Observations of X- ray and EUV fluxes during X-class solar flares and response of upper ionosphere during 23rd and 24th Solar cycle

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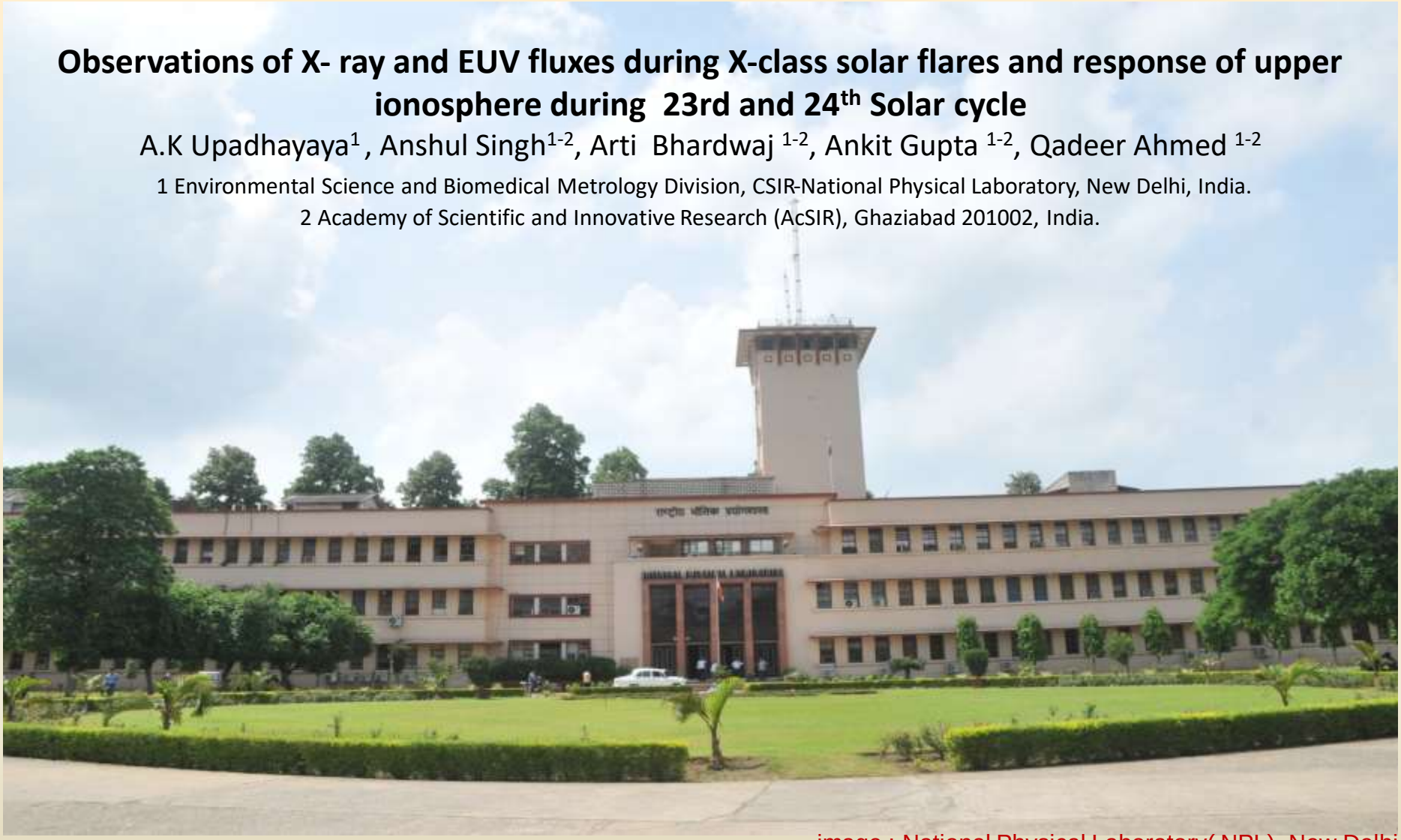

image : National Physical Laboratory(NPL), New Delhi

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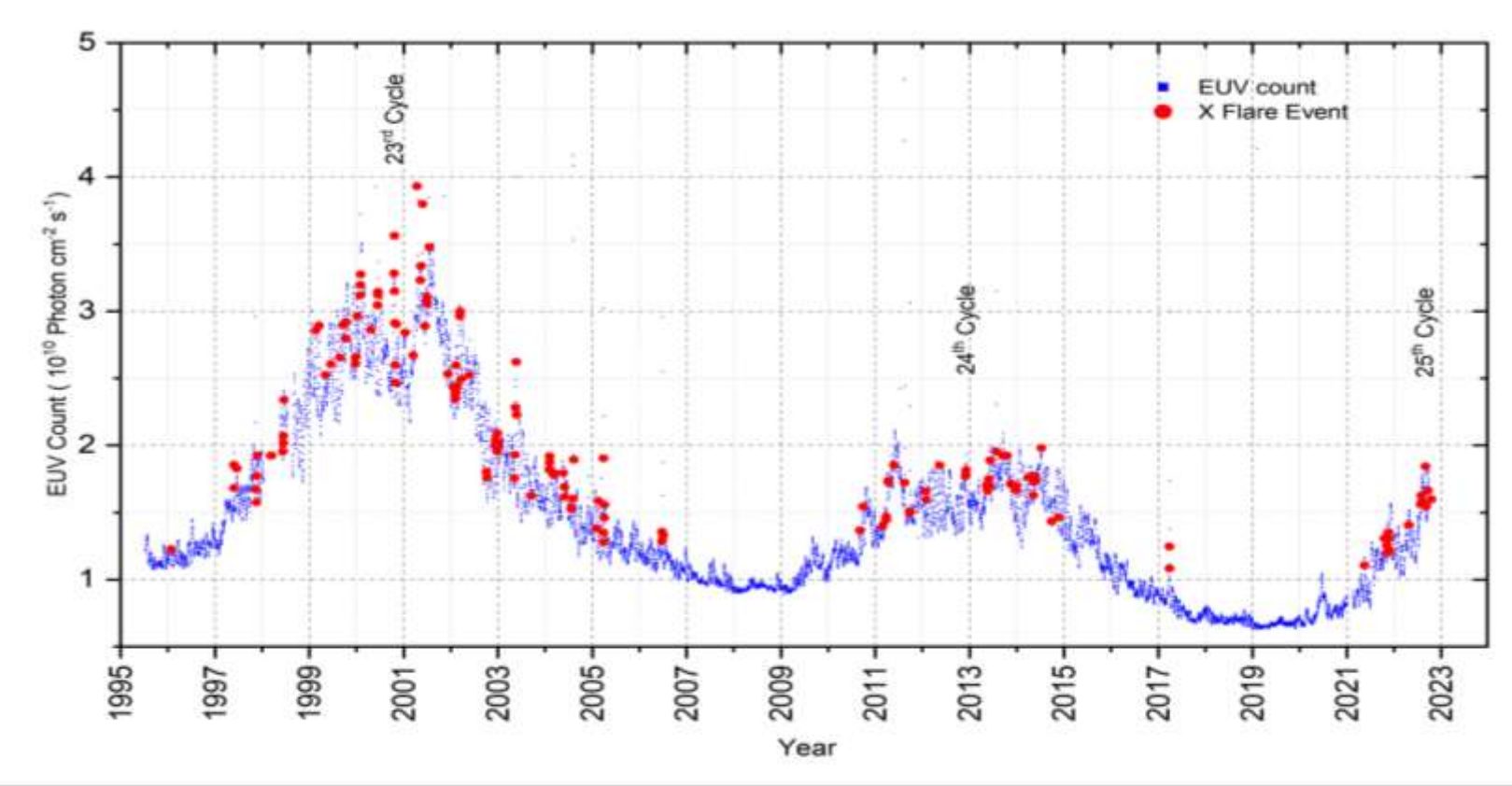
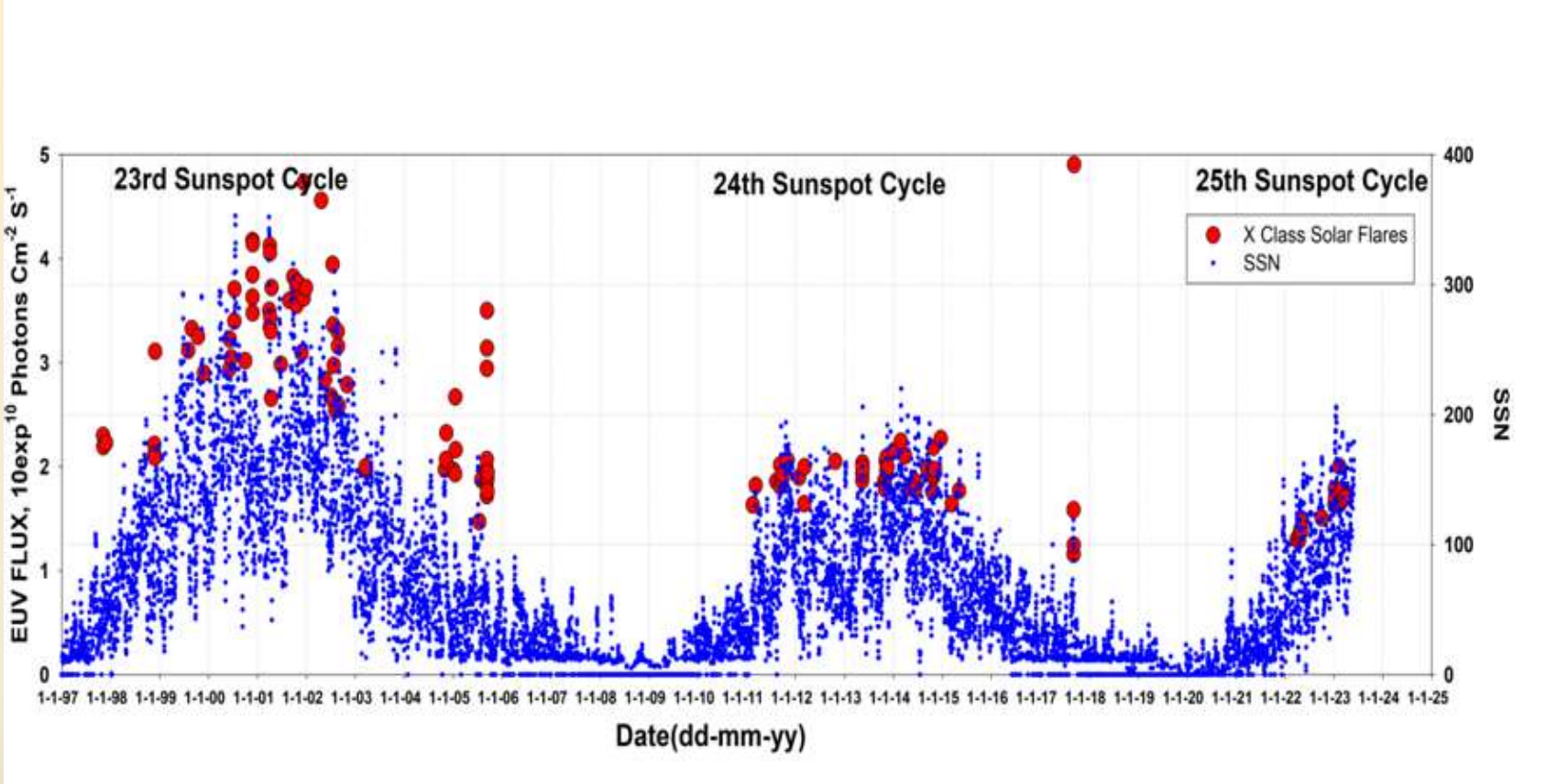
In our study for the 10 most intense X class solar flares observed during the 23rd, 24th and 25th (till 10th June 2023) Sunspot cycle's we have made use of three sets of data:

- (1) EUV photon fluxes measured by the Solar EUV Monitor (SEM) experiment on the Solar Heliospheric Observatory (SOHO),
- (2) X-ray fluxes measured by the X-ray sensors on Geosynchronous Operational Environmental Satellite, GOES 8-16 and
- (3) the midday TEC observed by Liu et al. [2006] with the ground-based receivers of the International GPS Service for Geodynamics (IGS) and the Taiwan network and,
- (4) TEC from Indian IGS station IISC Bangalore.



Plot depicting variation of EUV flux during different phases of 23rd, 24th and 25th Sunspot Cycles along with occurrence of X- Class Flares.



Plot depicting variation of EUV flux for X class flares during different phases of 23rd, 24th and 25th sunspot cycle along with SSN (https://www.sidc.be/SILSO/infosndtot) with time.

Most of the X-class solar flares for the 23rd , 24th and 25th (till June1, 2023) Sunspot Cycle occurred during the solar maximum phase of this cycle

Table 1. Ten Intense X Class Solar Flares Observed During the Sunspot Cycle 23rd, 24th & 25th

S. No.	Cycle	Date	Peak Flux[a]		Time UTC			Active Region	Δ Peak Flux[a]		Peak TEC	Peak Δ TEC	Peak TEC Time (UTC)	Peak TEC Time (IST)
			X-Ray	EUV	Start	Max.	End		X-Ray	EUV				
1	23	04 Nov. 03	28.0	3.50	19:29	19:50	20:06	S19W833B	18.4	1.52	65.65	-24.6	10:36	16:06
2	23	02 Apr. 01	20.0	4.12	21:32	21:51	22:03	NaN	17.0	1.02	39.24	31.0	00:01	05:31
3	23	28 Oct. 03	17.2	5.78	09:51	11:10	11:24	S16E084B	18.3	3.47	82.18	-19.4	11:07	16:37
4	23	07 Sep. 05	17.0	1.98	17:17	17:40	18:03	S11E77SXI	18.1	0.74	31.28	-13.5	08:01	13:31
5	23	15 Apr. 01	14.4	3.72	13:19	13:50	13:55	S20W852B	14.5	1.4	NaN	NaN	NaN	NaN
6	23	29 Oct. 03	10.0	6.79	20:37	20:49	21:01	S15W022B	10.7	3.52	101.91	20.5	08:52	14:22
7	23	06 Nov. 97	9.4	2.19	11:49	11:55	12:01	S18W632B	9.1	0.56	59.31	12.3	09:28	14:58
8	23	02 Nov. 03	8.3	3.30	17:03	17:25	17:39	S14W562B	9.2	1.04	65.33	NaN	08:03	13:33
9	23	20 Jan. 05	7.1	12.13	06:36	07:01	07:26	N14W61SXI	7.9	10.37	44.14	1.0	08:01	13:31
10	23	06 Dec. 06	6.5	2.09	18:29	18:47	19:00	S05E64SXI	6.6	0.73	36.76	9.9	08:15	13:45
11	24	09 Aug. 11	6.9	1.86	07:48	08:05	08:08	NaN	7.0	0.49	41.02	NaN	10:45	16:15
12	24	07 Mar. 12	5.4	2.00	00:02	00:24	00:40	N17E27	5.4	0.48	60.14	-19.8	05:54	11:24
13	24	25 Feb. 14	4.9	2.24	00:39	00:49	01:03	S12E82	5.0	0.36	75.66	NaN	08:15	13:45
14	24	05 Nov. 13	3.3	2.05	22:07	22:12	22:15	S13E44	3.4	0.36	NaN	NaN	NaN	NaN
15	24	14 May. 13	3.2	2.04	00:00	01:11	01:20	NaN	3.2	0.27	59.11	0.5	11:51	17:21
16	24	24 Oct. 14	3.1	2.19	21:07	21:41	22:13	NaN	3.1	0.44	84.29	12.2	11:04	16:34
17	24	13 May. 13	2.8	1.93	15:48	16:05	16:16	N14E83	2.8	0.16	58.67	-41.8	10:42	16:12
18	24	05 May. 15	2.7	1.77	22:05	22:11	22:15	NaN	2.7	0.3	64.97	9.2	12:19	17:49
19	24	29 Oct. 13	2.3	1.79	21:42	21:54	22:01	NaN	2.3	0.13	NaN	0.0	NaN	NaN
20	24	10 Jun. 14	2.2	1.86	11:36	11:42	11:44	S15E80	2.2	0.18	49.93	4.3	10:55	16:25
21	25	20 Apr. 22	2.2	1.35	03:41	03:57	04:04	NaN	2.2	0.08	56.92	-2.7	09:16	14:46
22	25	17 Feb. 23	2.2	1.64	19:38	20:16	20:50	NaN	2.2	0.13	75.01	1.9	10:40	16:10
23	25	03 Mar. 23	2.1	1.78	17:42	17:52	17:59	NaN	2.0	0.11	85.44	4.3	10:16	15:46
24	25	09 Jan. 23	1.9	1.79	18:37	18:50	18:57	NaN	1.9	0.19	59.33	5.1	09:10	14:40
25	25	10 May. 22	1.5	1.48	13:50	13:55	13:59	NaN	1.5	0.25	50.08	0.4	09:03	14:33
26	25	30 Mar. 22	1.3	1.30	17:21	17:37	17:46	NaN	1.4	Na	58.11	1.1	10:24	15:54
27	25	06 Jan. 23	1.2	1.64	00:43	00:57	01:07	NaN	1.2	0.09	56.9	2.1	10:54	16:24
28	25	29 Mar. 23	1.2	1.70	02:18	02:33	02:40	NaN	1.2	0.1	79.09	4.1	10:37	16:07
29	25	17 Apr. 22	1.1	1.29	03:17	03:34	03:51	NaN	1.1	0.09	61.57	10.0	12:10	17:40
30	25	30 Apr. 22	1.1	1.40	13:37	13:47	13:52	NaN	1.1	0.05	68.21	-1.4	08:27	13:57

[a]EUV, XUV fluxes in 10^{10} Photons/cm^2.s, X-ray fluxes in 10^{-4} W/m^2 and TEC in TEC units (10^{16} e$^-$/m^2).

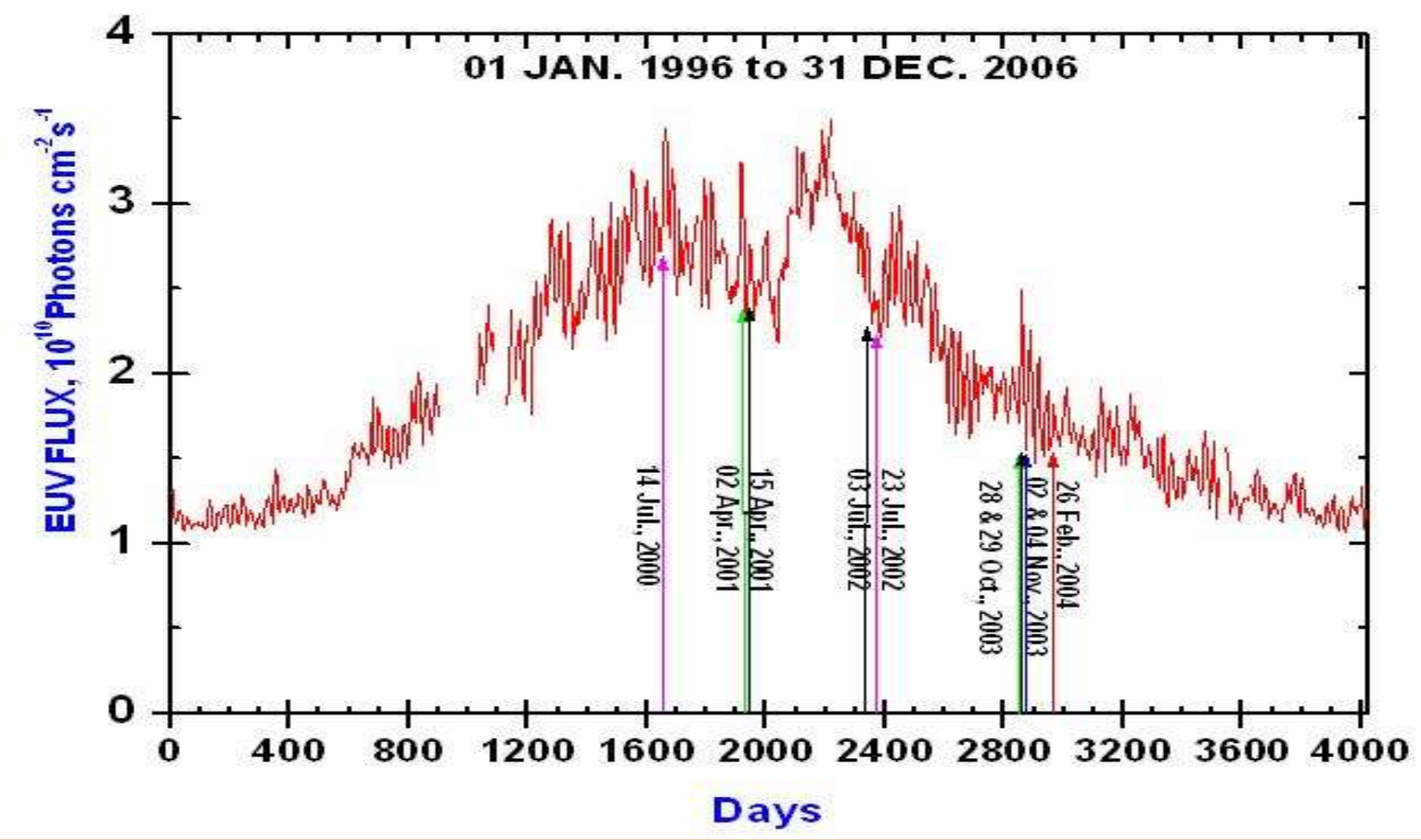
Occurrence of X class Flares during 23rd, 24th and 25th Sunspot Cycle

Cycle	Phase	Period	Start	End	Total X Flares	Mid Point	Total X flares
23	Rising	initial	01-08-1996	31-01-1998	3	24-03-1999	47
23	Rising	mid	24-06-1998	23-12-1999	14		
23	Rising	maxima	15-05-2000	14-11-2001	30		
23	Falling	maxima	15-11-2001	14-05-2003	18	24-05-2005	39
23	Falling	mid	24-08-2004	23-02-2006	21		
23	Falling	last	31-05-2007	30-11-2008	0		
24	Rising	initial	01-12-2008	31-05-2010	0	08-08-2011	28
24	Rising	mid	08-11-2010	07-05-2012	12		
24	Rising	maxima	15-10-2012	14-04-2014	16		
24	Falling	maxima	15-04-2014	14-10-2015	15	05-02-2017	19
24	Falling	mid	05-05-2016	04-11-2017	4		
24	Falling	last	31-05-2018	30-11-2019	0		
25	Rising	initial	01-12-2019	31-05-2021	0	22-09-2022	14
25	Rising	mid	22-12-2021	21-06-2023	14		
25	Rising	maxima	15-01-2024	14-07-2025	NA		

Note : The number of X class flares in the rising phase of the sunspot cycles are comparatively higher than in the falling phase of the cycle

Observations of X-ray and EUV Fluxes during solar flare and response of upper ionosphere

Solar EUV photon flux integrated in the wavelength band 26-34 nm during the period 01 January, 1996 to 31 December, 2006 (23rd Cycle). Most of the X-class solar flares occurred during the maximum phase of the solar cycle.



Mahajan et al., 2010

Since the X-ray and the EUV emissions originate from different portions of the solar disc, it is necessary to check how close are the changes in the intensity of the two spectral bands during a flare.

Time series of X-ray fluxes in the 0.1 – 0.8 nm bands and EUV fluxes in the 26 – 34 nm band for the ten X-class flares of 23 rd Sunspot Cycle listed in Table 1. Fluxes two hours before and two hours after the maximum phase of the flares are shown.

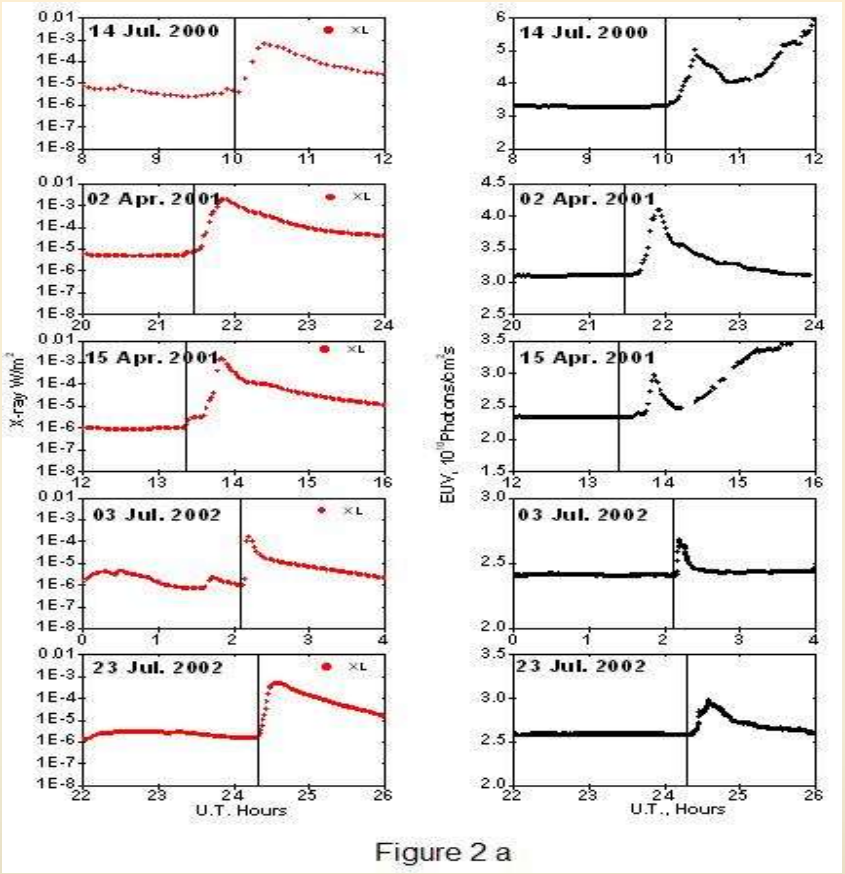


Figure 2 a

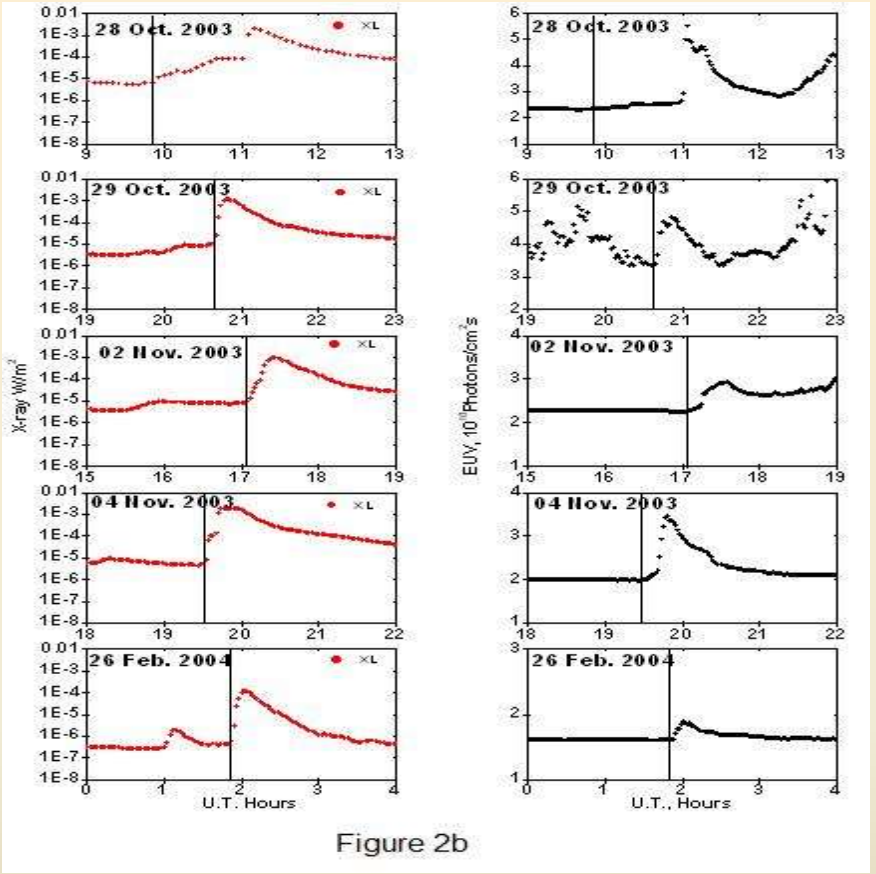


Figure 2b

A close look at Figures 2a and 2b shows

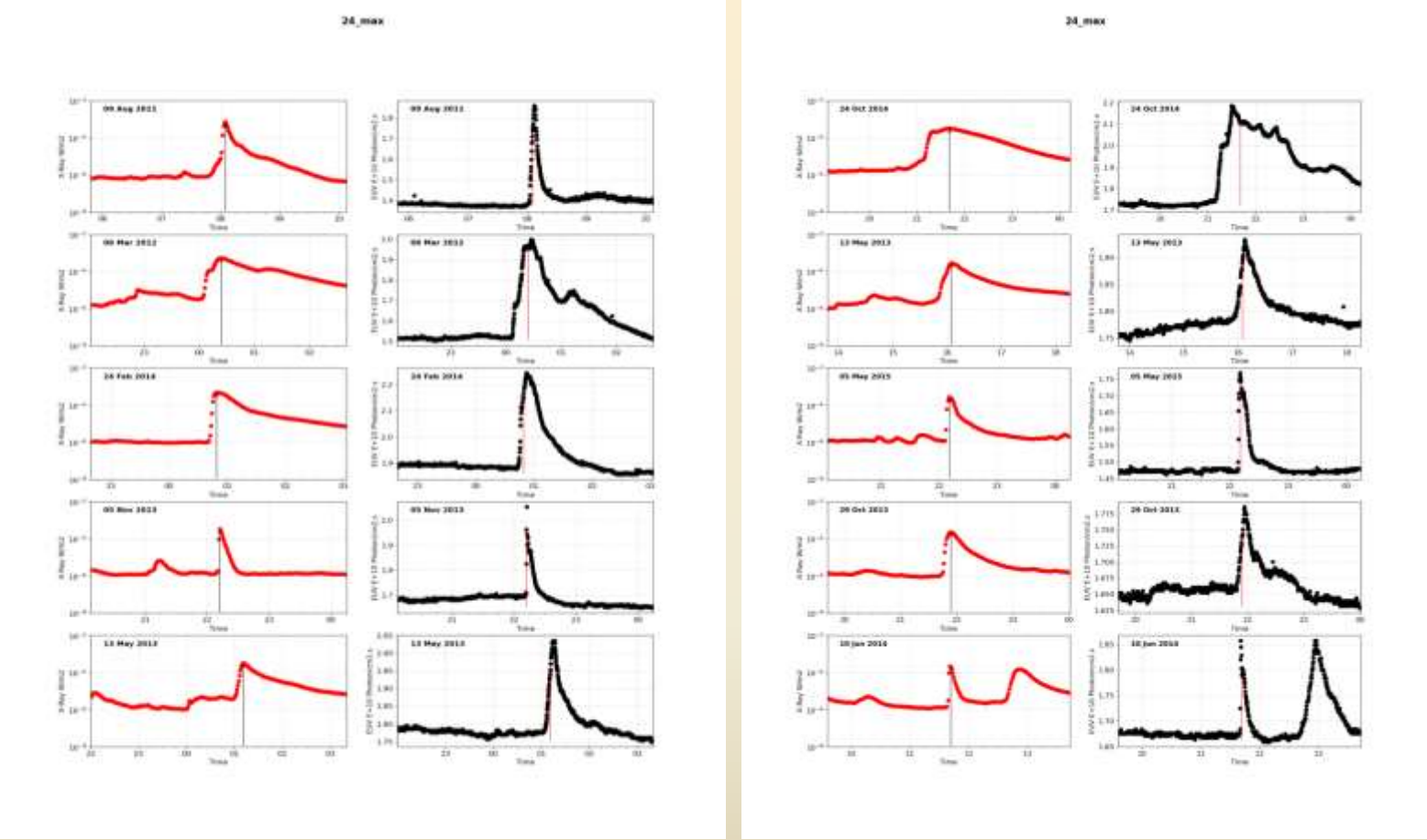
(a) that the two fluxes do not always go hand-in-hand. For example, although for the flare of 4 November 2003 the peak X-ray flux (28 × 10−4 W/m2) was the highest ever observed, the peak flux in the EUV band (3.5 × 10 10 photons/cm2 s) was not the highest. On the other hand, while the flux in the EUV band for the flare of 28 October 2003 (5.49 × 1010 photons/cm2 s) 20 January 2005 (12.13 X 10^{10} photons/cm2 s) was the highest, the X-ray flux (17.2 × 10−4 W/m2) was not so.

(b) In most of the cases, EUV peaked few minutes (2-3 min)after the X-ray peak. However in several cases, more than one prominent EUV peaks were observed after the primary x ray peak (The post flare enhancements in EUV mostly are because of solar flare particle hitting the SEM detector so can be errorneous).

S.N.	Date	Peak Flux*		Time U. T.			Active	ΔPeak Flux*		ΔTEC
		X-ray	EUV	Start	Max.	End	Region	X-ray	EUV	TECU
1.	14 Jul., 2000	05.7	5.06	10:03	10:24	10:43	N22W07	05.7	1.79	4.5
2.	02 Apr., 2001	20.0	4.12	21:32	21:51	22:03	N18W82	20.0	1.01	7.1
3.	15 Apr., 2001	14.4	2.98	13:19	13:50	13:55	S20W85	14.4	0.65	2.6
4.	03 Jul., 2002	01.5	2.68	02:08	02:13	02:16	S20W51	01.5	0.28	0.5
5.	23 Jul., 2002	04.8	2.97	00:18	00:35	00:47	S13E72	04.8	0.40	1.2
6.	28 Oct., 2003	17.2	5.49	09:51	11:10	11:24	S16E08	17.2	2.95	14.7
7.	29 Oct., 2003	10.0	4.82	00:37	20:49	21:01	S15W02	10.0	1.48	7.1
8.	02 Nov., 2003	08.3	2.93	17:03	17:25	17:39	S14W56	08.3	0.68	2.5
9.	04 Nov., 2003	28.0	3.50	19:29	19:50	22:06	S19W83	28.0	1.53	4.5
10.	26 Feb, 2004	01.1	1.88	01:50	02:03	02:10	N14W14	01.1	0.26	0.6

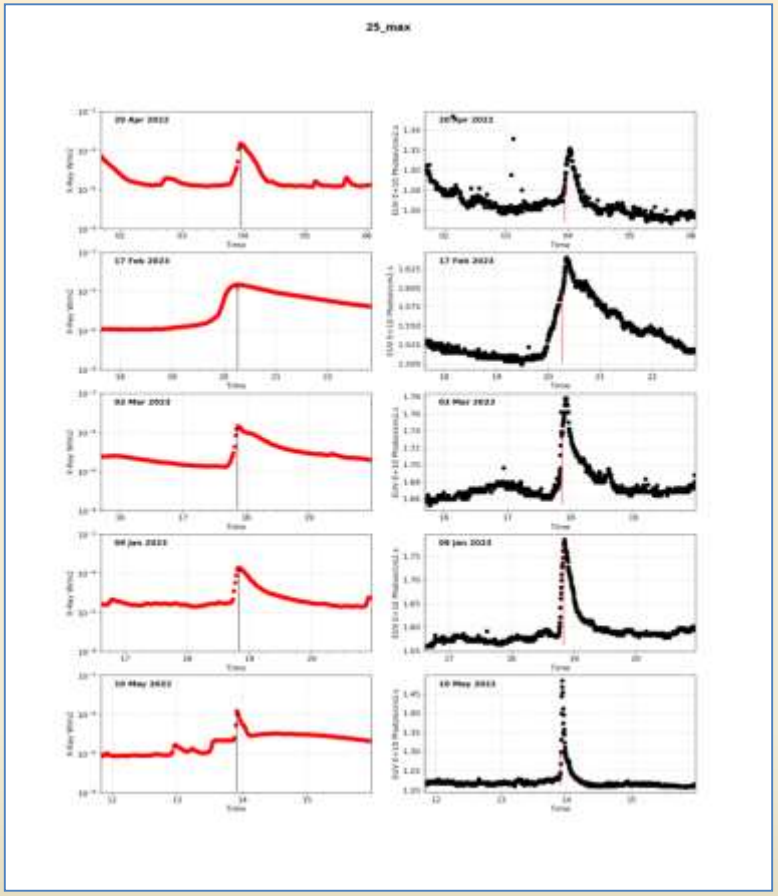
*EUV, XUV fluxes in 10^{10} Photons/cm^{2}s, X-ray fluxes in 10^{-4} Watts/m^2.

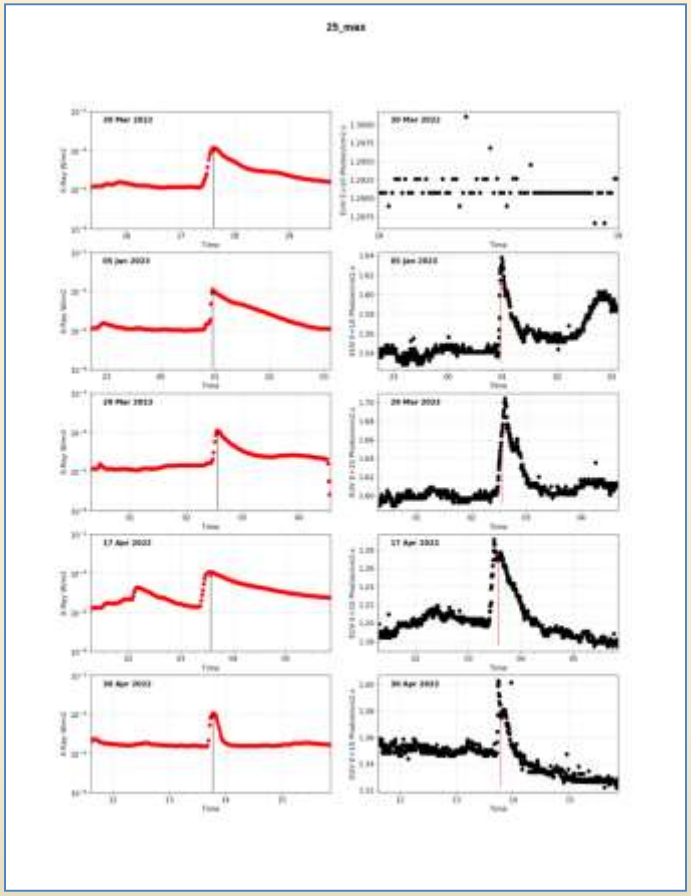
Time series of X-ray fluxes in the 0.1 – 0.8 nm bands and EUV fluxes in the 26 – 34 nm band for the ten X-class flares of 24th Sunspot Cycle listed in Table 1. Fluxes two hours before and two hours after the maximum phase of the flares are shown.



In 24th Cycle :
Similar observation as in 23rd cycle was observed
For example, although for the flare of 9 August 2011 the peak X-ray flux (6.9 × 10−4 W/m2) was the highest ever observed, the peak flux in the EUV band (1.85 × 1010 photons/cm2 s) was not the highest.
On the other hand, while the flux in the EUV band for the flare of 10 June 2014 (1.85 × 10^{10} photons/cm2 s) was the highest, the X-ray flux (2.2 × 10−4 W/m2) was not so.

Time series of X-ray fluxes in the 0.1 – 0.8 nm bands and EUV fluxes in the 26 – 34 nm band for the ten X-class flares of 25th Sunspot Cycle listed in Table 1. Fluxes two hours before and two hours after the maximum phase of the flares are shown.



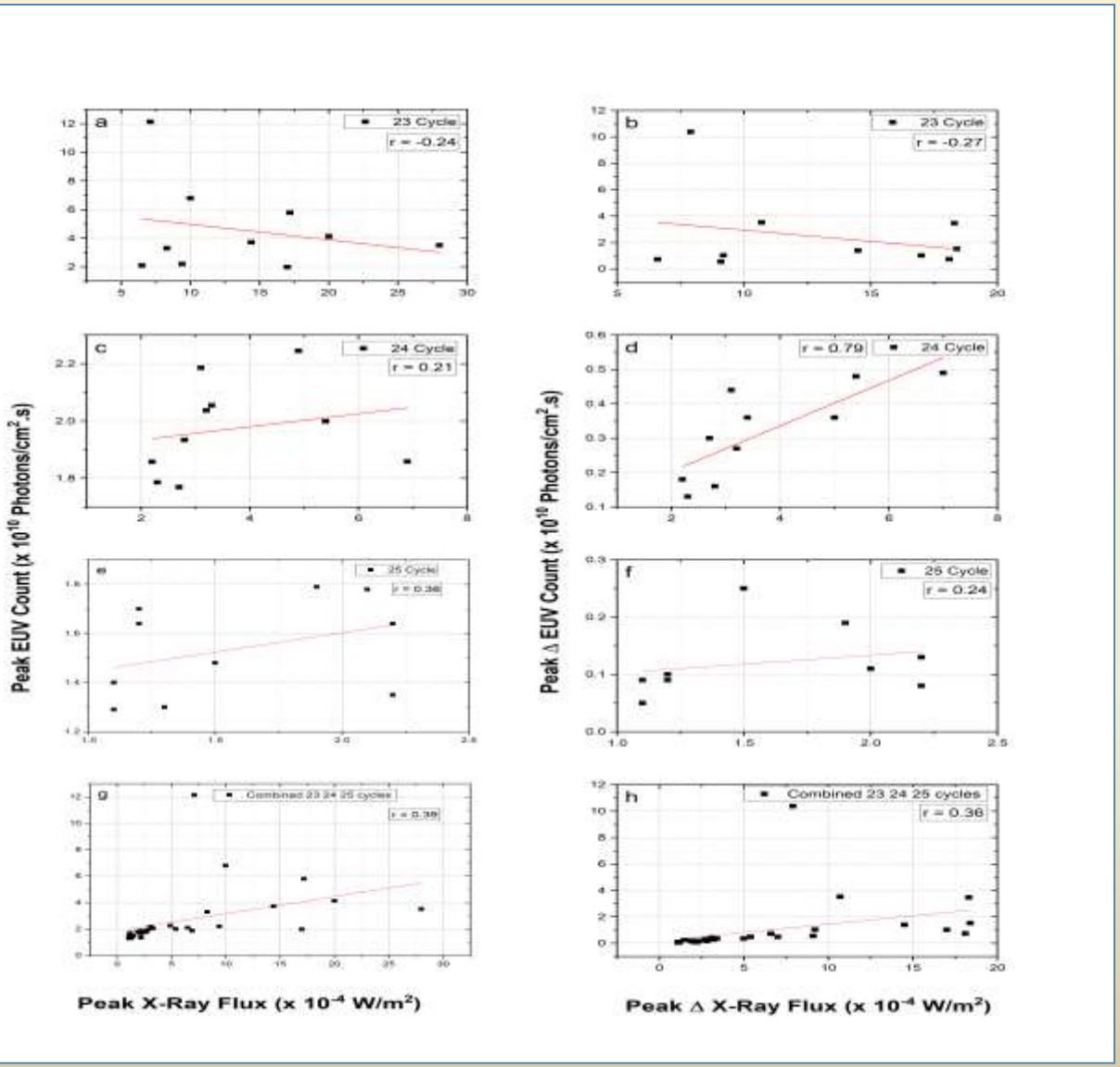


Similar observations were are also observed till day in 25th cycle

For example, although for the flare of 20 April 2022 the peak X-ray flux (0.22 × 10−4 W/m2) was the highest ever observed, the peak flux in the EUV band (1.35 × 1010 photons/cm2 s) was not the highest.

On the other hand, while the flux in the EUV band for the flare of 09 January 2023 (1.78 × 1010 photons/cm2 s) was the highest, the X-ray flux (0.19 × 10−4 W/m2) was not so.

Plots of peak X-ray/ peak ΔX-ray fluxes Vs SEM/SOHO measured peak EUV / peak ΔEUV fluxes, (a) for the 10 intense X-class solar flares, during the 23rd , 24th and 25th (till June1, 2023) Sunspot Cycle.



The correlation coefficient for the flare in the different cycles are low and hence does question the use of X-ray flux as a proxy for EUV flux during flares.

Plots of peak X-ray/ peak ΔX-ray fluxes Vs SEM/SOHO measured peak EUV / peak ΔEUV fluxes, (a) for the 10 X-class solar flares, (b) for 70 X-class solar flares, which occurred during the period Jan. 1996 to Dec. 2006,(c) and (d) X-ray fluxes multiplied by Cos(CMD).

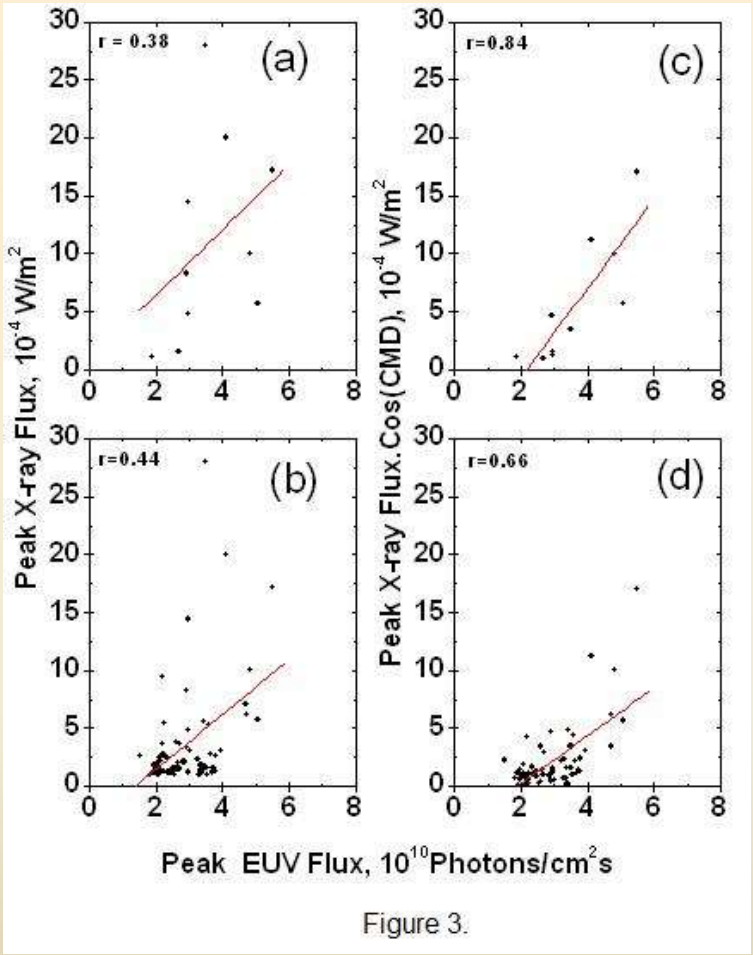


Figure 3.

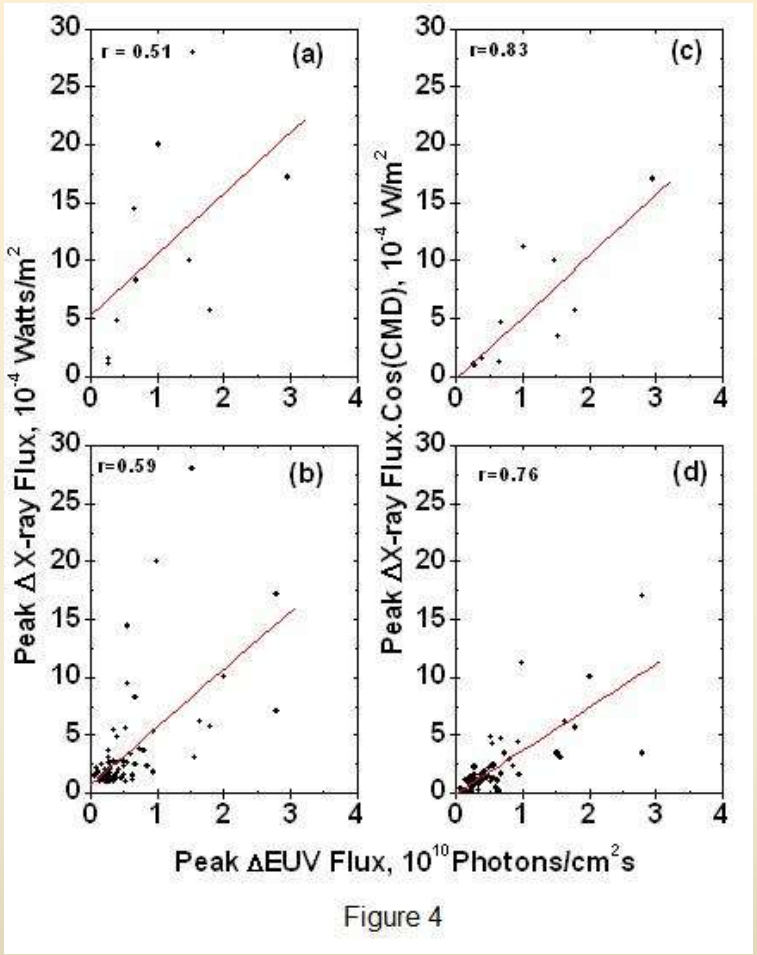
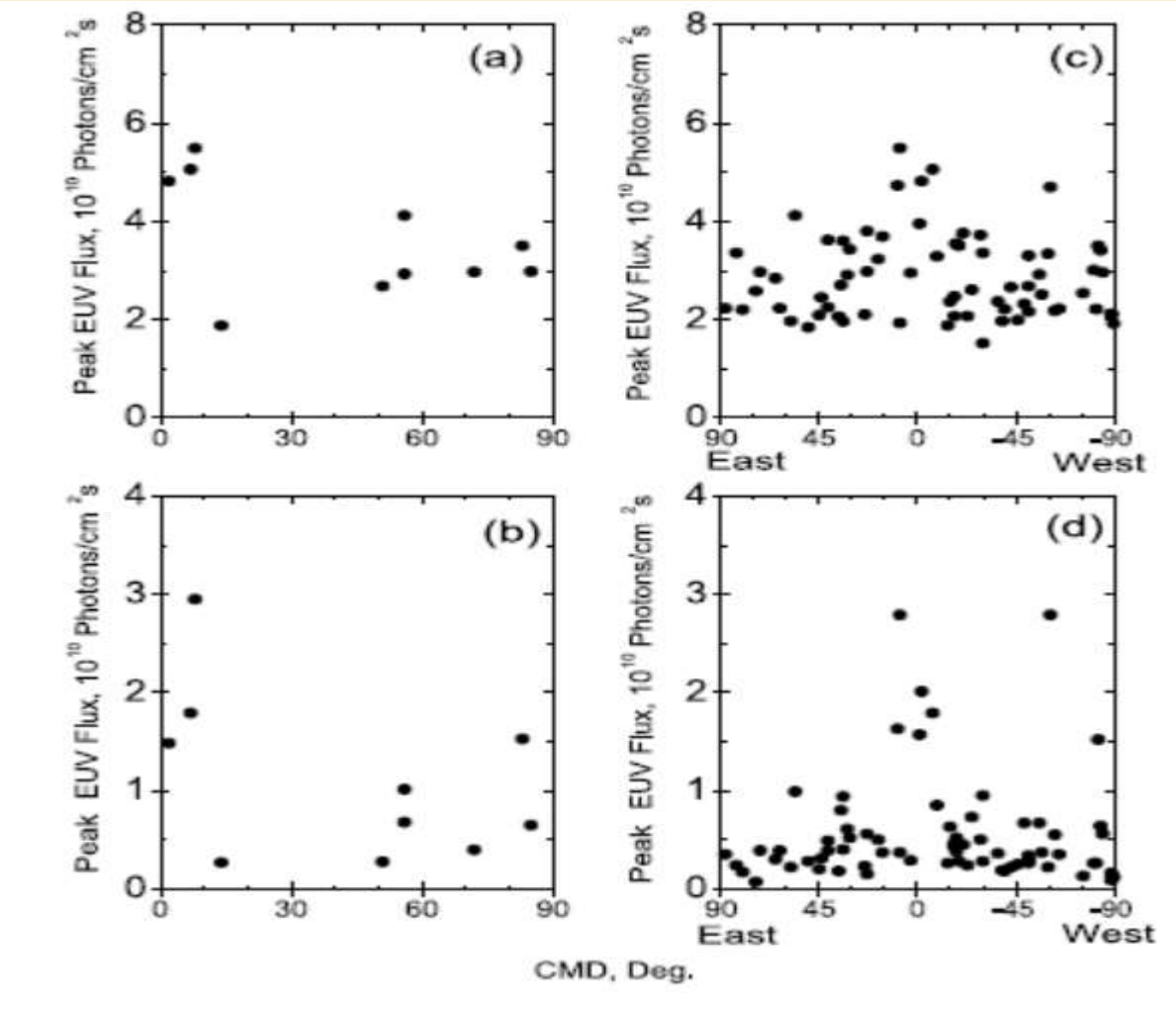


Figure 4

Donnelly [1971] reported the relative strength of impulsive EUV emission from flare decreases with increasing CMD particularly near the limb. To take care of this CMD-EUV effect we have multiplied X –ray flux by Cos (CMD).

The data sample in Figure 2a was rather small, and as mentioned earlier, Horan et al. [1983] from an analysis of SOLRAD II satellites measurements of solar emissions in the soft X-ray band (0.1 to 0.8 nm plus 0.8 to 2.0 nm) and the EUV band (10 to 15 nm plus 70 to 103 nm) had found a high degree of correlation between the peak X-ray and EUV fluxes during X class flares. We therefore verify the relationship seen in Figure 3a by adding data for another 60 X class flares (total 70 flares) observed during the period from January 2006 to December 2006. This mass plot is shown in Figure 3b. We again find that the **correlation between the peak X-ray flux and peak EUV flux is rather poor.**

Dependence of EUV flux on the location of flares on solar disc(CMD)



It can be noted that the EUV flashes (i.e., EUV) are generally more intense at the central meridian than at any other location,

Plots of peak EUV flux and peak Δ EUV flux vs. CMD. (a) and (b) for the 10 flares (c) and (d) for 70 flares.

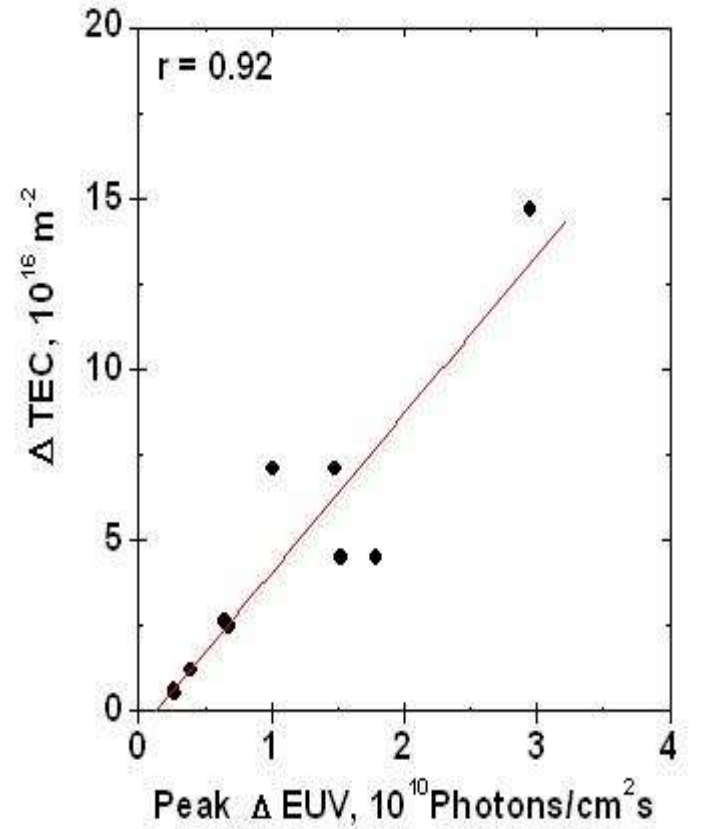


Figure 7.

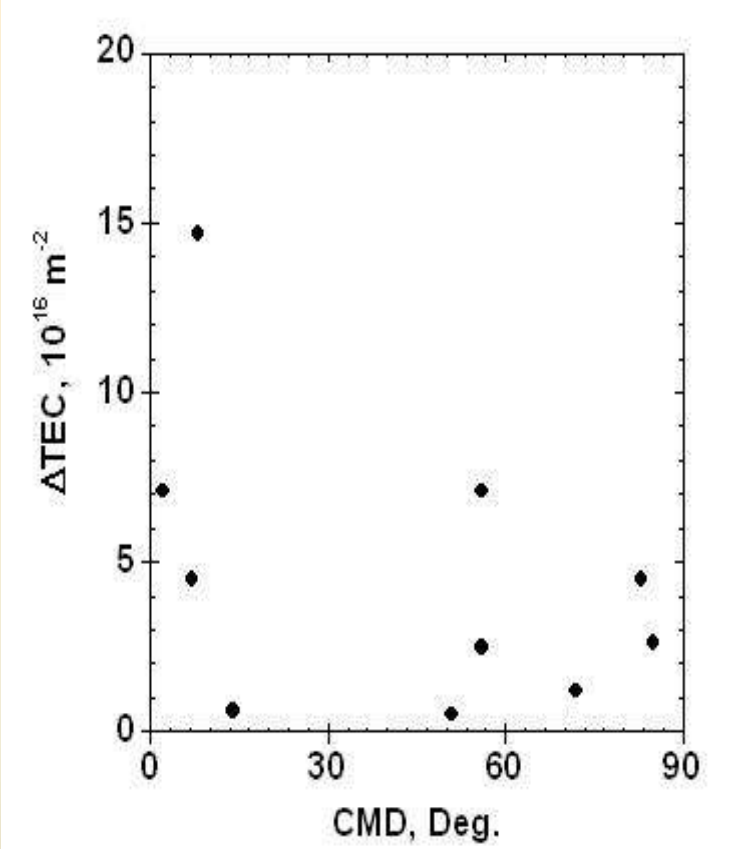


Figure 8

Peak ΔTEC Vs peak ΔEUV flux for the ten flares and Plot of ΔTEC Vs CMD for the ten flares.

Conclusion:

By using X-ray and EUV data observed during X class flares by GOES and SEM/SOHO during sunspot cycle 23, 24 th and 25 we conclude that

(1) X-ray and EUV fluxes are poorly related to each other and therefore that X-ray fluxes are not adequate to study solar flare effects in upper ionosphere. However, if these fluxes are adjusted for the CMD factor, they can be a good proxy for the EUV flux, and since enhancement in TEC is found to be linearly related to increase in EUV flux, ΔTEC may be used for estimating EUV flux during flares.

(2) The local time of occurrence of the flares determines the magnitude of enhancement in TEC for flares originating from nearly similar longitudes on the solar disc, and hence proximity to the central meridian alone only may not only be important.

Acknowledgments.

The authors are thankful to the (1) WorldData Center, Boulder, Colorado, USA, for making the solar flare data available on its web site and (2) SEM/SOHO team for making data from SEM experiment available at their web site.

Thanks for your kind attention