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Statistical analysis of soft X-ray solar flares during solar cycles 22, 23, and 24

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Abstract This paper presents a statistical analysis of soft X-ray flares during the period January 1986 to June 2017 covering the last three solar cycles (SCs) 22, 23, and 24. We have analyzed the distribution of flare number, the relationship between the occurrence rate of soft X-ray flares and solar activity, and the duration of different intensity class (B, C, M, and X) solar flares during the period of investigation. The total occurrence rates of M and X class flares are 10.33%, 6.77%, and 5.45% in SCs 22, 23, and 24, respectively, which indicates that SC 22 is an SC with frequent large flares. Meanwhile, the M and X class flares are mainly concentrated in solar maximum (71.13%) in SC 22. The correlation coefficients between the annual number of flares and solar F10.7 index, X-ray flux in 0.1–0.8 nm, and EUV flux in 0.1–50 nm in SC 24 (0.91, 0.88, and 0.96) are greater than that in SCs 23 (0.87, 0.85, and 0.86) and 22 (0.88 and 0.81). The median values of the duration of M and X class flares are 39.00 and 71.50 minutes in SC 22, 21.00 and 26.50 minutes in SC 23, and 19.00 and 24.00 minutes in SC 24. The duration of M and X class flares in SC 22 is obviously longer than that in SCs 23 and 24. In addition, the duration of flares increases with the increase of flare intensity.

Keywords Solar flare · Solar cycle · Flare duration

1 Introduction

Since the first discovery of flares by Carrington and Hodgson in 1859, statistical studies of solar flares have been carried out in different ways. Many papers have been published

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analyzing the relationship between solar flares and some parameters of solar activity, the temporal and spatial distributions of solar flares, and the ionospheric disturbance caused by solar flares (e.g., Donnelly 1976; Garcia 1990; Joshi 1995; Švestka 1995; Li et al. 1998; Temmer et al. 2000; Ataç and Özgüç 2001; Joshi and Joshi 2004; Joshi et al. 2006; Temmer et al. 2006; Xiong et al. 2011; Belucz et al. 2013; Chowdhury et al. 2013; Xiong et al. 2014a, 2014b, 2014c, 2019; Belucz et al. 2015; Chen et al. 2016; Abdel-Sattar et al. 2018; Joshi and Chandra 2019).

Some authors have studied the relationship between solar flares and different solar radiation parameters (X-ray flux, EUV flux, sunspot numbers, etc). Le et al. (2011) used X-ray flux at 0.1–0.8 nm and EUV flux at 26–34 nm generated by X, M, and C class flares to analyze the variation characteristics of X-ray and EUV flux during the flare and the relationship between them. The results show that the EUV enhancement does not linearly increase with X-ray flux from C to X class flares. The correlation coefficients between enhancements in X-ray and EUV flux during X, M, and C class flares only reach 0.66, 0.58, and 0.54, respectively. Zhang et al. (2011) made a statistical analysis of the correlation between the sudden increase of total electron content (SITEC) and X-ray flux at 0.1–0.8 nm, EUV flux at 0.1–50 nm and EUV flux at 26–34 nm. They found that SITEC is more correlated with EUV flux at 26–34 nm than with X-ray flux at 0.1–0.8 and EUV flux at 0.1–50 nm. Temmer et al. (2001) found that the correlation coefficient of the sunspot numbers with the total number of flares occurring per month is 0.93 from January 1975 to December 1999. Lee et al. (2012) conducted a statistical analysis of the occurrence rate of solar flares relative to the sunspot area and its variation from 1996 to 2010. For large and compact sunspot groups, the occurrence rate of flare increased significantly with the increase of sunspot area. Joshi et al. (2015) found the soft X-

ray flare index has a good positive correlation (>0.6) with the sunspot number, sunspot area, and F10.7 index during solar cycles (SCs) 21, 22, and 23.

Statistics studies on the temporal parameters of solar flares have been investigated in different methods. Pearce et al. (1993) proposed the asymmetry index of solar flare events, which was used to define the asymmetry of the evolution time of the flares, so as to compare the decay time and rise time of the flares. Applying this index to the hard X-ray flare events from 1980 to 1985, they found that the asymmetry of the flares was not obvious, but the decay time is longer than the rise time. This is contrary to the results of Temmer et al. (2001) obtained by analyzing the $H\alpha$ flare events between 1975 and 1999 showing that there was a significant asymmetry in the rise time and the decay time of the flare events with the decay time lasting about 1.5 times longer than the rise time. Veronig et al. (2002) performed a statistical analysis of the temporal parameters of the flare events during 1976–2000, such as the flare duration, rise time, and decay time. The results show that the duration of total flares is concentrated around 12 minutes and the flare duration, rise time, and decay time increase with the increase of the flare important class. The same conclusion was obtained in Joshi et al. (2010), who also found that this phenomenon is more pronounced for the duration and decay time for SCs 21 and 22, while it is the same for SC 23.

In order to explore the distribution characteristics of solar flares in different SCs, we have statistically analyzed the distribution of flare number, the relationship between the occurrence rate of soft X-ray flares and solar activity, the flare duration for different intensity classes during the last three SCs (1986−1995/1996−2008/2009−2017). The statistical investigation would be helpful for revealing some rules about flare distribution, estimating the radiation flux during solar flares, and monitoring solar flare events. The paper is structured as follows. In Sect. 2, the data set and statistical analysis methods are presented. In Sect. 3, the results are presented and discussed, comprising the statistical analysis of the flare number (Sect. 3.1), the relationship between the occurrence rate of soft X-ray flares and solar activity (Sect. 3.2), and the flare duration (Sect. 3.3). Section 4 contains a summary of the main results and conclusions.

2 Data and method

The primary parameters of solar flares that occurred from 1986 to 2017 can be collected from the website: ftp://ftp. ngdc.noaa.gov/, including the start time, peak time, end time, and intensity class. The continuous data of solar radio 10.7 cm flux (F10.7 index), X-ray, and solar EUV fluxes are utilized to evaluate the relationship between solar flares and different solar irradiation fluxes. In the present work,

we use the observed daily, monthly, and yearly F10.7 index and the X-ray data observed by Geostationary Operational Environmental Satellite (GOES) in the wavelength bands of 0.1–0.8 nm during 1986–2017 (available at ftp://ftp.ngdc.noaa.gov/). The data of EUV flux are obtained from the solar EUV monitor (SEM)/SOHO experiment, which measures EUV fluxes integrated into the wavelength bands 0.1–50 nm. The EUV fluxes during 1996–2017 are used in this study, which can be downloaded from the website: http://www.usc.edu/. The flare list obtained by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite separates from the GOES flare list, which observes the X-ray radiation of flares in a wide range of energies from 3 keV to >300 keV (Abdel-Sattar et al. 2018). The flare duration obtained by RHESSI during 2002–2017 is used to compare with that of GOES (available at https://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_list.txt).

In the study of the distribution of flare duration, we use the 95% confidence interval as a measure of statistical significance of the class effect of flare duration,

$$c_{95} = \frac{1.58(Q_3 - Q_1)}{\sqrt{n}}, \tag{1}$$

which means 95% of the data are gathered within the limits $\pm c_{95}$, where Q_1 and Q_3 denote the first and the third quartile, respectively, and n is the total number of data values (Temmer et al. 2001; Veronig et al. 2002). Meanwhile, we analyze the variation of skewness (SK) of the duration distribution of different class flares

$$SK = \frac{\frac{1}{n}\sum(X - \bar{X})^3}{\sigma^3}, \tag{2}$$

where n is the number of variables, X represents each variable, $\bar{X}$ is the mean of all variables, and σ is the standard deviation. For the right-skewed distributions with positive SK, the median value is smaller than the arithmetic mean. For the left-skewed distributions with negative SK, the median value is larger than the arithmetic mean. The greater the absolute value of the SK, the greater the degree of deviation (Joshi et al. 2010). Furthermore, the 90th percentile, which means only 10% of flares have the duration than the 90th percentile, is used as a descriptive statistics parameter to describe the duration distribution (Temmer et al. 2001).

3 Results and discussion

3.1 Statistics analysis of solar flare number

Since the influence of class A flares on the space environment is small, this paper does not include them in the statistical analysis. Only class B and above flares are included

Table 1 The number, proportion, and monthly average number of solar flares of different intensity classes and total classes in SCs 22, 23, and 24

SC	Class				
	B	C	M	X	Total
SC 22	6482	12532	2038	154	21206
	30.57%	59.10%	9.61%	0.72%	100%
	54.02	104.43	16.98	1.28	176.72
SC 23	8422	13125	1439	126	23112
	36.44%	56.79%	6.23%	0.54%	100%
	53.99	84.13	9.22	0.81	148.15
SC 24	5401	7541	701	45	13688
	39.45%	55.10%	5.12%	0.33%	100%
	50.01	69.82	6.49	0.42	126.74
Total	20305	33198	4178	325	58006
	35.01%	57.23%	7.20%	0.56%	100%
	52.88	86.45	10.88	0.85	151.06

in the statistical analysis and only these flares are included in the calculation of the number of flares for total intensity classes. According to the flare event reports given GOES data from 1986 to 2017, the number of flares during this period is 58006. Table 1 shows the number, proportion, and monthly average number of flares for B–X classes during SCs 22, 23, and 24. As can be seen from Table 1, the numbers of M and X class flares in the SC 22 are obviously more than that in the SCs 23 and 24 (2038 vs. 1439 vs. 701, 154 vs. 126 vs. 45), although the time span of the SC 23 is longer than SC 22 (13 years vs. 10 years). The total occurrence rates of M and X class flares are 10.33%, 6.77%, and 5.45% in SCs 22, 23, and 24, respectively. Furthermore, the monthly average number of M (16.98, 9.22, and 6.49) and X (1.28, 0.81, and 0.42) class flares shows a downward trend during SCs 22–24, which is the same as the statistics result of M and X class flares in SCs 21, 22, and 23 (Joshi et al. 2010). On the whole, class M and X flare events appeared more frequently in SC 22 than SC 23, and the latter appeared more frequently than SC 24. Therefore, a comprehensive comparison of the proportion, number, and monthly mean number of M and X class flares in the three SCs indicates that the SC 22 is an SC with frequent large flares (Temmer et al. 2001).

Through further comparison of the proportion (30.57%, 36.44%, and 39.45%) and the monthly average number (54.02, 53.99, and 50.01) of class B flares in SCs 22, 23, and 24, it can be found that the proportion of class B flares shows an upward trend, while the monthly average shows a downward trend. By detailed comparing the number (6482, 8422, and 5401) of B class flares in three SCs, it can be found that the number of B class flares in SC 23 is far greater than that in the SCs 22 and 24, which is because there is a longer

time span in SC 23. Therefore, a comprehensive comparison of the number, proportion, and monthly mean number of B class flares in the three SCs indicates that the difference in the occurrence of small flares is not obvious in three SCs.

By calculating the average monthly number of $H\alpha$ flares during SCs 21 and 22, Temmer et al. (2001) found that the average number of S class flares during SC 21 is much larger than that during SC 22 while the average monthly occurrence of importance>1 flares are smaller in SC 21 than in SC 22. Meanwhile, they pointed out that the SC 21 is a cycle with frequent small flares and the SC 22 is a cycle with frequent large flares. Through further analysis, they believed that SC with frequently small flares produces few large flares, which is related to the storage and release of energy during flares. The generation of a large flare needs to store a large amount of energy in a certain active area, and it takes a certain amount of time. The occurrence of a series of small flares will release a lot of small magnetic energy, which will make it difficult to store enough energy forming a big eruption flare. Therefore, the energy release caused by the frequent occurrence of small flares leads to a decrease in the occurrence rate of large flares (Švestka 1995).

From Table 1, we can also find that the monthly average number of flares at total intensity classes during SC 22 (176.72) is more than that of during SCs 23 (148.15) and 24 (126.74). Meanwhile, the monthly mean numbers of different class flares in the SC 22 are greater than that in the SCs 23, and the latter is more than SC 24. It indicates that solar activity shows a downward trend during SCs 22–24. This is consistent with the results obtained by Pandey et al. (2015) that the occurrence of soft X-ray flare events has exhibited a downward trend since SC 21.

3.2 The relationship between the occurrence of soft X-ray flares for different intensity classes and solar activity intensity

Figure 1 shows the temporal variations of X-ray flux in 0.1–0.8 nm and F10.7 index during solar flare events for different intensity classes (B, C, M, and X) in SCs 22, 23, and 24. Generally, the year with an annual mean of solar F10.7 index above 180 is called high solar activity year, and the year with an annual mean of index less than 90 is called low solar activity year. It can be seen from Fig. 1 that the M and X class flares are mainly concentrated in solar maximum (71.13%) during SC 22. In SC 23, M and X class flares are dispersed over time, which occurred not only in the high solar activity years (35.98%) but also in the rising and decreasing phases of solar activity intensity. In SC 24, the temporal distributions of M and X class flares are similar to that in SC 22, and both have a double peak structure. The two peaks of the number for two-class flares during SC 22 occur in 1989 and 1991, where M-class flares numbers are 620 and 590, and

Fig. 1 The temporal distribution of flares for different intensity classes (B-green, C-magenta, M-blue, and X-red) and solar F10.7 index in SCs 22, 23, and 24
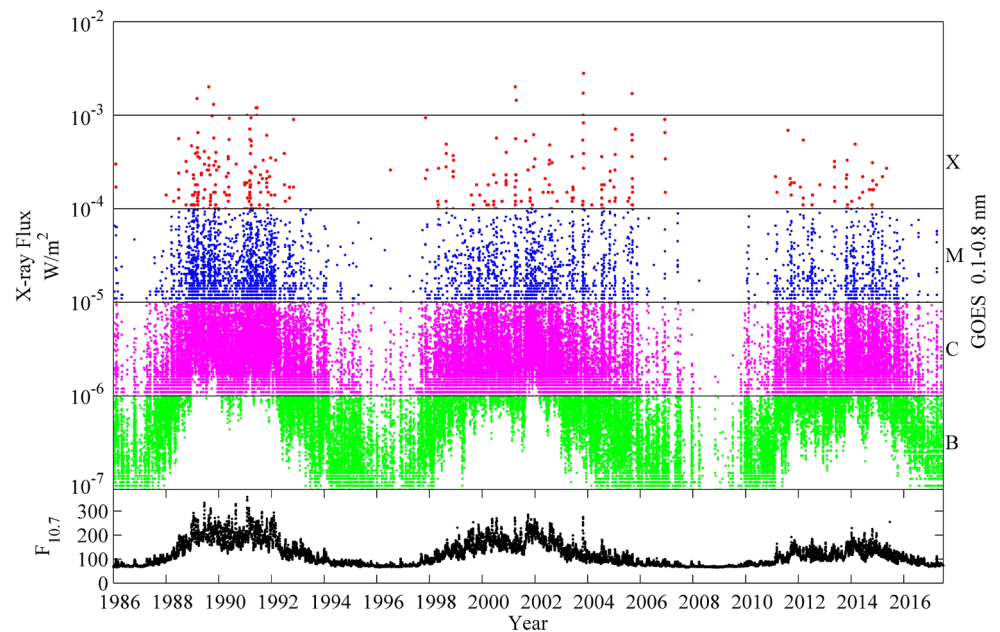
X-class flares numbers are 59 and 54, respectively, forming a symmetrical double peak. The two peaks of SC 24 occur in 2012 and 2014, where M-class flares numbers are 123 and 205, and X-class flares numbers are 7 and 16, respectively, forming an asymmetrical double peak.

To clearly demonstrate the temporal distribution characteristics of solar flares, Fig. 2 shows the temporal distribution of the monthly number of solar flares, the 12-month moving average of solar flares, and the monthly mean of solar F10.7 index in SCs 22, 23, and 24. The 12-month moving average of total solar flares reaches the peaks in 1989 and 1991 during SC 22, which was coincident with that of the solar F10.7 index. In SC 23, there was no obvious double peak in the distribution of the monthly number for total solar flares, while the solar F10.7 index shows a small peak in June 2000 and a large peak in December 2001. During SC 24, the solar F10.7 index and the 12-month moving average of total solar flares only have a small peak in 2014. Meanwhile, it can be seen that the 12-month moving average of the C, M and X class flares in SC 22 exhibited obvious double peaks, and that of the C and M class flares in SC 24 also exhibited double peaks. Ravindra and Javaraiah (2015) confirmed in their analysis of sunspot areas that there is also a double peak in SC 23, and the peaks occur in 2000 and 2002, which is consistent with the time in which the solar F10.7 index appeared double peak given in Fig. 2. Also, it can draw a conclusion from Figs. 1 and 2 that B class flares appear mainly in the low solar activity years and less in high solar activity years during SCs 22, while the B class flares in SC 24 not only appear in low solar activity years but also large-scale in high solar activity years. By calculating, 66.67% of B class flares occur in the low solar activity

years of SC 22 while 52.33% of B class flares in SC 24 appear in the middle and high solar activity years. It confirms the conclusion of Feldman et al. (1997) that the X-ray background of high solar activity year is relatively high, which caused that the B class flares cannot be detected. And they pointed out the increase of X-ray background during the solar maximum period is mainly related to the increase of flare events and stable coronal heating. From the distribution of the solar F10.7 index in SC 24, it can be found that the solar F10.7 index obviously exceeds 180 only in 2014. Therefore, low-class solar flares in SC 24 are easily detected because of the relatively low X-ray background.

To clarify the relationship between the number of flares and solar activity index in the three SCs, the correlation analysis has been conducted between the annual number of flares and the annual mean values of the solar F10.7 index, X-ray flux in 0.1–0.8 nm, and EUV flux in 0.1–50 nm. The results are shown in Fig. 3, which shows that the temporal distribution of the annual number of flares (black), the annual mean values of solar F10.7 index (blue), X-ray flux in 0.1–0.8 nm (red), and EUV flux in 0.1–50 nm (green) and the correlation coefficients between the number of flares and the three solar activity parameters in SCs 22–24. It can be seen from Fig. 3 that the annual number of flares has a good correlation with the annual average of solar F10.7 index, 0.1–0.8 nm X-ray flux, and 0.1–50 nm EUV flux in the three SCs. The correlation coefficients between the annual number of flares and the annual average of the solar F10.7 index are 0.88, 0.87, and 0.91 in the three SCs, respectively. It is higher than that with 0.1–0.8 nm X-ray flux in three SCs (0.81, 0.85, and 0.88), while less than that with 0.1–50 nm EUV flux in SC 24 (0.96). The correlation coefficients between the annual number of flares and three solar activity parameters in SC 24

Fig. 2 The temporal evolution of the average monthly number of flares (red), the 12-month moving average values (black), and the average monthly value of solar F10.7 index in SCs 22, 23, and 24
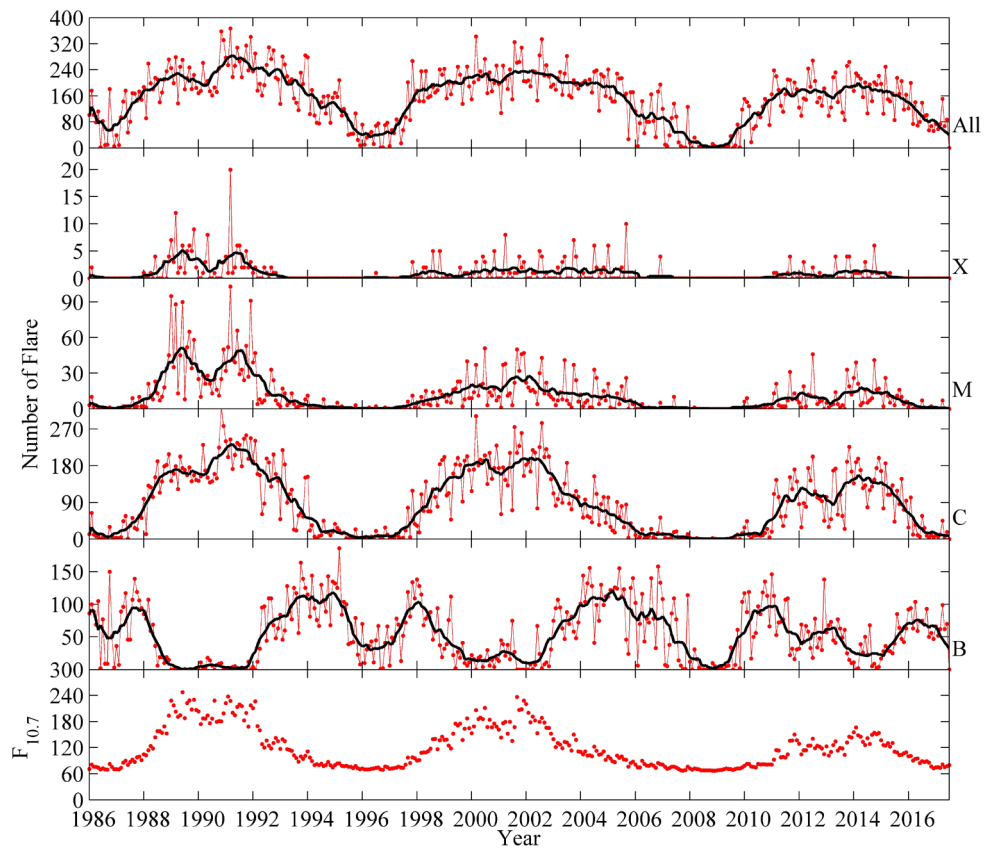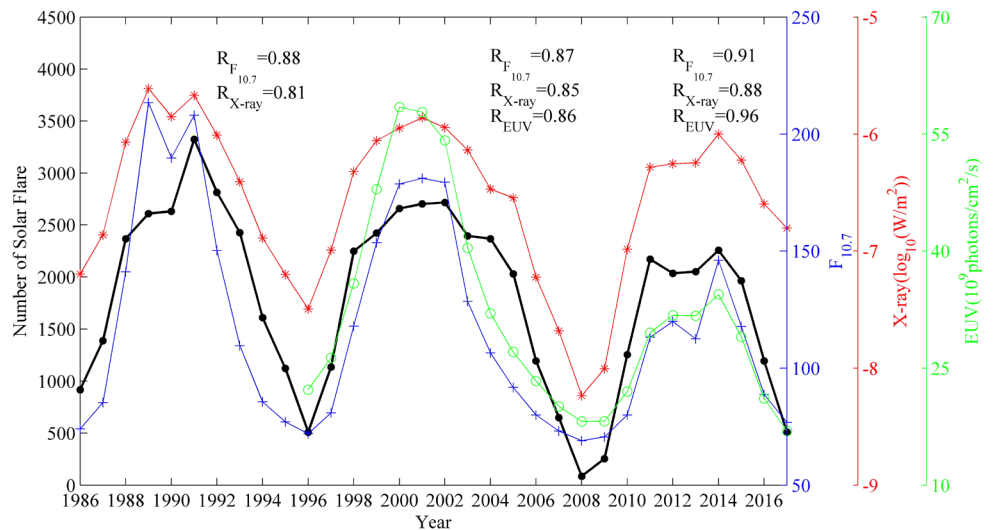
Fig. 3 The relationship between the annual number of flares (black) and the annual average values of solar F10.7 index (blue), X-ray flux in 0.1–0.8 nm (red), and EUV flux in 0.1–50 nm (green) during SCs 22, 23, and 24

(0.91, 0.88, and 0.96) are greater than that in SCs 23 (0.87, 0.85, and 0.86) and 22 (0.88 and 0.81). Moreover, the correlation coefficients of the number of flares with solar F10.7 index and EUV flux in 0.1–50 nm are above 0.90 in SC 24. From the temporal variations of the number of flares, solar F10.7 index, X-ray flux, and EUV flux in Fig. 3, we can find that the solar activity in SC 22 is stronger than that in SC 23, and both of them are significantly stronger than that during SC 24 (Kossobokov et al. 2012). Generally, the solar activity

intensity of SC has declined since SC 22, which is consistent with the results obtained by Table 1 and the statistical analysis of Joshi et al. (2010) during SCs 21–23.

de Toma et al. (2004) noted that SC 23 was weaker than SC 22 in most solar activity indices, including magnetic flux; they proposed that it was a distinct, magnetically simpler variant from previous cycles. Lukianova and Mursula (2011) found that there is a changed relation between sunspot numbers and proxies of solar UV/EUV radiation
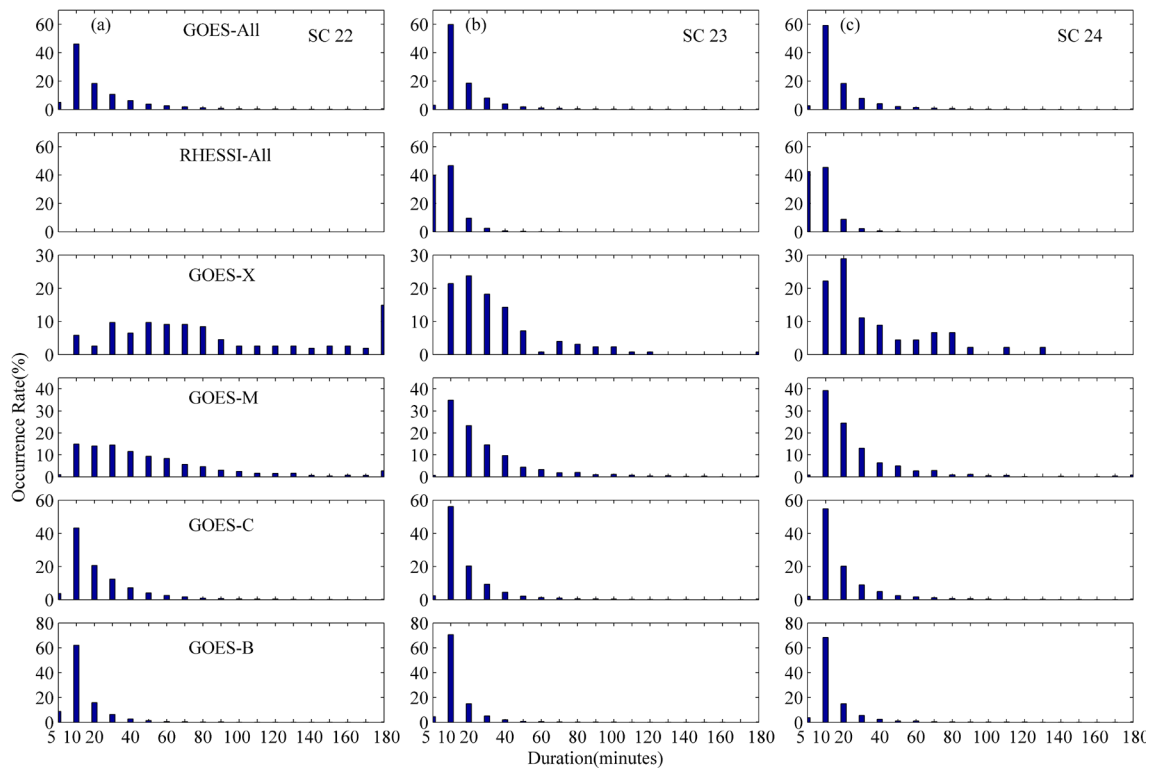
Fig. 4 The distribution of the duration of total flares and different intensity class (B, C, M, and X) flares observed by GOES and RHESSI in SCs 22, 23, and 24

in 2001/2002, which continues systematically during the whole declining phase of SC 23. They suggested that the reduction in photospheric fields started abruptly in 2001/2002. Since solar activity is a manifestation of the Sun's magnetic field, some authors used the variation of Sun's magnetic field to explain the decrease of solar activity in SC 23. McDonald et al. (2010) noted that the weaker interplanetary magnetic field in the solar minimum of SC 23 reaches a value some 28% lower than that of the minima of SCs 19–22. Wang et al. (2009) emphasized that the declining phase of SC 23 is remarkable for a decrease in the interplanetary magnetic field, polar-field, and shrinkage of coronal-hole areas. Although some authors have used different ways to explain the weak solar activity during SC 23, the solar activity in SC 24 is significantly weaker than that of SCs 22 and 23, which still needs further investigation.

3.3 Statistics analysis of duration of solar flares

Figures 4a, b, and c show the distribution of the flare duration for total soft X-ray intensity classes (GOES and RHESSI) as well as for different intensity classes (B, C, M, and X) in SCs 22, 23, and 24, respectively. The left and right bar graphs of each panel indicate the occurrence rates of the flare duration that are no larger than 5 minutes and not less than 180 minutes, respectively. The other bar graphs show the occurrence rates of the flares at 10-minute intervals in different time ranges. From Fig. 4, it can be found that the proportions of the total soft X-ray intensity class flares observed by GOES in three SCs with a duration of 5–15 minutes are 46.10%, 59.90%, and 59.20%, respectively. We can also find that 10 minutes is the period with the highest occurrence rate of flare duration during SCs 23 and 24 in GOES and RHESSI data. However, the occurrence rate of flare duration for ≤ 5 minutes is obviously higher in RHESSI data (39.90% and 42.40%) than in GOES data (3.08% and 2.68%) during SCs 23 and 24. In general, the duration of solar flares observed by RHESSI is shorter than that observed by GOES. The duration of B and C class flares in three SCs are similar and concentrated in 10 minutes, while that of M and X class flares are different and with a large time span of 10–90 minutes. The distributions of M and X class flares duration in SCs 23 and 24 are similar, while that in SC 22 is obviously different from these two cycles. In SCs 23 and 24, the duration of classes M and X are concentrated on 10-30 minutes, while that of SC 22 is with a large time span of 10–90 minutes and no obvious concentration bar. Furthermore, the duration of 5.19% X class flares is more than 180 minutes in SC 22. On whole, the duration of total flares and different intensity class flares in SC 22 is longer than in SCs 23 and 24. Meanwhile, we can find that the duration of flares increases with the increase of flare intensity in three SCs.

Table 2 The mean, median plus 95% confidence interval, skewness, and 90th percentile values of the duration of the different intensity class flares and total flares in SCs 22, 23, and 24. All values are given in minutes

SC	Class	Mean	Median$\pm c_{95}$	SK	P_{90}
SC 22	B	15.52	10.00$\pm$0.20	15.12	29.00
	C	24.46	16.00$\pm$0.28	3.79	51.00
	M	52.34	39.00$\pm$1.61	2.52	107.00
	X	97.59	71.50$\pm$11.2	2.09	201.50
	Total	24.94	15.00$\pm$0.22	5.28	54.00
SC 23	B	14.28	10.00$\pm$0.14	10.18	25.00
	C	20.17	13.00$\pm$0.19	5.72	38.00
	M	30.24	21.00$\pm$0.96	4.62	62.00
	X	35.35	26.50$\pm$3.66	2.19	78.40
	Total	18.73	12.00$\pm$0.14	6.41	36.00
SC 24	B	16.60	10.00$\pm$0.21	10.01	29.00
	C	21.35	14.00$\pm$0.25	5.25	42.00
	M	28.67	19.00$\pm$1.25	5.14	56.40
	X	36.98	24.00$\pm$9.13	1.33	79.00
	Total	19.90	12.00$\pm$0.18	6.98	39.00

To clearly demonstrate the duration of total and different class flares, Table 2 shows the mean values, median values plus 95% confidence interval, skewness values, and 90th percentile values of the duration for the different intensity class flares and total flares. From Table 2, we can find that all values of the skewness are positive. It indicates that the distribution of flare duration is a right-skewed distribution. Additionally, the skewness values from B to X class flares are 15.12, 3.79, 2.52, and 2.09 in SC 22, which means that the skewness decreases with the increase of flare intensity class. The same conclusion can be also obtained in SCs 23 and 24. In SCs 22, 23, and 24, the median of duration from B to X class flares are 10.00, 16.00, 39.00 and 71.50, 10.00, 13.00, 21.00 and 26.50, and 10.00, 14.00 19.00 and 24.00 minutes. The median values of duration for B and C class flares are similar and about 10–16 minutes in three SCs, while the median of the duration of M and X class flares are 39.00 and 71.50 minutes in SC 22, 21.00 and 26.50 in SC 23, and 19.00 and 24.00 minutes in SC 24, respectively. On average, the duration of M and X class flares in SC 22 are above 1.85 (1.86 and 2.05) and 2.69 (2.70 and 2.98) times that of SCs 23 and 24, respectively. The duration of M and X class flares in SC 22 is obviously longer than that in SCs 23 and 24, which is caused by the different intensity of solar activity in three SCs (Temmer et al. 2001). The mean solar F10.7 indexes are 133.40, 116.32, and 102.82 in SCs 22, 23, and 24, respectively, which indicates the solar activity intensity in SC 22 is 1.15 and 1.30 times that in SCs 23 and 24. Wilson (1987) found that a flare near solar maximum is about 1.6 times longer than one occurring near solar minimum.

From Table 2, we can find that the median duration of X class flares is 7.15, 2.65, and 2.40 times that of B class flares in three SCs. It indicates the duration of flares increases with increasing intensity class in three SCs, which is in agreement with the result during SCs 21, 22, and 23 reported by Joshi et al. (2010). Temmer et al. (2001) and Veronig et al. (2002) statistically analyzed Ha and soft X-ray flares and found that the flare duration increases with the importance and intensity classes. Temmer et al. (2001) reported that the duration of flares during 1975–1999 increases from flare importance class S to >1 by a factor of 4.07. During the period January 1976 to December 2000, the duration of flares increases from flare intensity class B to X by a factor of 3 (Veronig et al. 2002). Moreover, the 95% confidence interval is as a measure of statistical significance for the difference in duration of the different intensity class flares. Except for the X-class and M-class flares in the SC 24, the difference in duration between one class and another class of flares is larger than the 95% confidence limit, which indicates that class effect is statistically significant. We also find that the 90th percentile of duration increase from flare intensity class B to X by a factor of 6.95 in SC 22 while these increases for SCs 23 and 24 are only by a factor of 3.14 and 2.72. It suggests that the flare duration increases with the increase of flare class and the flare duration difference between the highest and lowest classes of the SC 22 is significantly greater than that of SCs 23 and 24.

To find out the relationship between the duration of different class flares and the solar activity, the solar F10.7 index, X-ray peak flux in 0.1–0.8 nm and EUV peak flux in 0.1–50 nm are used to indicate the intensity of solar activity in this paper. Figure 5 presents the temporal evolution of the yearly mean values of duration for total flares and different intensity class (B, C, M, and X) flares, the annual average value of solar F10.7 index, the yearly mean value of X-ray flux in 0.1–0.8 nm, and the yearly mean value of EUV flux in 0.1–50 nm during SCs 22, 23, and 24. From Fig. 5, we can find that the duration of flares increases with the increase of flare intensity in three SCs and the duration of total flares and M and X class flares are obviously longer in SC 22 than in SCs 23 and 24, which confirms the results in Fig. 4 and Table 2 and is in agreement with the previous results (Wilson 1987). As shown in Fig. 5, there is a positive correlation between the duration of total and M and X class flares and three solar fluxes while a negative correlation for the duration of B and C class flares. The negative correlation between the duration of B and C class flares and three solar fluxes is very obvious in 2010 and 2008. Compared with the high years of solar activity, the duration of B and C class flares increases by up to 14.17 and 34.67 minutes in 2010 and 2008, respectively.

To detail obtain the correlation between the duration of different class flares and the yearly mean values of solar

Fig. 5 The temporal evolution of the yearly mean values of duration (black) for total flares and different intensity class (B, C, M, and X) flares and the annual average values of solar F10.7 index (blue), X-ray flux in 0.1–0.8 nm (red), and EUV flux in 0.1–50 nm (green) during SCs 22, 23, and 24
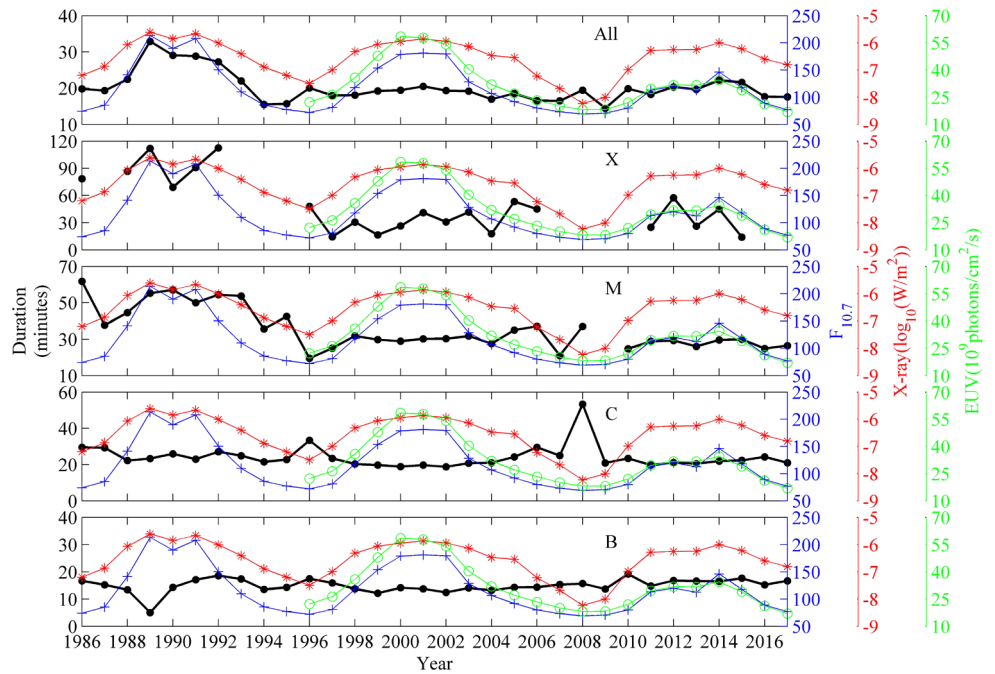

Table 3 The correlation coefficients between the yearly mean duration and the annual average values of solar F10.7 index, X-ray flux in 0.1–0.8 nm, and EUV flux in 0.1–50 nm of the different intensity class flares and total flares in SCs 22, 23, and 24

Solar radiation fluxes	Class				
	B	C	M	X	Total
F10.7	−0.41	−0.36	0.40	0.61	0.75
X-ray peak flux in 0.1–0.8 nm	−0.45	−0.30	0.43	0.67	0.83
EUV peak flux in 0.1–50 nm	−0.54	−0.46	0.31	0.40	0.40

F10.7 index, X-ray peak flux, and EUV peak flux, we calculated the correlation coefficients between the yearly mean duration of flares and the yearly mean values of three solar fluxes in SCs 22, 23, and 24. The results are shown in Table 3. We can find that there is a positive correlation between the solar F10.7 index and the duration of total and M and X class flares (0.75, 0.40, and 0.61) while a negative correlation for the duration of B and C class flares (-0.41 and -0.36). A similar conclusion was reached while analyzing the relationship between the duration of different class flares and the X-ray flux and EUV flux, which is also listed in Table 3. Temmer et al. (2001) calculated the correlation coefficient of the yearly duration of flares and the yearly mean sunspot numbers from 1975 to 1999 and found the correlation coefficient is a quite high value (0.71). The correlation is in agreement with the correlation between the solar F10.7 index and the duration of total flares. Meanwhile, Table 3 also shows that the duration of M and X class flares increases

with the intensity of solar activity, while that of B and C class flares decreases.

4 Summary

In this paper, 58,006 solar flare events occurred during SCs 22, 23, and 24 (1986–1995/1996–2008/2009–2017) have been analyzed from the number, the relationship between the occurrence of soft X-ray flares and solar activity, and the duration. The main findings are summarized as follows.

1. The total occurrence rates of M and X class flares are 10.33%, 6.77%, and 5.45% in SCs 22, 23, and 24, respectively. A comprehensive comparison of the proportion, number, and monthly mean number of M and X class flares in the three SCs indicates that the SC 22 is an SC with frequent large flares.

2. The M and X class flares are mainly concentrated in solar maximum (71.13%) during SC 22. In SC 23, M and X class flares occurred not only in the high solar activity years (35.98%) but also in the rising and decreasing phases of solar activity. In SC 24, the temporal distributions of M and X class flares are similar to that in SC 22. By calculating, 66.67% of B class flares occur in the low solar activity years of SC 22 while 52.33% of B class flares in SC 24 appear in the middle and high solar activity years. It indicates that the low-class solar flares are easily detected in the relatively low X-ray background.

3. There are good positive correlations between the annual number of flares and the annual average of solar F10.7 index, the yearly mean value of X-ray flux, and the yearly

average of EUV flux during three SCs. The correlation coefficients between the annual number of flares and the annual average of the solar F10.7 index in the three SCs (0.88, 0.87, and 0.91) are higher than that with 0.1–0.8 nm X-ray flux in three SCs (0.81, 0.85, and 0.88), while less than that with 0.1–50 nm EUV radiation flux in SC 24 (0.96). Moreover, the temporal variations of the number of flares, solar F10.7, X-ray flux, and EUV flux in three SCs indicate that the solar activity intensity is significantly weaker in SC 24 than in SCs 22 and 23 and has declined since SC 22.

4. The median values of the duration of M and X class flares are 39.00 and 71.50 minutes in SC 22, 21.00 and 26.50 minutes in SC 23, and 19.00 and 24.00 minutes in SC 24. The duration of M and X class flares in SC 22 is obviously longer than that in SCs 23 and 24, which is because solar activity is much higher in SC 22 than in SCs 23 and 24. Meanwhile, the duration of M and X class flares increases with the intensity of solar activity, while that of B and C class flares decreases. The duration of flares increases with the increase of flare intensity, which is in agreement with the result during SCs 21, 22, and 23 reported by Joshi et al. (2010).

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