

Variation in the Flaring Potential of Different Sunspot Groups During Different Phases of Solar Cycles 23 and 24 Postprint

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Date: 2024-02-28T00:00:00+00:00

Abstract

In this present study, we have analyzed different types of X-ray solar flares (C, M, and X classes) coming out from different classes of sunspot groups (SSGs). The data which we have taken under this study cover the duration of 24 yr from 1996 to 2019. During this, we observed a total of 15015 flares (8417 in SC-23 and 6598 in SC-24) emitted from a total of 33780 active regions (21746 in SC-23 and 12034 in SC-24) with sunspot only. We defined the flaring potential or flare-production potential as the ratio of the total number of flares produced from a particular type of SSG to the total number of the same-class SSGs observed on the solar surface. Here we studied yearly changes in the flaring potential of different McIntosh class groups of sunspots in different phases of SC-23 and 24. In addition, we investigated yearly variations in the potential of producing flares by different SSGs (A, B, C, D, E, F, and H) during different phases (ascending, maximum, descending, and minimum) of SC-23 and 24. These are our findings: (1) D, E, and F SSGs have the potential of producing flares $\$ \$$ 8 times greater than A, B, C and H SSGs; (2) The larger and more complex D, E, and F SSGs produced nearly 80% of flares in SC-23 and 24; (3) The A, B, C and H SSGs, which are smaller and simpler, produced only 20% of flares in SC-23 and 24; (4) The biggest and most complex SSGs of F-class have flaring potential 1.996 and 3.443 per SSG in SC-23 and 24, respectively. (5) The potential for producing flares in each SSG is higher in SC-24 than in SC-23, although SC-24 is a weaker cycle than SC-23. (6) The alterations in the number of flares (C+M+X) show different time profiles than the alterations in sunspot numbers during SC-23 and 24, with several peaks. (7) The SSGs of C, D, E, and H-class have the highest flaring potential in the descending phase of both SC-23 and 24. (8) F-class SSGs have the highest flaring potential in the descending phase of SC-23 but also in the maximum phase of SC-24.

Full Text

Preamble

Variation in the Flaring Potential of Different Sunspot Groups During Different Phases of Solar Cycles 23 and 24

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Received 2023 October 28; revised 2023 December 7; accepted 2023 December 21; published 2024 January 31

Abstract

In this study, we analyze different types of X-ray solar flares (C, M, and X classes) originating from various classes of sunspot groups (SSGs). Our dataset covers a 24-year period from 1996 to 2019, during which we observed a total of 15,015 flares (8,417 in SC-23 and 6,598 in SC-24) emitted from 33,780 active regions (21,746 in SC-23 and 12,034 in SC-24) containing sunspots. We define flaring potential, or flare-production potential, as the ratio of the total number of flares produced by a particular type of SSG to the total number of that same-class SSG observed on the solar surface. Here we examine yearly changes in the flaring potential of different McIntosh-class sunspot groups during various phases of SC-23 and 24.

Additionally, we investigate yearly variations in the flare-producing potential of different SSGs (A, B, C, D, E, F, and H) during different phases (ascending, maximum, descending, and minimum) of SC-23 and 24. Our findings are: (1) D, E, and F SSGs have a flare-producing potential approximately 8 times greater than A, B, C, and H SSGs; (2) The larger and more complex D, E, and F SSGs produced nearly 80% of flares in SC-23 and 24; (3) The smaller and simpler A, B, C, and H SSGs produced only 20% of flares in SC-23 and 24; (4) The largest and most complex F-class SSGs have flaring potentials of 1.996 and 3.443 flares per SSG in SC-23 and 24, respectively; (5) The flare-producing potential for each SSG is higher in SC-24 than in SC-23, although SC-24 is a weaker cycle than SC-23; (6) The variations in the number of flares (C+M+X) show different time profiles than the variations in sunspot numbers during SC-23 and 24, with several peaks; (7) C, D, E, and H-class SSGs exhibit the highest flaring potential in the descending phase of both SC-23 and 24; (8) F-class SSGs show the highest flaring potential in the descending phase of SC-23 but in the maximum phase of SC-24.

Key words: (Sun:) sunspots –Sun: flares –Sun: activity –Sun: magnetic fields –Sun: filaments –prominences

1. Introduction

The dynamo mechanism occurring in the solar core is responsible for the Sun's various activities. Sunspots on the solar chromosphere serve as a visual indicator of this activity. Sunspot regions possess very strong magnetic fields and appear dark because their temperature is lower than the surrounding plasma. This temperature reduction occurs because the convection process is strongly suppressed in plasma embedded within intense magnetic fields, preventing energy from reaching the surface. As the Sun rotates continuously, sunspot regions move across the visible disk. Sunspots are temporary phenomena whose shape, size, magnetic field polarity, and location vary continuously. They may persist for days, weeks, or even up to a month. Scientists have been collecting sunspot data for nearly 400 years, since the invention of the telescope around 1610 (Eddy 1976; Vaquero et al. 2007), to understand solar activity. High-magnitude magnetic fields emerge from the Sun's interior and appear on the surface as dark spots known as sunspots (Wang et al. 2005). Sunspots can appear singly, in pairs, or in larger groups.

Sunspot number (SSN) correlates with various solar activity parameters including solar wind parameters (Ahluwalia 2011), galactic cosmic rays (GCRs) in Earth's orbit (Forbush 1966), interplanetary magnetic field (IMF) B (Ahluwalia 2013), and geomagnetic indices Ap/aa (Mayaud 1972). Numerous studies have quantitatively demonstrated that sunspot rotation contributes to the transport of energy and helicity from the photosphere to the corona (Kazachenko et al. 2009; Vemareddy et al. 2012), and observational data analysis has confirmed a temporal and spatial relationship between solar flares and sunspot rotation (Zhang et al. 2007; Yan & Qu 2007; Yan et al. 2008a, 2008b, 2009; Jiang et al. 2012).

Based on morphology, SSGs have been classified into different categories. Cortie (1901) initially classified sunspot groups into five categories, while Waldmeier (1938) later proposed a new classification of nine categories (A, B, C, D, E, F, G, H, and J) known as the Zurich classification. Finally, McIntosh (1990) modified the Zurich classification to describe the relationship between diverse SSGs and X-ray solar flares, emphasizing important sunspot characteristics such as class, size, and magnetic complexity. The reorganized Zurich classification (also known as the McIntosh classification) consists of seven SSG classes: A, B, C, D, E, F, and H.

Regions on the Sun's surface where sunspots are observed are known as solar active regions (ARs). These ARs may or may not contain sunspots and can produce solar flares, coronal mass ejections (CMEs), and other phenomena. The magnetic fields of solar ARs are highly complex and stressed. The morphology of sunspot groups and associated ARs correlates with the incidence of X-ray solar flares (Bornmann 1992). The tendency of ARs to produce solar flares is determined by magnetic field complexity, as intense flares (M and X class) are mostly produced by ARs with very complex magnetic fields, while weak

flares (A, B, and C class) are produced by ARs with less complex magnetic field configurations. According to the NOAA Space Weather Scale, solar X-ray flare events below M-class do not significantly affect Earth's communications and navigation systems.

During solar flare production across a vast range of wavelengths (Švestka 1966), the chromosphere's brightness suddenly increases, becoming visible on the solar disk. Solar Energetic Particles and CMEs may also be observed during flare emergence, though not all are directly associated with flares. When the energy of embedded material exceeds the suppressive energy of a complex magnetic field, material is ejected from the chromosphere into interplanetary space. Solar X-ray flares emit enormous quantities of energy on the order of 10^{27} - 10^{32} erg, depending on the flare class (Fletcher et al. 2011). These flares affect the entire outer near-space environment and infrastructure on Earth (mobile towers, electricity grids, satellites, etc.). During flare emergence, substantial solar material—including heavy ions, electrons, and protons—may be accelerated to near-light speeds, accompanied by the release of large amounts of magnetic energy across a wide electromagnetic spectrum. High-energy solar flares are generally associated with faster CMEs (Moon et al. 2002; Youssef 2013). Earthward-erupting CMEs can cause moderate to severe geomagnetic storms that may be destructive to Earth's space environment and infrastructure, including communication systems, pipelines, mobile towers, electronic systems, and Global Positioning System navigation.

Many studies have analyzed correlations between different flare classes and solar activity parameters, as well as the temporal and spatial distributions of solar flares and ionospheric disturbances (e.g., Donnelly 1976; Garcia 1990; Švestka 1995; Joshi 1995; Li et al. 1998; Temmer et al. 2000; Atac & Özgüç 2001; Joshi & Joshi 2004; Joshi et al. 2006; Temmer et al. 2006; Belucz et al. 2013; Chowdhury et al. 2013; Xiong et al. 2011, 2014a, 2014b, 2014c, 2019; Belucz et al. 2015; Chen et al 2016; Abdel-Sattar et al. 2018; Joshi & Chandra 2019). Strong flares mostly occur in complex SSGs. Carrington (1859) and Hodgson (1859) independently investigated the first observed solar flare in 1859, which appeared as an increase in brightness.

H α wavelength emission from the chromosphere has been observed since Hale (1920) invented the spectrohelioscope. White light flares are occasionally observed during H α observations. A two-code system known as "importance" indicates flare size and optical brightness. The first code is a number from 1 to 4 representing apparent area, with subflares designated by the letter "S." The second code (f, n, or b) indicates relative brilliance—faint, normal, or bright—yielding 15 total importance codes: Sf, Sn, Sb, 1f, 1n, 1b, etc.

X-ray radiation is also emitted during solar flares. By measuring the energy strength of these X-ray solar flares, we classify them into five groups represented by the letters A, B, C, M, and X, where A-class are the weakest and X-class the strongest. Each letter corresponds to powers of 10: -8, -7, -6, -5, and -4 Wm $^{-2}$, respectively. Various agencies continuously monitor X-ray flare flux

using geostationary satellites, frequently reporting the highest flux of an X-ray flare. The X-ray solar flare classes are defined as follows: (i) A-class: the weakest, generally known as subflares; (ii) B-class: small flares with negligible Earth effects, also considered subflares; (iii) C-class: small flares without plasma ejection and with minor noticeable effects on Earth; (iv) M-class: medium-sized flares that may be associated with CMEs and cause short radio blackouts; (v) X-class: large, very powerful flares with substantial plasma ejection, generally associated with CMEs that may cause intense geomagnetic storms and long-lasting radio blackouts.

The A, B, C, and M classes are each divided into ten equally separated subclasses, while the X class remains open-ended, with each level being ten times more powerful than the previous one and the highest flux reaching nearly 10^{-4} Wm^{-2} .

The “Large and Complex” sunspot group classification correlates better with the Ap and Dst indices than with SSN, unlike “Small and Simple” groups (Lou 2000; Zharkov et al. 2007). Sammis et al. (2000) analyzed the occurrence rate of higher-class X-ray flares based on magnetic classes and sunspot group area (SSGA), establishing that flare size is proportional to SSG size. Lee et al. (2012) separated sunspot groups into “Large” and “Small” classes based on area, finding that flare production probability increases with SSGA. Shibata et al. (2013) investigated Sun-like stars with large sunspot areas using Kepler satellite data regarding superflare production, concluding that highly active sunspot regions can generate flares with energies exceeding the most energetic solar flare observed to date—these should be called “superflares.” A superflare could be generated by the Sun once every 800 years. Through mathematical analysis, Aulanier et al. (2013) reported that the energy of the largest possible flare may be six times greater than the highest energy of the most recently observed flare.

Our study focuses on the soft X-ray flare (C, M, and X class) productivity of McIntosh-classified SSGs (A, B, C, D, E, F, and H) during different phases (ascending, maximum, descending, and minimum) of solar cycles SC-23 and 24. We group McIntosh-classified sunspots into two types—small-simple and large-complex—based on their X-ray flare production capacity, as discussed by Kilcik et al. (2011). We define flaring potential as the proportion of flares produced from a particular SSG relative to the number of that particular SSG observed during the stipulated time period. Previous studies in this area were conducted for shorter durations (Lee et al. 2012) or concentrated only on intense flares (M and X class) (Hudson et al. 2014). Here we consider a 24-year period (1996–2019) covering SC-23 and 24, comprising a broad range of flares (C, M, and X class) associated with different sunspot regions.

2. Sunspot Classification

We employ the latest categorization of SSGs presented by McIntosh (1990), also known as the modified Zurich categorization of SSGs.

2.1. McIntosh (Modified Zurich) Categorization

In the McIntosh categorization, the G-class SSG from the Zurich system was merged with the E and F classes, and the J-class SSG was merged with the H class. Consequently, the modified Zurich classification by McIntosh—known as the “McIntosh classification”—depends on three components, generally signified as Zpc. Here, “Z” depends on the morphology and evolution of the SSG, “p” denotes the type of main spot (essentially describing the penumbra), and “c” denotes the level of complexity of sunspot distribution within the group. This system is illustrated in Figure 1 of McIntosh (1990) [Figure 1: see original paper].

Based on parameter “Z,”SSGs are divided into seven categories: (i) A: a unipolar SSG without penumbra, representing either the initial or final stage of SSG development; (ii) B: a bipolar SSG without penumbra around any sunspot; (iii) C: a bipolar SSG with penumbra at either end, where in extreme cases the penumbra surrounds the largest leading umbrae; (iv) D: a bipolar SSG with penumbra around spots at both ends, with length $\leq 10^\circ$; (v) E: a bipolar SSG with penumbra around spots at each end, with $10^\circ < \text{length} \leq 15^\circ$; (vi) F: a bipolar SSG with penumbra around spots at each end and length $> 15^\circ$; (vii) H: a unipolar SSG with penumbra.

The second component “p” describes the penumbra around the largest spot of an SSG, with six groups: “x, r, s, a, h, and k.” The third component “c” describes sunspot distribution within a group, with four types: “x, o, i, and c.”

3. Data Selection and Method of Analysis

We studied various types of solar ARs, considering seven SSG classes (A, B, C, D, E, F, and H) from McIntosh’s classification, to examine variations in occurrence and flaring potential during SC-23 and 24. SSG data were obtained from the Heliophysics Integrated Observatory (HELIO) website (http://voparis-helio.obspm.fr/hec/hec_{gui}.php) by selecting the NOAA/USAF solar AR summary for the period 1996-2019, covering SC-23 and 24. From the same HELIO website, we also obtained soft X-ray solar flare data from NASA’s Geostationary Operational Environmental Satellite (GOES) for 1996-2019 (SC-23 and 24). We considered only C, M, and X-class flares, neglecting A and B class flares.

For daily analysis of total flare numbers and related SSGs during SC-23 and 24, we matched solar AR and flare datasets by considering only those flares associated with a specified AR. We studied the variation of total solar flare number (C+M+X) across different stages of SC-23 and 24. We selected daily SSN as our solar activity indicator, as it is considered the best indicator of solar activity. SSN data were acquired from the Sunspot Index and Long-term Solar Observations (SILSO) website (<https://www.sidc.be/SILSO/datafiles>).

To determine different threshold values for solar cycles, we computed smoothed

SSN by first taking a 365-day moving average, then defining the duration between two successive minimum values as a solar cycle. We separated different phases using the same convention as Hynönen (2013) and Kilpua et al. (2015). We calculated the mean value of smoothed SSN and standard deviation (SD) between the minimum value and subsequent maximum, defining the ascending phase as the duration when smoothed SSN values lie between the mean SSN value ± 1 SD. To determine the descending phase, we calculated the mean value of smoothed daily sunspot number (DSSN) and SD between the maximum value and subsequent minimum, defining the descending phase as the time when smoothed SSN lies between DSSN ± 1 SD. We defined the maximum phase as the duration between ascending and descending phases of a given SC, and the minimum phase as the time between descending and ascending phases of two successive cycles.

We plotted total counts of flares (C, M, and X class) observed each month from 1996–2019 to examine their variation during different SC phases. We plotted yearly flaring potential values for different SSG classes from 1996–2019 to ascertain their variation during different stages of SC-23 and 24. We also plotted the percentage of different SSG classes and their flaring potential during both SCs (23 and 24).

4. Results and Discussion

Daily SSN data from January 1996 to December 2019 (SC-23 and 24) were smoothed using the 365-day SG smoothing method, with the resulting plot shown as a brown curve in Figure 1. The gray dotted vertical line separates the two cycles (23 and 24). The brown curve clearly shows that sunspot variations during each cycle exhibit double peaks, with the first peak lower than the second. SC-24's highest peak is lower than SC-23's, indicating that solar activity during SC-24 (maximum SSN 110, duration 11 years from 2009–2019) was lower than during SC-23 (maximum SSN 180, duration 13 years from 1996–2008). In SC-24, the change between first and second peaks is larger than in SC-23, showing that solar activity increased substantially during SC-24's second peak compared to SC-23.

We studied variations in total soft X-ray solar flare production (C, M, and X class combined) by the Sun during SC-23 and 24. We counted all flares originating each month from 1996–2019, covering both cycles. We applied 12-month SG smoothing to total flares (C+M+X class) produced each month from 1996–2019 to observe variations during different phases of SC-23 and 24, indicated by the orange curve in Figure 1. This allows analysis of X-ray flare number variations (C, M, and X class) alongside SSN variations during different SC stages. The orange curve in Figure 1 clearly shows that the number of flares emerging from the Sun also exhibits two peaks during both cycles, similar to SSN. However, it is particularly noteworthy that despite SC-24 being a weak cycle compared to previous cycles, the peaks of the total smoothed monthly flare number in SC-24 are greater than those in SC-23. Although SC-24 was weak regarding solar

activity (with much lower SSN), Nandy (2021) also reported that SC-24 was the weakest cycle of the past century, yet the Sun produced more flares during SC-24' s maximum phase months than in the previous SC-23. Joshi & Joshi (2004) also reported lower solar activity during SC-23 regarding soft X-ray flare events, as computed through the soft “X-ray flare index (FISXR).” We observe a sharp increase during SC-24' s ascending phase and a sharp decrease during its descending phase in flare numbers, whereas SC-23 showed gradual increases during the ascending phase and gradual decreases during the descending phase. Feldman et al. (1997) also found that flare activity increases during an SC' s maximum phase due to stable coronal heating. It is crucial to study the unique characteristics of SC-24, which differ completely from previous cycles. During the minimum phase between cycles in 2008, the Sun produced negligible counts of soft X-ray flares (C, M, and X class). This would become clearer if similar studies were conducted for earlier cycles.

We studied the flaring potential of each SSG (A, B, C, D, E, F, and H) during SC-23 and 24. Based on maximum flaring potential during these cycles, we grouped solar ARs into two categories: first, A, B, C, D, and H class regions with maximum flaring potential of approximately 1.2 flares per AR (Figure 2); and second, E and F class solar ARs with maximum flaring potential exceeding 1.2 flares per AR (Figure 3).

Figure 2 shows that SSGs (A, B, C, D, and H) exhibit different patterns of flaring potential variation during the ascending, maximum, and descending phases of SC-23 and 24. During SC-23, flaring potential is higher in ascending and descending phases than in the maximum phase, showing an oscillatory nature from ascending to descending phase. In SC-24, they do not display oscillatory behavior. Instead, their flaring potential increases continuously from the minimum phase' s lowest value to the descending phase' s highest value, then decreases. In both cycles, the flare generation potential of SSGs (A, B, C, and H) decreases to near zero, except for D class, whose flaring potential never reaches zero.

All SSGs show similar variation patterns within each cycle separately. The peak flaring potential of SSGs A, B, C, D, and H in SC-24 exceeds their peak values in SC-23. D-class SSGs have flaring potentials two or more times greater than A, B, C, and H-class SSGs.

Figure 3 depicts flaring potential variations for E and F class SSGs. Both SSGs show similar variation patterns during both cycles. During SC-23, flaring potential increases gradually from its minimum in the ascending phase to its maximum in the descending phase, then decreases continuously to its lowest value in the minimum phase between cycles 23 and 24. In SC-24, the flaring potential of E and F class SSGs increases from their minimum phase lowest value to their highest values—approximately 5.7 in the descending phase for E-class and in the maximum phase for F-class SSGs—then decreases. The highest flaring potential of F-class SSGs is nearly twice that of E-class SSGs. In SC-23, their flaring potential peaked in the descending phase, while in SC-24 it peaked in the maximum phase for F-class and descending phase for E-class SSGs.

Notably, F-class SSGs were very active during SC-24's maximum phase (a weak cycle). While F-class SSGs show the highest flaring potential in both cycles, their variation pattern differs from the other six SSG classes. A-class SSGs produce the fewest flares, with highest flaring potential values of approximately 0.12 and 0.13 in SC-23 and 24, respectively. The A, B, C, D, E, and H SSGs show similar flaring potential variation patterns but are distinct between SC-23 and 24. Interestingly, all SSGs reach their highest flaring potential values during the descending phases of both SC-23 and 24, except for F-class SSGs in SC-24. Thus, geo-effective flare (C, M, and X class) production generally reaches its maximum during the SC's descending phase.

Based on maximum flaring potential values, we can divide the seven SSGs into two groups: first, A, B, C, and H-class groups; and second, D, E, and F-class groups. The second group's highest flaring potential is 3–10 times larger than the first group's. Eren et al. (2017) also grouped McIntosh-classified SSGs into these two categories, finding the first group's flaring potential to be 8 times greater than the second's. The first group comprises large, complex SSGs, while the second consists of small, simple SSGs.

We investigated the percentage of flares originating from different SSG classes during SC-23 and 24, shown graphically in Figure 4. Both cycles show approximately the same pattern of flare production across SSG classes. D-class SSGs produce the highest number and percentage of flares (31.48% in SC-23 and 34.83% in SC-24), while A-class SSGs produce the minimum (1.0% in SC-23 and 1.32% in SC-24). Combined, D, E, and F class SSGs produce over 80% of flares, while A, B, C, and H class SSGs produce merely 20%. Arranging SSGs by increasing percentage of flares produced yields the series A, B, H, C, F, E, and D during both cycles. Eren et al. (2017) reported the same results. Earlier studies consistently showed that morphologically complex ARs produce more flares (Atac 1987; Gallagher et al. 2002; Ternullo et al. 2006; Norquist 2011; Lee et al. 2012; McCloskey et al. 2016), which our study confirms. The percentage of flares from D-class SSGs increased by 3% in SC-24 compared to SC-23, while flares from F-class SSGs decreased by 6%. Changes in flare percentages from other A, B, C, and H SSGs are negligible between cycles. In SC-24, the largest and most complex F-class sunspots were less active compared to SC-23.

We examined flare production potential of various SSGs during 1996–2008 (SC-23) and 2009–2019 (SC-24), shown in Figure 5 and Table 3. Figure 5 shows that all SSGs had higher flare production potential in SC-24 compared to SC-23, despite SC-24 being a weaker cycle. The increase in flaring potential of F-class SSGs exceeds that of all other SSGs in SC-24 compared to SC-23. The flaring potential of SSGs A through F in Figure 5 shows an exponential pattern (Eren et al. 2017). A-class SSGs have the lowest flaring potential, while F-class SSGs have the highest. Interestingly, even though SC-24 was weaker, all SSGs showed higher flaring potential compared to SC-23. The increment in flaring potential is lowest for the smallest and simplest SSG “A” and highest for the largest and most complex SSG “F” in SC-24 relative to SC-23.

Statistical results for each SSG are listed in Tables 1, 2, and 3. In Table 1, NA, NB, NC, ND, NE, NF, and NH represent the number of flares produced by A, B, C, D, E, F, and H-class SSGs, respectively. The number of flares from B, E, and F-class SSGs decreased substantially in SC-24 compared to SC-23. Table 2 lists the total number of SSGs in different categories counted during SC-23 and 24. The number of F-class SSGs in SC-24 is nearly one-third that of SC-23. Table 3 shows that the D-class group's flaring potential is four times lower than the F-class group's. The increase in flaring potential for various SSG categories in SC-24 relative to SC-23 is twice as large for F-class groups as for E-class groups and three times as large as for D-class groups.

This study confirms that we can predict mid-term solar flaring activity using modified Zurich (McIntosh) class SSGs. We find that D, E, and F SSGs combined produced approximately 81.25% and 77.78% of flares in SC-23 and 24, respectively. Kilcik et al. (2011) previously established that the number of D, E, and F-class SSGs correlates very well with various solar and geomagnetic activities, unlike international SSNs, while A, B, C, and H-class SSGs do not correlate well. These results lead us to conclude that D, E, and F-class sunspot regions produce the maximum number of geo-effective events. Based on our long time series study, we observed that D, E, and F-class ARs contribute about 37% in SC-23 and 33.95% in SC-24 among all ARs producing flares. Hudson et al. (2014) analyzed solar flare productivity from various individual solar ARs across four cycles, finding that the complex nature of solar AR magnetic fields plays a vital role in flare generation compared to AR size. Aulanier et al. (2013) found that nearly 30% of ARs with very complex, highly concentrated magnetic fields produce solar flares, implying that AR magnetic field complexity and flare production are directly linked. Aulanier et al. (2013) and Shibata et al. (2013) theoretically found that solar AR magnetic field complexity and flare production potential are connected.

According to Shibata et al. (2013), an AR with $\sim 10^{23}$ Weber magnetic flux can produce a superflare with energy around 10^{34} erg, which is one order of magnitude higher than a large solar AR. Even an AR with a larger area, as noted by Aulanier et al. (2013), has a greater likelihood of releasing solar flares, though these flares are not expected to have much more energy than the strongest documented solar flare, which had an energy of 10^{32} erg.

5. Summary and Conclusions

In this study, we smoothed daily SSN using a 365-day average to determine different cycle phases and separated the two cycles with a dotted demarcation line, using these phases in our subsequent analysis. We restricted our study to SC-23 and 24 (1996-2019), considering only C, M, and X-class solar flares because these are geo-effective, while excluding A and B-class flares as they do not affect Earth's environment. We considered McIntosh-classified SSGs (A, B, C, D, E, F, and H) as flare originators and neglected flares not correlated with any sunspot region. Flare production potential is defined as the total number of

flares originating from an SSG divided by the total number of that same-class SSG observed in a year/month/cycle. We examined variations in yearly and solar cycle flare production potential of different SSGs during SC-23 and 24.

First, SC-24 has been observed to be weaker than SC-23 based on lower peak SSN values, and it has been stated that SC-24 is the weakest cycle of the last century (Nandy 2021). SC-23 lasted 13 years (1996–2008), while SC-24 lasted 11 years (2009–2019). Both SSN and solar flare numbers show double peaks in SC-23 and 24. The variation in total flare numbers (C, M, and X class) during SC-23 and 24 shows the same periodicity as the sunspot cycle. Intriguingly, the weaker SC-24 produced more flares during each month of its maximum phase than the stronger SC-23. SC-24 requires detailed study to enhance our understanding of solar processes.

Second, we examined for the first time the variance in flaring potential for different Zurich class SSGs during all phases of SC-23 and 24. We revealed that the maximal flaring potential of large, complex D, E, and F-class sunspot regions is three to ten times greater than that of small, simple A, B, C, and H-class regions. F-class SSGs show the strongest flaring potential, with the greatest change between SC-23 and SC-24, while A-class SSGs have the lowest flaring potential and the least change. Except for F-class SSGs, which have highest flaring potential during SC-24' s maximum phase, all SSGs reach their highest flaring potential during the descending phases of SC-23 and 24. This leads us to conclude that the Sun produces more flares per SSG during the solar cycle' s descending phase. The most complex SSG “F” was extremely active during SC-24' s maximum phase. Results may differ if A and B-class flares are included with C, M, and X-class soft X-ray flares.

Third, the Sun' s flaring pattern during SC-24 differed substantially from SC-23, with much different flaring activity during SC-24' s maximum phase compared to SC-23, where activity was highest during ascending and descending phases. The peak flaring potential levels of different SSGs from A to F in Figure 5 show an exponentially increasing pattern (Eren et al. 2017). In SC-24, the Sun' s flare output increased sharply from ascending to maximum phase, then decreased sharply from maximum to descending phase, whereas during SC-23, flare production increased and decreased gradually.

Fourth, we counted a total of 8,417 flares and 21,746 SSGs in SC-23, and 6,598 flares and 12,034 SSGs in SC-24. Our study reveals that the total number of flares produced in SC-23 exceeds that in SC-24.

Fifth, 2019 marked the end of SC-24 as solar activity reached minimal levels. During this year, no soft X-ray flares of C, M, or X class associated with the Earth-facing portion of the Sun were observed.

Acknowledgments

This work is partially supported by the Institute of Eminence (IoE) Program (Scheme No: 6031) of BHU, Varanasi.

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