A ES

ISSN: 2096-3246
Volume 54, Issue 02, December, 2022

Special Issue

A COMPARATIVE STUDY OF X-CLASS SOLAR FLARES AND THEIR ASSOCIATION WITH SUPER-ACTIVE REGIONS FOR THE SOLAR CYCLES 23 AND 24.

Vishnu Singh Rathore[1*], Ankit [2] , Nirmal kumar

[1] Assistant Professor, Department of Physics, J. S. University Shikohabad, India,
vishnurathore1989@gmail.com

[2]Assistant Professor, Department of Physics, J. S. University Shikohabad, India,
yadavankitskb798@gmail.com

Abstract – X-class flares and their association with super-active regions (SARs) were analyzed for 23-24 solar cycles. Results show that, total number of X-class flares occur simultaneously relate as (≥ X10) to 4.80 %, X5.0-X9.9 to 9.60%, X3.0-X4 to 12.80%, X2.0-X2.9 to 15.20%, X1.0-X1.9 to 57.60% for SC 23. Similarly, total number of X-class flares occur simultaneously relate as (≥ X10) to 0.00%, X5.0-X9.9 to 8.16%, X3.0-X4.9 to 8.16%, X2.0-X2.9 to 22.40% and X1.0-X1.9 to 61.20%. Distribution of X-class flares for the SC 23 and 24 shows scattered manner. It is also observed that, SC 24 was weak than SC 23 and the total number of X-class flares diminished in comparison to earlier solar cycles. SARs generated 29.16% of the X1.0-X1.9 flares, 36.84% of the X2.0-X2.9 flares, 43.75% of the X3.0-X4.9 flares, 83.33% of both the X5.0-X9.9 flares, and 100.00% of the ≥ X10 flares for SC 23 and 20.00% of the X1.0-X1.9 flares, 36.36% of the X2.0-X2.9 flares, 25.00% of the X3.0-X4.9 flares, 75.00% of the X5.0-X9.9 flares, and 0.00% of the ≥ X10 flares for SC 24.

Keywords: Solar Flares, Active-regions, solar cycle

Introduction

Intense complex magnetic fields, confined in limited region on the Sun that traveled with Earth facing side with normal rotation are active regions (ARs) (Yang et al. 2017). All solar activity including X-rays occurred due to ARs (Bruzek 1972). Level of the solar activities of the sun can be simply probes using sunspots numbers present over the sun (van Driel-Gesztelyi and Green 2015), which is also found to be cyclic in nature. This cycle exhibits a time period of ~ 11 years on average and is referred to as the solar cycle (Schwabe and Schwabe 1844). A solar cycle has many active regions, but only a few ARs would produce remarkably strong solar flares (Wang and Liu 2015).

Sunspots, which are related to ARs can produce Solar flare, on the basis of released energy it may be categorized into classes X, M, C, or B (Carrington 1859). The flux peak energy of the order 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7} watts m^{-2} are categorized as class flares X, M, C, or B respectively, measured by the geostationary operational environment satellite (GOES) since 1996. A Super Active region can produce exceptionally strong flares. Firstly, Bai (1987) introduced the concept of the active region. Then several researchers studied SARs and given various definitions (Romano and Zuccarello, 2007; Roy, 1977; Tian et al., 2002; Wu and Zhang, 1995; Singh et al., 2022)

In this paper, a comparative study of intense X-class solar flares and their relationship with SARs observed for solar cycles 23-24 have been studied. A total number 174 X-class intense flares were observed, which were associated with a total of 88 active regions. 17 active regions are selected as SARs according to the criteria of a super active region given in (Chen and Wang 2015; Chen et al. 2011). Further categorization of X class flares in to X1 to X10 have been accounted for understanding the SARs and ARs nature. Data selection process and the details discussion is given in next sections.

Materials and Methods

To show the progress of a solar cycle, 13-month smoothed monthly sunspot numbers (SMSNs) are used. The SMSNs profile collected from the website http://www.sidc.be/silso/datafiles#total. The period from the minima to the maxima of SMSNs is presented as the ascending phase and that from one month after the maximum of SMSNs to the minimum of SMSNs is known as a descending phase of the solar cycle. The maxima of SMSNs are defined as the solar cycle size or the solar cycle intensity (Le et al. 2014). The maximum SMSNs of solar cycle 23 is 180.3, observed in November 2001, and 116.4 of solar cycle 24 observed in April 2014.

The X-ray solar fluxes on their peak emission in the 0.1 – 0.8 nm are simply monitored by Geostationary Orbital Environmental Satellite (GOES-15) under the NOAA/NASA. The flares mentioned in this paper can be obtained from the website https://www.spaceweatherlive.com/en/archive. For each SARs observed during the 23 and 24 solar cycles, flare index has been calculated, and relative **β-γ-δ** magnetic field of sunspot group days also taken into account to show the high magnetic field. The start date and end date of SARs has been included also.

Results and Discussion

The Statistical distribution of X-class flares

A total of 125 flares occurred in solar cycle 23 and 49 flares occurred in solar cycle 24. The range-wise distribution of solar flares was as follows: 102 flares (58.62%) were in the range of X1.0-X1.9, 30 flares (17.24%) were in the range of X2.0-X2.9, 20 flares (11.49%) were in the range of X3.0-X4.9, 16 flares (9.19%) were in the range of X5.0-X9.9, and 6 (3.44%) were ≥ X10. In solar cycle 24, no flare occurred in the range ≥ X10. The distributions of X-class flares are shown in Figure 1. Fifty percent of flares of different intensities occurred in the descending phase of the solar cycle 23, while the appearance of X-flares in the observed pattern is more in the ascending phase of the solar cycle 24, except for (X2.0 - X2.9) intensity.

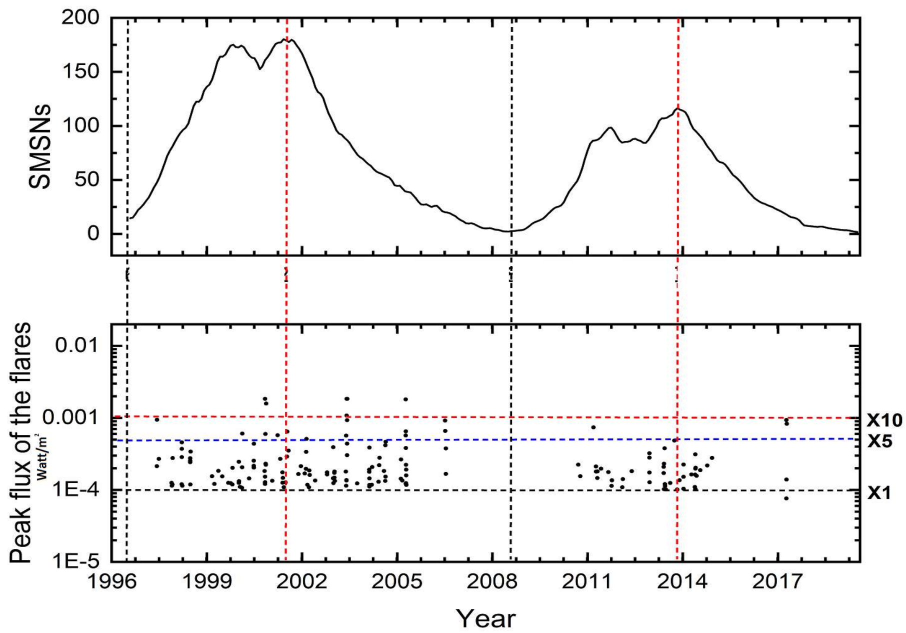

Figure 1: The distributions of X class flares during solar Cycle 23-24.

For the cycle 23, distribution of all X class flares of different intensities is tabulated in table 1. From table 1, it is evident that 57.60% of the X1.0-X1.9 flares, 15.20% of the X2.0-X2.9 flares, and 12.80% of the X3.0-X4.9 flares, 53.27% of the X1.0-X4.9 flares, 9.60% of the X5.0-X9.9 flares, and 4.80% of the ≥ X10 flares occurred during solar cycle 23. It is also noted that 45.83% and 54.16% of the total X1.0-X1.9 flares, 63.15% and 36.84% of the total X2.0-X1.9 flares, 31.25% and 68.75% of the total X3.0-X4.9 flares, 46.72% and 53.27% of the total X1.0-X4.9 flares and 33.33% and 66.67% of the total ≥X5 flares appeared in ascending and descending phases of this solar cycle, respectively. On average, 44.80% of solar flares occurred during the ascending phase and 55.20% during the descending phase of this solar cycle. It is also observed that 44.00% and 72.20% of the X1.0-X1.9, 42.00% and 58.00% of the X2.0-X2.9 flares, 50.00% and 56.25% of the X3.0-X4.9 flares, 45.00% and 67.20% of the X1.0-X4.9 flares, and 55.50% and 61.10% of the ≥ X5.0 flares appeared one year before and two years after (N_{12}) and two years before and three years after (N_{23}) this solar cycle maxima respectively.

Table 1: The statistical distributions of all X –class flares in solar cycle 23.

Flare intensity	N_a	N_d	N_t	Ratio N_a/N_t	Ratio N_d/N_t	N_{12}	N_{23}	Ratio N_{12}/N_t	Ratio N_{23}/N_t
X1.0-X1.9	33	39	72	45.83%	54.16%	32	52	44.00%	72.20%
X2.0-X2.9-	12	7	19	63.15%	36.84%	8	11	42.00%	58.00%
X3.0-X4.9	5	11	16	31.25%	68.75%	8	9	50.00%	56.25%

X1.0-X4.9	50	57	107	46.72%	53.27%	48	72	45.00%	67.20%
≥X5	6	12	18	33.33%	66.67%	10	11	55.50%	61.10%

Note: N_a and N_d denote number of flares in the ascending and descending phases of solar cycle 23, respectively. N_t denotes the total number of solar flares that occurred during a solar cycle. N_{12} represents the number of solar flares that occurred one year before the solar cycle peak and the two years after it. N_{23} represents the number of solar flares that occurred two years before the solar cycle peak and the three years after it. To see the more distribution of flares around the peak, asymmetry time windows is considered, because before peak (in ascending phase) the number of flares is lesser than after peak (in descending phase)

Table 2 represents the distribution of all X-class flares of different intensities that occurred in solar cycle 24. It is observed that, on average, of all flares intensity, mostly X-flares (63.20%) occurred in the ascending phase of the cycle with the pattern of flares intensity, 70.00% of X1.0-X1.9, 45.50% of X2.0-X2.9, 75.00% of X3.0-X4.9, 64.44% of the X1.0-X4.9 flares and 50.00% of ≥ X5.0 and 36.70% flares in the descending phase of this solar cycle with the pattern of flares intensity, 30.00% of X1.0-X1.9, 54.54% of X2.0-X2.9, 25.00% of X3.0-X4.9, 35.55% of the X1.0-X4.9 flares and 50.00% of ≥ X5.0 flares.

Maxima of solar cycle 24 Shows 70% of the X1.0-X1.9 flares appeared in the N_{21} range (two years before and one year after the peak) and 93.00% of them occurred in the N_{32} range(three years before and two years after the peak). Also, 63.60 % and 72.20% of the X2.0-X2.9 flares appeared in N_{21} and N_{32} range respectively. 100.00% of the X3.0-X4.9 flares appeared in both the $N_{21}$and N_{32} range. 71.10% and 88.80% of the X1.0-X4.9 flares appeared two year before and one year after (N_{21}) and three years before and two years after (N_{32}) of this solar cycle maxima, respectively. It is also found that there is no ≥ X5 flare appeared two years before and one year after (N_{21}) the solar cycle maxima, but 50.00% of this level flares appeared three years before and two years after (N_{32}) of this solar cycle maxima. It is also noticed that no ≥X10 flare occurred in solar cycle 24 that means this solar cycle is weaker than their preceding solar cycles.

Table 2: The statistical distributions of all X –class flares that occurred in solar cycle 24.

Flare intensity	N_a	N_d	N_t	**Ratio N_a/N_t**	**Ratio N_d/N_t**	N_{21}	N_{32}	**Ratio N_{21}/N_t**	**Ratio N_{32}/N_t**
X1.0-X1.9	21	9	30	70.00%	30.00%	21	28	70.00%	93.00%
X2.0-X2.9-	5	6	11	45.50%	54.54%	7	8	63.60%	72.70%
X3.0-X4.9	3	1	4	75.00%	25.00%	4	4	100.00%	100.00%
X1.0-X4.9	29	16	45	64.44%	35.55%	32	40	71.10%	88.88%
≥X5	2	2	4	50.00%	50.00%	0	0		

Note: N_a and N_d denote flare numbers in the ascending and descending phases of solar cycle 24, respectively. N_t denotes the total number of solar flares that occurred during this solar cycle. N_{21} represents the number of solar flares that occurred two years before the solar cycle peak and the one year after it. N_{32} represents the number of solar flares that occurred three years before the solar cycle peak and the two years after it, because before peak (in ascending phase) the number of flares is higher than after peak (in descending phase)

Association of solar flares with Super Active Regions (SARs)

There were 174 X-class flares produced by 88 active regions. Out of 88 ARs, 59 ARs were associated with 125 solar flares that occurred in solar cycle 23, while 29 ARs were associated with 49 solar flares that occurred in solar cycle 24. Out of 88 ARs, only 17 active regions, are selected as super active regions according to criteria for the definition of SARs is given by Chen et al. (2011) such as the maximum area of the sunspot group, the solar flare index (of M and X class -class flare), the maximum 10.7 cm radio flux. Along with these criteria we have considered ARs as super active regions which produced a large number of solar flares (of M and X Class) in which at least one X –class flare was involved. Out of 17, 70.60% (12) of SARs belong to solar cycle 23, and 29.41% (5) belong to solar cycle 24.

Table 3: The ratio of different intensity X-class flares produced by SARs during solar cycles 23-24.

Cycle No.	**ARs**	**SARs**	**N_{1SAR} / N_{1t}**	**N_{2SAR} / N_{2t}**	**$N_{(3-4)SAR}$/ $N_{(3-4)t}$**	**$N_{\geq 5\text{-}9.9 SAR}$/$N_t$**	**N_{10SAR}/N_t**
Solar cycle 23	59	12	21/72= 29.16%	7/19= 36.84%	7/16= 43.75%	10/12= 83.33%	6/6= 100.00%
Solar cycle 24	29	5	6/30= 20.00%	4/11= 36.36 %	1/4= 25.00%	3/4= 75.00%	0.00%

Note: N_{1t} and N_{1SAR} denote the total numbers of X1.0-X1.9 and the numbers of X1.0-X1.9 solar flares produced by SARs during solar cycles 23 and 24 respectively. N_{2t} and N_{2SAR} indicate the total numbers of X2.0-X2.9 and the numbers of X2.0-X2.9 solar flares produced by SARs during solar cycles 23 and 24 respectively. $N_{(3-4)t}$ and $N_{(3-4)SAR}$ represent the total numbers of X3.0-X4.9 and the numbers of X3.0-X4.9 solar flares produced by SARs during solar cycles 23 and 24 respectively. Remains can be understood in the same manner.

Table 3 shows that during solar cycle 23, out of 59 active regions, 12 are SARs (20.00%) and (80.00%) are ARs. These 12 SARs produced 29.16% of the X1.0-X1.9 flares, 36.84% of the X2.0-X2.9, 43.75% of the X3.0-X4.9 flares, 83.33% of the X5.0-X5.9 flares, and 100.00% of the ≥X10 flares. Whereas in solar cycle 24, 17.24% of (5 ARs)the total ARs (29) is considered as super active regions (SARs), which produced 20.00% of the X1.0-X1.9 flares, 36.40% of the X2.0-X2.9, 25.00% of the X3.0-X4.9 flares, and 75.00% of the X5.0-X5.9 flares. There were no ≥ X10 level flares in solar cycle 24.

Table 1 shows that more than 50.00% of solar flares of different intensities (except X2.0-

X2.9 intensity level) occurred during the descending phase of the solar cycle 23. Similar results have also been reported by Le et al. (2014) and Bruevich et al. (2017) for solar cycles 21-23. This property is associated with the results reported by Le et al. (2013a) that the descending phase of solar cycles accounts for most of the occurrences of major geomagnetic storms. On average of all flares intensity, 47.00% and 63.00% of the flares appeared one year before and two years after (N_{12}) and two years before and three years after (N_{23}) this solar cycle maxima, respectively. But from table 2, we note that during the solar cycle 24 most of the large flares occurred in the ascending phase of the cycle and 76.15% and 80.80% of the flares appeared two years before and one year after (N_{21}) and three years before and two years after (N_{32}) this solar cycle maxima respectively. Bruevich et al. (2017) also reported that most of the large flares (≥ X2.7) occurred in the ascending phase and the maximum of solar cycle 24. Table 3 shows that 83.33% and 75.00% of the X5.0-X9.9 flares, were produced by SARs during the 23and 24 solar cycles respectively, and 100.00% of ≥ X10 were produced by SARs during the solar cycle 23 and none of ≥ X10 flares occurred in solar cycle 24.This suggests that solar cycle 24 is weaker than 23. Many authors also showed that solar cycle 24 is weaker than 23 (Richardson 2013; Singh et al. 2014; Kakad et al. 2019).

It is supposed that the weak polar fields observed during the solar activity minimum period of solar cycle 23 are the main cause of the weakness of the solar cycle 24 (Jiang et al. 2015). These weak polar fields were observed due to the results of several bigger bipolar magnetic regions emerging at low latitudes with a `distinct' orientation of their magnetic polarities in the North-South direction, which suppresses the polar field's evolution. Since these magnetic opposite polarities regions emerged within $\pm 10^0$ latitude from the solar equator, they are known to possess a strong effect (Jiang et al., 2015). Le et al. (2013b) reported that in solar cycles 22 and 23, 77.40% of the ground level enhancements events arise from the Super Active Regions, with 22.60% from others. Table 3 shows the ratio of different intensity X-class solar flares produced by SARs during cycles 23–24.

Summary and Conclusion

In the present study, statistical distribution corresponding to X-class flares and their inter correlation with super active regions during two recent solar cycles, 23-24 are analyzed and presented. Le et al.(2014) also studied the statistical distributions of X-class flares and their correlation with active regions during solar cycles 21-23 and reported that most X-class flares occurred in the descending phase of the three solar cycles. In present study we have selected next solar cycle 24 along with 23, to observe the trend of distribution of solar flares in different phases of these selected solar cycles The one basic difference in present study is that the maxima of solar cycle 23 noted in November 2001 with maximum of SMSNs is 180.3, whereas in previous study (especially Lee et al 2014) the peak of solar cycle 23 was recorded in April 2000 with maximum sunspot numbers 120.8. Due to this difference the number of flares of different intensities as in table 1, slightly differ in ascending and descending phase of solar cycle 23 in comparison to Lee at al 2014 work, but total numbers of solar flares and their distribution trend remain the same.

During the solar cycle, 23-24, a total of 39392 C-class weak solar flares, 3295 M-class moderate solar flares, and 174 X-class intense flares were observed. These X-class intense solar flares are associated with 88 active regions. Out of 88 active regions, only 17 are selected as super active regions. We observe that a more significant number of solar flares occurred in cycle 23 as compared to cycle 24 and more than 50.00% of flares of different intensities (except X2.0-X2.9 intensity level) occurred in the descending phase of solar cycle 23, while 60.00-65.00% flares occurred in ascending phase of solar cycle 24. The stronger flares of ≥ X10 occurred only in solar cycle 23. The maximum of SMSNs is 180.3 and 116.4 for solar cycles 23 and 24, respectively. This suggests that solar cycle 24 is weaker than 23. It is also observed that the most intense X-class solar flares occurred during the descending phase of cycle 23. This property is quite similar to that the descending phase of solar cycles accounts for most of the occurrences of gigantic geomagnetic (Le et al. 2013a). Besides, the results correspond that in the solar cycle 24, 50.00% stronger flares occurred in the ascending phase and 50.00% in the descending phase of the cycle. Many authors (Ataç et al., 2009; Mariş et al., 2004) also reported that flare activity is low level in the ascending phase and remarkably high in descending phase of solar cycle 23. Bai, et al. (2006) reported a high flare activity in the early descending phase of SC23. It is well known that solar activity on the northern and southern hemispheres of solar disk is not uniform. In present study, it is found 58 solar flares occurred in northern and 67 solar flares occurred in southern hemisphere of solar cycle 23, It means that solar flare activity dominated in southern hemisphere for solar cycle 23. During solar cycle 24, 40.80% (20) solar flares occurred in northern and 59.10% (29) flares occurred in southern hemisphere It is evident that flares of x-class also dominated in southern hemisphere, but Solar cycle 24 shows reverse trend in comparison to SC 23, which started in December 2008, and had a double-peaked solar maximum, with first peak occurring in 2011 and the second peak came in April 2014. Bruevich et al. 2017 have studied the N-S distribution of large (≥ M1) solar flares in solar cycle 24 and reported that strong solar flares dominated in the Northern Hemisphere (NH) in 2011 and shifted to Southern Hemisphere (SH) in 2014. In present study, the 50.00% strong flares (of X5.0-X9.9 level) appeared in NH and 50.00% in SH (Descending phase).

Joshi,et al. 2019 have also studied the N-S distribution and asymmetry of GOES SXR flares during solar cycle 24 and reported that more flares occurred in the NH during the ascending phase of the cycle, while during the later phases of the cycle, the excess of flares shifted towards the southern hemisphere. Recently, Isaeva et al.(2020) statistically analyzed the flare activity in solar cycle 24 and reported that 744 flares of M and X-class occurred in solar cycle 24, and out of 744, 310 flares occurred in northern hemisphere and the remaining 434 occurred in southern hemisphere. It means that southern hemisphere, was appreciably more active in terms of the numbers of flares. He also noted that there were 1720 active regions and 234 active regions (13.60%) were associated with 744 of M and X-class. In present study, we found that 49 X-class solar flares were associated with 29 active regions.

The stronger flares of ≥ X10 occurred only in solar cycle 23. The maximum of SMSNs is 180.3 and 116.4 for solar cycles 23 and 24, respectively. This suggests that solar cycle 24 is weaker than 23. It is also observed that the most intense X-class solar flares occurred during the descending phase of cycle 23. This property is quite similar to that the descending phase of solar cycles accounts for most of the occurrences of gigantic geomagnetic (Le et al. 2013a). Besides, the results correspond that in the solar cycle 24, 50.00% stronger flares occurred in the ascending phase and 50.00% in the descending phase of the cycle. Mohamed et al. (2018) also showed that most power full solar flares occurred in descending phase of solar cycle 23

From Tables 1 and 2 it can also see that 100.00% of the X3.0-X4.9 flares appeared in the vicinity of maxima of solar cycle 24, whereas only 50.00-60.00% of this level flares occurred around the solar maxima of solar cycle 23. Table 3 shows that SARs in cycle 23 produced 83.33% of ≥ X5 and 100.00% of ≥ X10 flares. 75.00% of ≥ X5 were produced by SARs and none of ≥ X10 flares in solar cycle 24. Table 4 shows properties of selected SARs during solar cycle 23-24.

After the above discussion we conclude that there were 174 X-class flares generated by 88 active regions during solar cycles 23-24. Of those, 58.62% were at the X1.0-X1.9 intensity level, 17.24% were at the X2.0-X2.9 intensity level, 11.49% were at the X3.0-X4.9 intensity level, 9.19% were at the X5.0-X9.9 intensity level, and 3.44% were at the ≥ X10 level. Solar flare activity is low in the ascending phase and high in the descending phase of solar cycle 23 (due to excess of more flares activity in SH). Solar flare activity is high during the ascending phase (due to the excess of high flare activity in the Northern Hemisphere in 2011) and low during the descending phase of solar cycle 24 (a negative result, because flare activity was high in the Southern Hemisphere in 2014).Super Active Regions (SARs) produced 27.77% of X1.0-X1.9, 36.84% of X2.0-X2.9, 43.75% of X3.0-X4.9, 83.00% of X5.0-X9.9, and 100.00% of ≥ X10 level in solar cycle 23. During solar cycle 24, 20.00% of X1.0-X1.9, 36.36% of X2.0-X2.9, 25.00% of X3.0-X4.9, 75.00% of X5.0-X9.9, and none of ≥ X10 level were produced by Solar Active Regions. The Statistical distribution of flares and maximum monthly sunspots numbers during solar cycle 23 and 24 show that solar cycle 24 is substantially weaker than solar cycle 23. Strong solar flares that are ≥ X10 level are associated with super active regions that are produced by a stronger solar cycle. For example, strong flares that are X28.0, X17.2, and X10.0 are associated with super active region 10486. Additionally, X20.0, X17.0, and X14.4 are produced from 9393, 10808, and 9415 SARs respectively, during solar cycle 23. It is also noted that most strong flares associated with SAR (10486) have a maximum flare index (77.74).

Acknowledgements:
Authors are thankful for SILSO and NOAA/NASA for providing sunspot index and Solar flares data, respectively.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ataç, T., Özgüç, A., Pektaş, R., 2009. The variability of foF2 in different phases of solar cycle 23. J. Atmos. Solar-Terrestrial Phys. 71, 583–588. https://doi.org/10.1016/j.jastp.2009.01.004

Bai, T., 1988. Distribution of flares on the sun during 1955-1985 - "Hot spots" (active zones) lasting for 30 years. Astrophys. J. 328, 860. https://doi.org/10.1086/166344

Bruevich, E.A., Kazachevskaya, T. V, Yakunina, G. V, 2017. Large Flares (M1–X7) in Solar Activity Cycle 24. Geomagn. Aeron. 57, 1077–1085. https://doi.org/10.1134/S0016793217080059

Bruzek, A., 1972. Properties of Solar Active Regions, in: de Jager, C., Dyer, E.R. (Eds.), Astrophysics and Space Science Library. Springer Netherlands, Dordrecht, pp. 49–60. https://doi.org/10.1007/978-94-010-3126-4_5

Carrington, R.C., 1859. Description of a Singular Appearance seen in the Sun on September 1, 1859. Mon. Not. R. Astron. Soc. 20, 13–15. https://doi.org/10.1093/mnras/20.1.13

Chen, A., Wang, J., 2015. Super-active regions in solar cycle 24. Proc. Int. Astron. Union 11, 309–314. https://doi.org/10.1017/s1743921316000223

Chen, A.Q., Wang, J.X., Li, J.W., Feynman, J., Zhang, J., 2011. Statistical properties of superactive regions during solar cycles 19-23. Astron. Astrophys. 534. https://doi.org/10.1051/0004-6361/201116790

Harra, L.K., Schrijver, C.J., Janvier, M., Toriumi, S., Hudson, H., Matthews, S., Woods, M.M., Hara, H., Guedel, M., Kowalski, A., Osten, R., Kusano, K., Lueftinger, T., 2016. The Characteristics of Solar X-Class Flares and CMEs: A Paradigm for Stellar Superflares and Eruptions? Sol. Phys. https://doi.org/10.1007/s11207-016-0923-0

Isaeva, E.S., Tomozov, V.M., Yazev, S.A., 2020. X-Ray Flares and Activity Complexes on the Sun in Solar Cycle 24. Astron. Reports 64, 58–65. https://doi.org/10.1134/S1063772920010035

Le, G.-M., Cai, Z.-Y., Wang, H.-N., Yin, Z.-Q., Li, P., 2013. Solar cycle distribution of major geomagnetic storms. Res. Astron. Astrophys. 13, 739–748. https://doi.org/10.1088/1674-4527/13/6/013

Le, G., Yang, X., Liu, Y., Li, P., Yin, Z., Chen, Y., 2014. Statistical properties of X-class flares and their relationship with super active regions during solar cycles 21–23. Astrophys. Space Sci. 350, 443–447. https://doi.org/10.1007/s10509-013-1773-y

Li, W., Wang, H., 1997. An analysis on the strongest active regions of solar cycle 21. Publ. Yunnan Obs. 1, 10–17.

Mariş, G., Popescu, M.D., Beşliu, D., 2004. Solar cycle 23 analysis. Proc. Int. Astron. Union 2004, 127–128. https://doi.org/10.1017/S174392130400537X

Mohamed, W., Yousef, S., Shaltout, M., 2018. On the classifications of the solar active regions (ARs); Case study for solar cycles 23 and 24. Egypt. J. Remote Sens. Sp. Sci. 21, 249–253. https://doi.org/10.1016/j.ejrs.2017.04.004

Romano, P., Zuccarello, F., 2007. Photospheric magnetic evolution of super active regions. Astron. Astrophys. 474, 633–637. https://doi.org/10.1051/0004-6361:20078110

Roy, J.-R., 1977. The north-south distribution of major solar flare events, sunspot magnetic classes and sunspot areas (1955–1974). Sol. Phys. 52, 53–61. https://doi.org/10.1007/bf00935789

Schwabe, Heinrich, Schwabe, Hofrath, 1844. Sonnen — Beobachtungen im Jahre 1843. Astron. Nachrichten 21, 234–235. https://doi.org/10.1002/asna.18440211505

Singh, A., Chaudhary, A., Rathore, V.S., Singh, A.K., 2022. A statistical analysis of X- class solar flares and their association with the super active regions during solar cycles 23- 24. J. Sci. Res. 66, 95–102. https://doi.org/10.37398/JSR.2022.660513

Tian, L., Liu, Y., Wang, J., 2002. THE MOST VIOLENT SUPER-ACTIVE REGIONS IN THE 22nd AND 23rd CYCLES. Sol. Phys. 209, 361–374. https://doi.org/10.1023/a:1021270202680

van Driel-Gesztelyi, L., Green, L.M., 2015. Evolution of active regions. Living Rev. Sol. Phys. 12, 1–98. https://doi.org/10.1007/lrsp-2015-1

Wang, H., Liu, C., 2015. Structure and evolution of magnetic fields associated with solar eruptions. Res. Astron. Astrophys. https://doi.org/10.1088/1674-4527/15/2/001

Wu, M., Zhang, Q., 1995. The strongest active regions for solar cycle 22. Publ. Yunnan Obs. 1, 1–12.

Yang, Y.-H., Hsieh, M.-S., Yu, H.-S., Chen, P.F., 2017. A statistical study of flare productivity associated with sunspot properties in different magnetic types of active regions. Astrophys. J. 834, 150. https://doi.org/10.3847/1538-4357/834/2/150