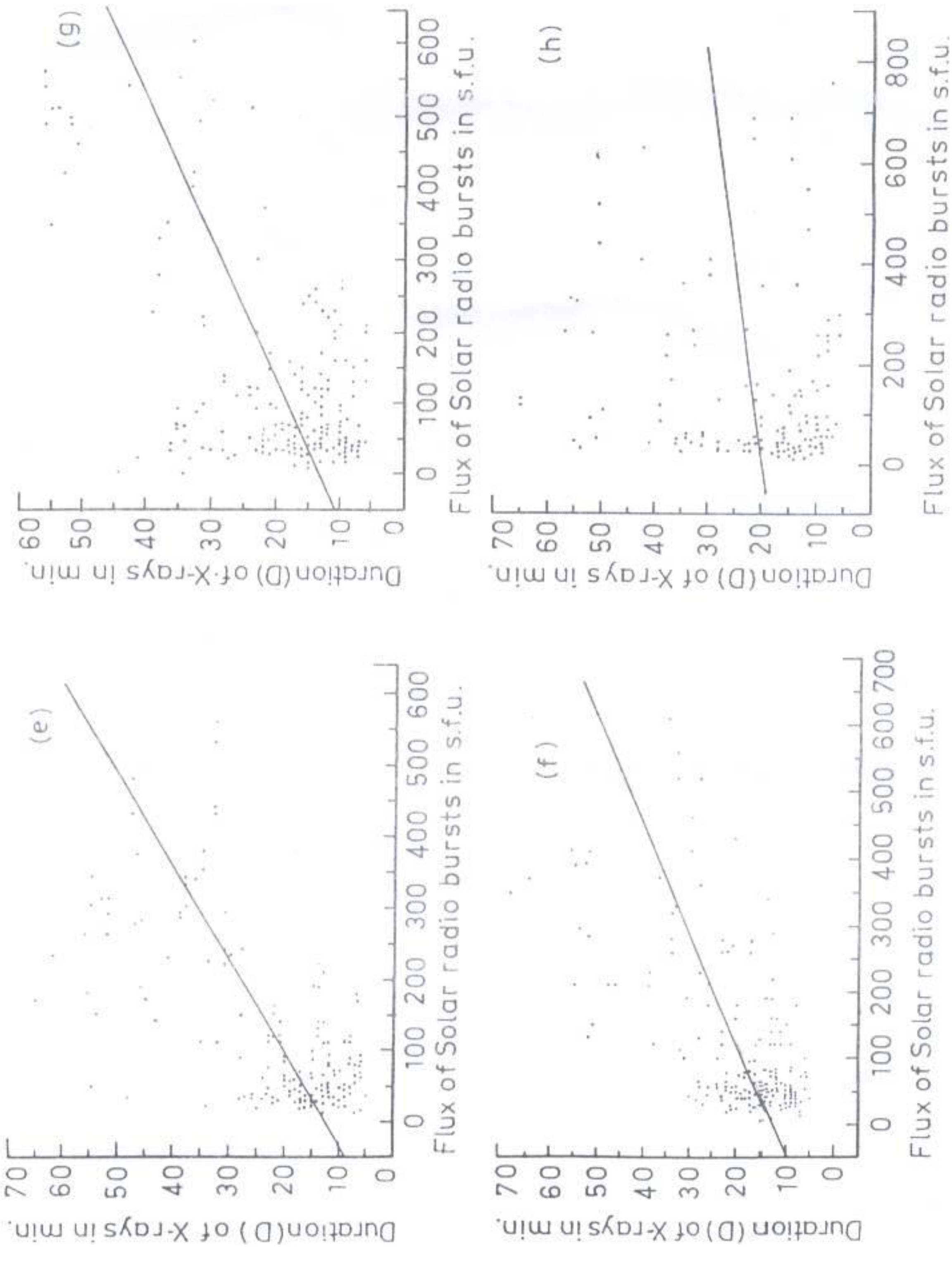

Figure 3e-3h.

Figure 3 (continued): Scatter Diagram Showing the Variation of the Duration of SXR Bursts with the Flux of Radio Bursts Observed at (a) 245, (b) 410, (c) 610, (d) 1415, (e) 2695, (f) 4995, (g) 8800, and (h) 15400 MHz.

Table 1: Correlation Coefficients at Various Frequencies.

Frequency (MHz)	245	410	610	1415	2695	4995	8800	15400
σ_d	0.35	0.6	0.6	0.8	0.73	0.72	0.43	0.42
σ_a	-0.29	-0.5	-0.51	-0.58	-0.64	-0.71	-0.54	-0.16
σ_f	-0.05	-0.06	-0.04	0.45	0.65	0.61	0.59	0.15
σ_{ff}	0.1	0.23	0.24	0.41	0.47	0.71	0.67	0.35

The graphical representations of the correlation coefficients in between flux of solar radio emission and flux of SXR bursts with respect to frequencies of solar radio bursts are not shown here.

From the scatter plots it is observed that the scatter is large and so the validity of the fitting procedure needs to be quantified with the error associated with the fit. For this purpose we calculate the 'Standard error of estimate'[12] for all of the above mentioned studies separately and is presented in Table II. The notations which have been used in present study are also given below:

E_d: standard error of estimate in between the duration of radio bursts and the duration of SXR bursts.

E_a : standard error of estimate in between the asymmetry 'A_s' of radio bursts and the duration of SXR bursts.

E_f : standard error of estimate in between the radio emission flux and the duration of SXR bursts

E_{ff} : standard error of estimate in between the radio emission flux and the flux of SXR bursts.

The variation of correlation coefficient σ_d is plotted against log f where 'f' is in MHz [Figure 4(a)]. σ_d is found to increase with the increase in frequency of observation of radio bursts up to 1.415 GHz and after peaking around 2 GHz, it declines with the rise of frequency. This sort of dependence helps us to conclude that the radio bursts up to decimeter range have one to one correspondence with the soft x-rays in respect of their durations, (i.e., soft x-rays become shorter or longer lived as and when the radio bursts are shorter or longer lived, respectively). But for the radio bursts above 5 GHz frequency, the correlation becomes poor, which indicates that soft x-ray emission is less dependent on radio emission at higher frequencies in respect of their longevity.

From Figure 4(c) it is observed that the correlation coefficient σ_a is negative all throughout the entire band of frequencies, and it decreases with the increase of frequency up to 5 GHz, after which it increases with the rise of frequency. From the results it is noticed that the asymmetry 'A_s' of radio bursts is anti-correlated with the duration of SXR bursts, indicating shorter lived SXR emission with smaller asymmetry in radio burst duration (larger values of 'A_s') and vice verse.

Similar plot for σ_f as shown in Figure 4(b) shows that the correlation coefficient is negative up to 610 MHz after which it becomes positive. It peaks around 4 GHz and then it declines with the increase in frequency. It is to be noted further that very poor correlation is observed in the frequency band 245 – 610 MHz, i.e., in the meter wave band. But in the microwave band the enhancement in the radio emission flux gives rise to greater durability in SXR emission and this fits quite well for the radio bursts observed around 4 GHz frequency.

The correlation coefficient in between flux of solar radio emission and flux of SXR bursts peaks around 5 GHz and then it declines with the increase in frequency.

DISCUSSION AND CONCLUSIONS

The foregoing analysis highlights that the microwave bursts at around 2 GHz frequency are best correlated with soft x-rays in respect of their duration (i.e., SXR bursts become shorter or longer lived according as their respective microwave bursts at around 2 GHz).

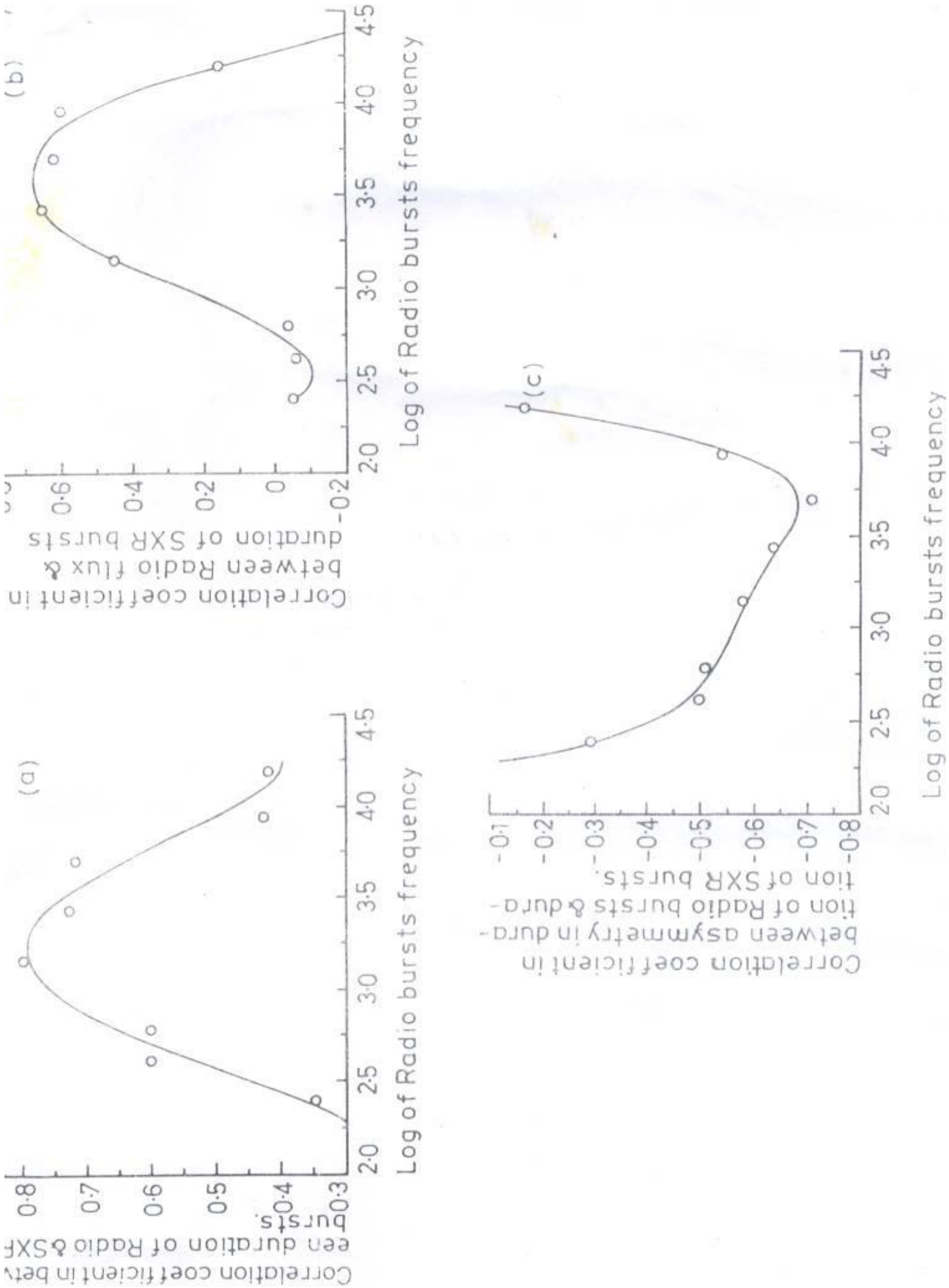

Figure 4: Curves Showing the Variation of Coefficients of Correlation σ with log f, where f is in MHz. Curve (a) is for σ_d, Curve (b) for σ_f, and Curve (c) for σ_a .

Table 2: Standard Error of Estimate at Various Frequencies.

Standard error of estimate	245 MHz	410 MHz	610 MHz	1415 MHz	2695 MHz	4995 MHz	8800 MHz	15400 MHz
E_d	11.01	9.9	10.5	11	6.4	7.2	7.5	12.7
E_a	17.7	11.32	11.62	11.37	8.6	7.84	9.34	14.84
E_f	19.8	21.5	22.2	18.1	10.4	9.6	9.52	14
E_{ff}	0.54	0.53	0.51	0.45	0.39	0.3	0.32	0.4

From this it can be inferred that if the electrons producing microwave bursts gyrate about the magnetic lines of force for a longer time, then the plasma condensation becomes long-lived for generating soft x-rays by free-free emission.

In the study of asymmetry it is observed that the asymmetry in duration of radio bursts is negatively correlated with the duration of SXR bursts which implies that as asymmetry increases (smaller 'A_s' values), the SXR bursts become more durable. It is known that a larger asymmetry in duration reflects a prolonged energy release as defined by Dennis and Zero[13] and a smaller asymmetry reflects the reverse. Hence, a prolonged energy release in radio emission causes long-lived SXR bursts and this inference can be drawn in a perfect manner for radio emission around 5 GHz frequency.

The correlation coefficient in between the flux of radio bursts and the duration of SXR bursts is examined to be negative in the frequency range 245-610 MHz, above which it is positive. This indicates that the increase in flux of meter-wave bursts causes decrease in duration of SXR bursts. But in the microwave band (at 4 GHz), as these two variables are positively correlated with each other, the increase in flux of radio bursts gives rise to long-lived SXR bursts. In a similar fashion in the microwave band the flux of both radio bursts and SXR bursts are highly correlated with each other (around 5 GHz radio band). The plasma condensation which is formed out of the flare emission around 4-5 GHz produces free-free emission which gives rise to enhanced x-ray emission with greater life time.

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