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On the Occurrence of Different Classes of Solar Flares during the Solar Cycles 23 and 24

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Abstract

In this study we review the occurrence of different types (*A, B, C, M, and X* classes) of solar flares during different solar cycle phases from 1996 to 2019 covering the solar cycles 23 and 24. During this period, a total of 19,126 solar flares were observed regardless the class: 3548 flares in solar cycle 23 (SC23) and 15,668 flares in solar cycle 24 (SC24). Our findings show that the cycle 23 has observed the highest occurrences of M-class and X-class flares, whereas cycle 24 has pointed out a predominance of B-class and C-class flares throughout its different phases. The results indicate that the cycle 23 was magnetically more intense than cycle 24, leading to more powerful solar flares and more frequent geomagnetic storms, capable of generating significant electromagnetic emissions that can affect satellites and GPS signals. The decrease in intense solar flares during cycle 24 compared to cycle 23 reflects an evolution in solar activity patterns over time.

Keywords

Solar Flare, Solar Cycle, Solar Cycle Phase, Solar Flare Class, Occurrence

1. Introduction

Life on Earth owes its existence to the Sun [1]. The Sun provides us with light and heat. Solar activity can greatly affect not only Earth's atmosphere but also the environment of all the planets in the solar system. Among solar events, solar flares are particularly intense. The 1859 Carrington Event was the most powerful solar flare ever observed, highlighting both the frequency and effects of solar energetic particle (SEP) events on human societies [2] [3]. Solar flares (SF) are violent explosions in the Sun's atmosphere that release enormous amounts of energy in the form of light, heat, and charged particles, which may be directed toward our planet, significantly increasing the fluxes of extreme ultraviolet (EUV) and X-rays for a short period [4] [5]. The occurrence of a solar flare on the Sun's surface could be dangerous for Earth, but this depends on the class of the solar flare. There are five classes of solar flares: Classes A, B, C, M, and X [6]-[8]. Class X flares are major events with extremely intense brightness and significant X-ray flux, on the order of 10^{-4} Wm^{-2}. Class M flares are less bright, with X-ray flux above 10^{-5} Wm^{-2}; they are capable of causing intense electromagnetic emissions and solar radio bursts, affecting spacecraft in low Earth orbit and the International Space Station (ISS) [8]-[10]. They can also interfere with satellite radio signals and GPS navigation signals [6] [11]. Other classes (A, B, and C) have weaker brightness and generally have little effect on Earth's ionosphere [6] [12]. The number of sunspots on the Sun's surface changes over time according to a cycle called the solar cycle, which lasts about 11 years [13] [14]. The solar cycle is divided into four phases [15] [16]: minimum phase, ascending phase, maximum phase, and descending phase. In each phase, we can observe different classes of solar flares. Solar flares occur when energy stored in the Sun's magnetic field is suddenly released or converted from magnetic energy to heat and motion [17]. The first discovery of the effects of a solar flare on the geomagnetic field was made by Carrington on September 1, 1859 [2] [6]. The inversion of the magnetic poles' polarity and their return to their original polarity are associated with visible sunspots on the Sun's surface, which begin with a thermonuclear explosion on the Sun, resulting in swelling and a flare on its surface, releasing radiation and charged particles trapped in the solar wind [18] [19]. The objective of this work is to determine whether certain classes are more predominant than others depending on the phase of the solar cycle. Thus, we selected data on solar flares that occurred during Solar Cycles 23 and 24. We will examine all solar flares produced according to their classes, considering each phase of these two solar cycles. In the following sections, we will present the data and methods used for analysis. Next, we will present the results obtained. Finally, the discussion and conclusion will be addressed.

2. Data and Methods

From 1996 to 2019, a large number of solar flares (SF) occurred on the Sun. From 1996 to 2008, solar flares were selected from the GOES archives available in the Hinode Solar Flare Catalogue: https://hinode.msfc.nasa.gov/. From 2008 to 2019, solar flares were selected from GOES archives available at https://www.spaceweatherlive.com/en/archive.htm. The selection was made using the position of the active regions (AR) from which the solar flare was emitted in the direction of the Earth. We also obtained data on X-ray flux in the wavelength range of 0.1 - 0.8 Å via GOES https://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html. Python software version 5 is used for data processing.

A total of 19,126 solar flares has been recorded regardless the class: 3548 flares in solar cycle 23 (SC23) and 15,668 flares in solar cycle 24 (SC24). For better analysis, we categorized them according to different solar flare classes and solar cycle phases [16] [20] (Minimum phase, Ascending phase, Maximum phase, and Decreasing phase). We observed the following distribution: 1455 in the minimum phase, 8946 in the ascending phase, 3344 in the maximum phase, and 5381 in the descending phase. The total number of solar flares observed was 3548 during Solar Cycle 23 (SC23) and 15,668 during SC24.

The occurrence is calculated as follows:

$$P(\text{class}) = \frac{\text{Number of flares in the class}}{\text{Total number of flares}} \tag{1}$$

For each class of solar flare, we have:

$$\begin{cases}
P(A) = \dfrac{\sum_{i=1}^{9}\sum_{j=0}^{9} A_{i.j}}{\sum_{i=1}^{9}\sum_{j=0}^{9}\left(A_{i.j}+B_{i.j}+C_{i.j}\right)+\sum_{i=1}^{9}\sum_{j=0}^{99} M_{i.j}+\sum_{i=1}^{45}\sum_{j=0}^{99} X_{i.j}} \\
P(B) = \dfrac{\sum_{i=1}^{9}\sum_{j=0}^{9} B_{i.j}}{\sum_{i=1}^{9}\sum_{j=0}^{9}\left(A_{i.j}+B_{i.j}+C_{i.j}\right)+\sum_{i=1}^{9}\sum_{j=0}^{99} M_{i.j}+\sum_{i=1}^{45}\sum_{j=0}^{99} X_{i.j}} \\
P(C) = \dfrac{\sum_{i=1}^{9}\sum_{j=0}^{9} C_{i.j}}{\sum_{i=1}^{9}\sum_{j=0}^{9}\left(A_{i.j}+B_{i.j}+C_{i.j}\right)+\sum_{i=1}^{9}\sum_{j=0}^{99} M_{i.j}+\sum_{i=1}^{45}\sum_{j=0}^{99} X_{i.j}} \\
P(M) = \dfrac{\sum_{i=1}^{9}\sum_{j=0}^{99} M_{i.j}}{\sum_{i=1}^{9}\sum_{j=0}^{9}\left(A_{i.j}+B_{i.j}+C_{i.j}\right)+\sum_{i=1}^{9}\sum_{j=0}^{99} M_{i.j}+\sum_{i=1}^{45}\sum_{j=0}^{99} X_{i.j}} \\
P(X) = \dfrac{\sum_{i=1}^{45}\sum_{j=0}^{99} X_{i.j}}{\sum_{i=1}^{9}\sum_{j=0}^{9}\left(A_{i.j}+B_{i.j}+C_{i.j}\right)+\sum_{i=1}^{9}\sum_{j=0}^{99} M_{i.j}+\sum_{i=1}^{45}\sum_{j=0}^{99} X_{i.j}} \\
P(A) = \dfrac{\sum_{i=1}^{9}\sum_{j=0}^{9} A_{i.j}}{\sum_{i=1}^{9}\sum_{j=0}^{9}\left(A_{i.j}+B_{i.j}+C_{i.j}\right)+\sum_{i=1}^{9}\sum_{j=0}^{99} M_{i.j}+\sum_{i=1}^{45}\sum_{j=0}^{99} X_{i.j}}
\end{cases} \tag{2}$$

where $P(A), P(B), P(C), P(M)$ and $P(X)$ are the probabilities of occurrence of A-class, B-class, C-class, M-class, and X-class solar flares respectively.

3. Results and Discussion

Many studies have reviewed on solar flares and solar energetic particles. Some of them show the important impact of these solar events on Earth and into the interplanetary medium [21]-[23] and some other have introduced the spatial distribution of solar events [24] [25].

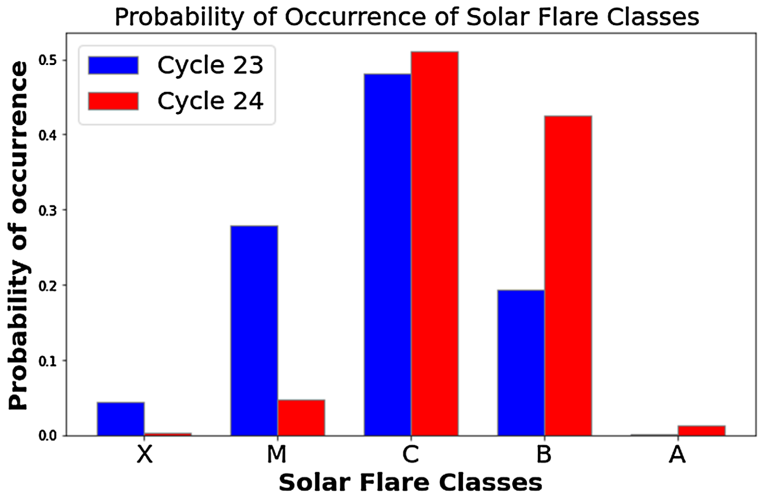

Figure 1. Occurrence of solar flare classes for solar cycles 23 and 24.

Figure 1 presents the occurrence of different classes of solar flares during Solar Cycles 23 and 24. from this figure, it is easy to see that the most important numbers of A, B, and C solar flares classes are observed during Solar Cycle 24 compared to those that occurred during Solar Cycle 23. However, M and X solar flares classes are more abundant during Solar Cycle 23 compared to Solar Cycle 24, which is consistent with the many findings of [26]-[28].

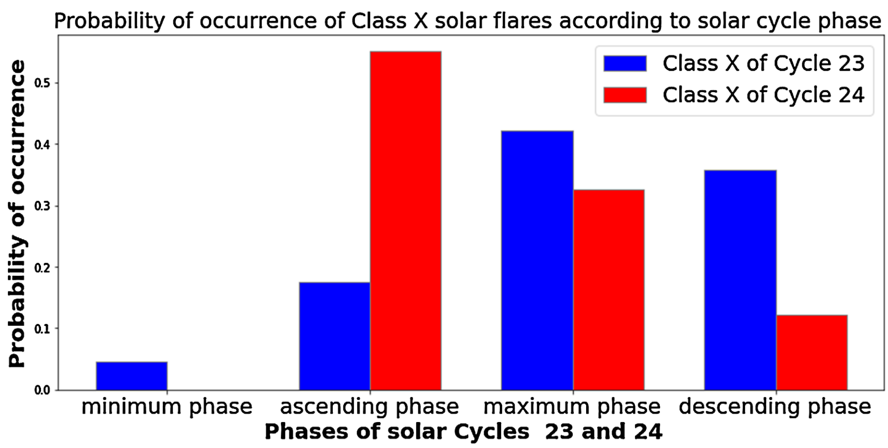

Figure 2. Distribution of solar flares during different solar cycle phases.

Figure 2 presents the distribution of solar flares according to the different phases of the solar cycle during the Solar Cycles 23 and 24. During the Solar Cycle 23, the solar maximum has recorded the highest number of solar flares [29], followed by the solar cycle descending phase [28] [30], the ascending phase [28], and finally, the minimum phase [28], which recorded the fewest solar flares. However, during Solar Cycle 24, the ascending phase recorded the highest number of solar flares. Similar to Solar Cycle 23, the descending phase ranked second, followed by the solar maximum, while the minimum phase also recorded the fewest solar flares during Solar Cycle 24.

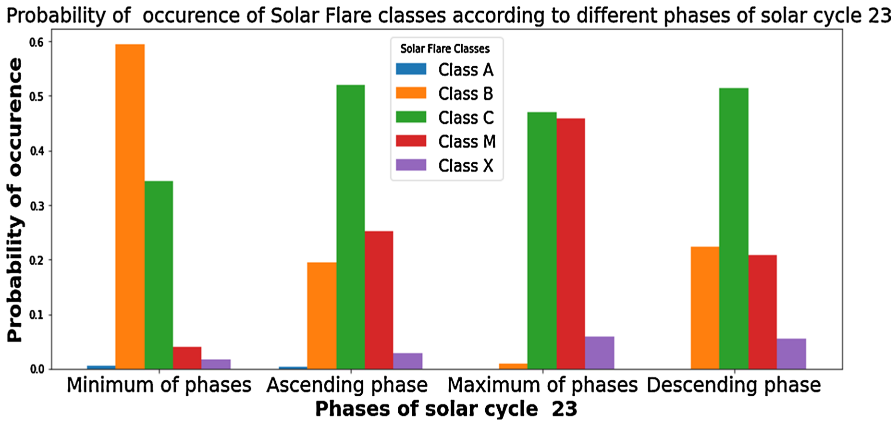

Figure 3. Occurrence of different classes of solar flares in all phases of solar cycle 23.

Figure 3 presents the occurrence of all classes of solar flares during the different solar cycle phases of the Solar Cycle 23. During the minimum phase of the solar cycle 23, all classes of flares were observed. Class B flares were the most frequent, representing 59% of the flares, followed by class C flares (34%). During the ascending phase of Solar Cycle 23, class C flares were the most commonly observed, accounting for 52% of the flares. Class A flares were very negligible, close to 0%. Additionally, 25% of the flares were class M, and 20% were class B. The solar maximum phase of Solar Cycle 23 was dominated by class C flares (47%) and class M flares (46%). Class X flares represented 6%, while class B accounted for 1%, and class A flares were at 0%. In the descending phase of Solar Cycle 23, class C flares dominated (51%), followed by class B flares (22%) and class M flares (21%). Class X flares made up 6%, and no class A flares were observed.

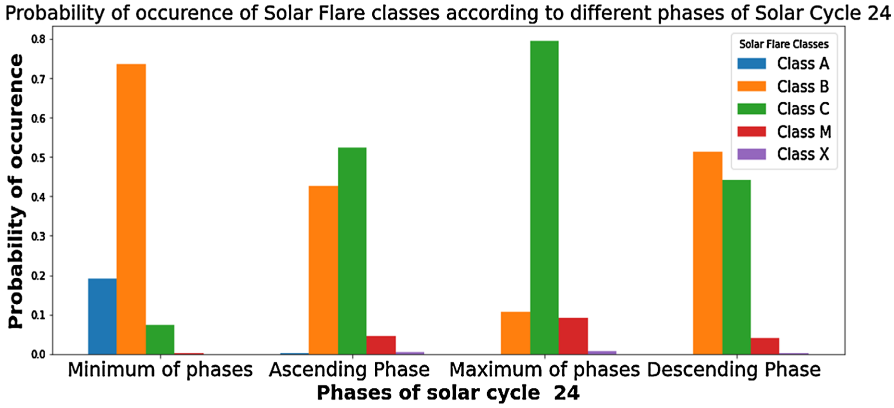

Figure 4. Occurrence of different classes of solar flares across all phases of solar cycle 24.

Figure 4 illustrates the occurrence of all classes of solar flares during the various phases of Solar Cycle 24. During the minimum of Solar Cycle 24, no M-class flares were detected, and X-class flares were negligible. The majority of flares observed were class B (74%), followed by class A (19%). During the ascending phase of Solar Cycle 24, class C and B flares dominated, accounting for 52% and 43%, respectively. M-class flares were only 5%, while X and A-class flares were rare. The solar maximum phase of Solar Cycle 24 was largely dominated by class C flares, which accounted for 79% of all solar flares. Class B accounted for 11%, M-class flares for 9%, X-class flares for 1%, and class A flares for 0%. In the descending phase of Solar Cycle 24, class B and C flares dominated, representing 52% and 44%, respectively. M-class flares accounted for 4%, and no A-class flares were recorded. X-class flares were negligible, approximately 0%.

Figure 3 and **Figure 4** show that class A flares, represented in blue, occur mainly during the minimum phases of both Solar Cycles 23 and 24. No A-class flares were observed during the maximum or descending phases. In Solar Cycle 23, the ascending phase recorded more A-class flares compared to the minimum phase, whereas in Solar Cycle 24, the minimum phase saw more A-class flares than the ascending phase.

Class B flares, represented in orange, were observed across all phases of both cycles. However, fewer B-class flares were recorded during the maximum phases compared to other phases. In Solar Cycle 23, class B flares were most prevalent during the solar minimum, followed by the descending phase, then the ascending phase, with the fewest flares occurring during the maximum phase. Conversely, in Solar Cycle 24, the ascending phase saw the most B-class flares, followed by the descending phase and the solar minimum, with the maximum phase recording the fewest flares. Additionally, the number of B-class flares was higher during Solar Cycle 24 than in Solar Cycle 23.

Class C flares, represented in green, were present in all phases of both cycles. However, the minimum phase recorded the fewest C-class flares compared to other phases. In Solar Cycle 23, the descending phase and maximum phase had the highest number of C-class flares, followed closely by the ascending phase, with the minimum phase showing significantly fewer flares. In contrast, during Solar Cycle 24, the ascending phase had the most C-class flares, followed by the descending and maximum phases, which showed nearly the same number, while the minimum phase recorded a very small number of C-class flares.

The occurrence of M-class flares, represented in red, showed a peak during the maximum phases of both cycles. In Solar Cycle 23, M-class flares were abundant during the maximum phase, followed by the ascending and descending phases, which recorded similar amounts, while the minimum phase saw fewer M-class flares. During Solar Cycle 24, the highest number of M-class flares occurred during the maximum phase and the ascending phase. There was a similar number of M-class flares during the ascending and descending phases of Solar Cycle 24, while very few M-class flares were detected during the solar minimum.

Class X flares, represented in purple, were observed across all phases of Solar Cycle 23, with the highest occurrence during the maximum phase, followed by the descending, ascending, and minimum phases. During Solar Cycle 24, X-class flares were more frequent during the ascending phase than during the maximum phase. However, the maximum phase still recorded more X-class flares than the descending phase. During the minimum phase of Solar Cycle 24, no X-class flares were detected.

The analysis of **Figure 1** shows that the amplitude of A, B, and C-class flares was higher during Solar Cycle 24 compared to Solar Cycle 23, in line with the findings of [28] [31]. On the other hand, M and X-class flares were more abundant during Solar Cycle 23 compared to Solar Cycle 24. X-class flares, the most powerful in terms of intensity, can cause major disturbances. Although less powerful than X-class flares, M-class flares remain significant, as they can cause intense electromagnetic emissions and solar radio bursts, affecting spacecraft in low Earth orbit and the International Space Station (ISS) [8]-[10]. These solar flares can also interfere with satellite radio signals and GPS navigation signals [6] [11]. Although present in large numbers during Solar Cycle 24, the other classes (A, B, and C) are of lower intensity and have little effect on Earth's ionosphere [6] [12].

The analysis of **Figure 2** shows that the distribution of solar flares follows the phases of solar cycle 23, with a minimum number of flares during the minimum phases and, similarly, a maximum number of flares recorded during the maximum phases of the cycle. However, this pattern is not followed during solar cycle 24. To understand this difference, we reviewed the literature and found several authors who have already addressed this issue. For instance, Gopalswamy *et al.* (2014, 2015) and Petrie (2015) highlight that the low solar activity during solar cycle 24 had significant consequences for coronal mass ejections (CMEs) in the heliosphere. The abnormal expansion of CMEs during solar cycle 24, caused by a reduction in heliospheric pressure, led to an increase in the number of small CME halos originating from regions far from the center of the solar disk. This phenomenon is attributed to a weakening of the heliosphere, forcing CMEs to reach pressure equilibrium with their environment at greater heliocentric distances, which causes their peak width to be farther from the Sun compared to solar cycle 23 [32]. Low solar activity reduces the number of energetic solar flares, and thus the number of space weather events [33].

The analysis of **Figure 3** and **Figure 4** reveals that, in both solar cycles, the occurrence of M and X-class flares is very high at the maximum phases. Furthermore, during solar cycle 23, the solar minimum is dominated by B and C-class flares, while the ascending and descending phases are marked by B, C, and M-class flares. The solar maximum of cycle 23 is dominated by C and M-class flares. During cycle 24, all phases are predominantly dominated by B and C-class flares. No A-class flares were observed during the phases of the solar cycle, except for the solar minimum, which recorded 1% and 19% of A-class flares in solar cycles 23 and 24, respectively. A similar distribution of solar flares is observed between the ascending and descending phases, with a low occurrence of X-class flares during all phases of solar cycle 23. The X-class flares recorded during cycle 24 are very rare, except at the maximum phases, where they represent 1% of the flares. Some studies have shown that highly energetic solar flares do not occur frequently on the surface of the Sun. According to these studies, over the last 125,000 years, fewer than 100 high-energy X-class solar flares have occurred [6] [34] [35]. Overall, we can deduce that solar cycle 24 recorded fewer intense solar flares (M and X-class) compared to solar cycle 23. Solar cycle 23 was magnetically more intense than solar cycle 24, showing significant seasonal variations in solar wind parameters and distinct differences in geomagnetic disturbances and solar plasma conditions. This reduced intensity during cycle 24 is reflected by a decrease in geomagnetic storms, illustrating a decline in magnetospheric energy transfer and the geoefficiency of solar plasma [36] [37]. This can be explained by the fact that the two solar cycles are antagonistic, with solar cycle 23 being magnetically more intense than solar cycle 24, as highlighted in [36] [38] [39]. Other authors have also found that solar cycle 23 was magnetically more intense than solar cycle 24 and attribute this difference to factors such as the decrease in helicoidal turbulence, despite the importance of bipolar magnetic regions in the dynamo model pip [40]. Some studies, on the other hand, emphasize that the decrease in the overall intensity and impulsive strength of geomagnetic activities observed during cycle 24 at all latitudes explains why solar cycle 23 was magnetically more intense than solar cycle 24 [41]. The findings regarding the greater abundance of X and M-class flares in cycle 23 compared to solar cycle 24 could justify these earlier results, which indicate that cycle 23 was magnetically more intense than solar cycle 24.

4. Conclusion

In this study, we have investigated the occurrence of different classes of solar flares (A, B, C, M, and X) during solar cycles 23 and 24. From our findings we can observe solar cycle dependence in each type solar flare class: 1) predominance of A and B classes of solar flare during solar minimum phase; 2) predominance of C class during the ascending and the descending phases; 3) predominance of M and X classes during the maximum phase of a given solar cycle. One can particularly notice that the solar cycle 23 exhibited more intense solar activity, with a higher frequency of M and X solar flares class, compared to cycle 24, where B and C-class flares predominated. This indicates a significant decrease in solar activity during cycle 24, accompanied by a reduction in intense solar flares and geomagnetic storms. This trend highlights important implications for space weather, particularly regarding potential disruptions to satellite operations and GPS signals. The study underscores the ongoing importance of monitoring solar activity to protect terrestrial technological systems. It also emphasizes the need for continued research on solar cycles to better understand the underlying mechanisms of these variations and their impact on space weather.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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