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Investigation of Solar Energetic Particles (SEPs) Associated with X-Ray Solar Flares

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Abstract

In this study we focus on the relationship between Solar Energetic Particles (SEPs) and X-ray Solar Flares (SFs) during solar cycles 23 and 24. The data was obtained from relevant websites, and the SEP data was classified according to our predetermined criteria. SEP data was separately analyzed for each X-ray SF class. To investigate the relationship, the temporal variation analysis was performed initially, followed by cross-correlation analysis. The obtained findings are as follows: i) All data sets used in the study follow the average 11-year Solar Cycle, ii) as shown in Figure 1 there is an agreement between all SF groups and SEP groups. iii) It can be clearly stated that all three categorized SEPs are particularly influenced by X-class SFs. iv) The resulting time delays indicate that SEP events occur after the flares.

1. Introduction

The Sun is a highly active star that spends approximately 70% of its lifetime at moderate levels of magnetic activity, around 15-20% in periods of grand minima, and about 10-15% in grand maxima (Usoskin, 2017). These activity periods can be most clearly understood through variations in the Sunspot Number (SSN). Due to its long-term record and the well-defined nature of the sunspot cycle, it has proven to be quite useful. Advancements in technology over time have enabled the observation of relatively smaller structures on the Sun. These smaller features have contributed to the development of various parameters/structures to characterize solar activity. Examples of such parameters/structures include prominences, solar flares (SFS), and indirectly, solar energetic particles (SEPs).

Solar energetic particles are high-energy charged particles that occur during eruptive solar events, such as solar flares and coronal mass ejections (CMEs). In other words, during these events, there are temporarily increased electron, proton, and ion currents, which are referred to as solar energetic particle (SEP) events in the interplanetary (IP) space. The most energetic of these charged particles (500 MeV) can reach the Earth's magnetosphere (Miteva et al., 2017). However, whether an SEP event will be detected, for example near Earth, depends on the location of the main event on the Sun: eruptions on the western position of the solar disk are much more likely to result in an SEP event observed at Earth (Klein and Dalla, 2017).

During SEP events, there are two different particle accelerators originated from the sun. The first one is associated with the reconnection process during a solar flare, known as "Impulsive" events and the second one is related to shock acceleration directed by CMEs, known as "Gradual" events (Reames, 2013). Nearly all the shock- accelerated particles will ultimately propagate out beyond the orbit of Earth. These charged particles can impact the Earth's magnetosphere and cause changes in geomagnetic activity. They are important events from the point of space weather studies.

Solar flares are abrupt increases in brightness observed on the solar surface, caused by the rapid release of magnetic energy. The release of magnetic energy during solar flares can lead to various phenomena, such as the emission of radiation across the entire electromagnetic spectrum, from radio waves to gamma rays. These events can release amount of energy, often exceeding 10^{32} ergs, into space within a short time span of tens of minutes (Fletcher et al., 2011). Solar flares are classified based on their observed wavelength, and two common classifications are the Hα and X-ray classifications. The X-ray classification system ranges from 1 to 8 Å and is further divided into classes A, B, C, M, and X, with class X representing the most powerful flares and class A being the weakest. Each of these categories is subdivided into nine divisions and classifications are logarithmic in scale.

Solar flares occur in different layers of the Sun's atmosphere, including the corona, chromosphere, and transition layer. A flare's temporal evolution exhibits distinctive dynamical patterns as well. The impulsive phase is the time of greatest energy release, which expels mass from the chromosphere and adds it to the corona (Hudson, 2011) The duration of these events can vary, lasting anywhere from a few minutes to several hours.

In this study, we investigated the relationship between Solar Energetic Particles (SEPs) and different X-ray Solar Flare classes. Data and Methods are presented in Section 2, The Results in Section 3, and the Discussion and Conclusion in Section 4.

2. Data and Methods

2.1. Data

The datasets used in this study cover the period between 1996 and 2020 which is almost equal two solar cycles (SC23 and SC24). The SEP data, specifically proton flux greater than 10 MeV, were obtained from the NASA webpage (https://omniweb.gSFsc.nasa.gov/). X-ray Solar Flare number data were acquired from the Space Weather Prediction Center (https://www.swpc.noaa.gov/), while sunspot number data were downloaded from the Sunspot Index and Long-term Solar Observations (SILSO) (https://www.sidc.be/SILSO/home). All datasets were processed into daily and monthly versions for the subsequent analyses.

2.2. Methods

In this study, our initial step involved calculating the monthly total values of all available data for analysis. We specifically excluded the calculation of data points with missing proton flux values to ensure the accuracy of our analysis. The SEP data were further categorized into three distinct groups: 0-10 pfu, 10-100 pfu, and >100 pfu.

To obtain a visual understanding of the distribution, histograms were plotted separately for each category. Additionally, the classes C, M, and X from the X-ray Solar Flare data were added on these histograms for comparison.

We then proceeded to cross-correlation analyses. To explore the relationship between the two sets the cross-correlation analysis was performed. This analysis enabled us to determine correlation coefficient any possible time delay between datasets.

3. Results

Figure 1 shows the temporal variations of used data sets. From these plots, we can clearly observe two solar cycles. Especially for the 10-100 and 100> pfu solar energetic particles, it is observed that the solar cycles exhibit a double/multiple-peaked structures.

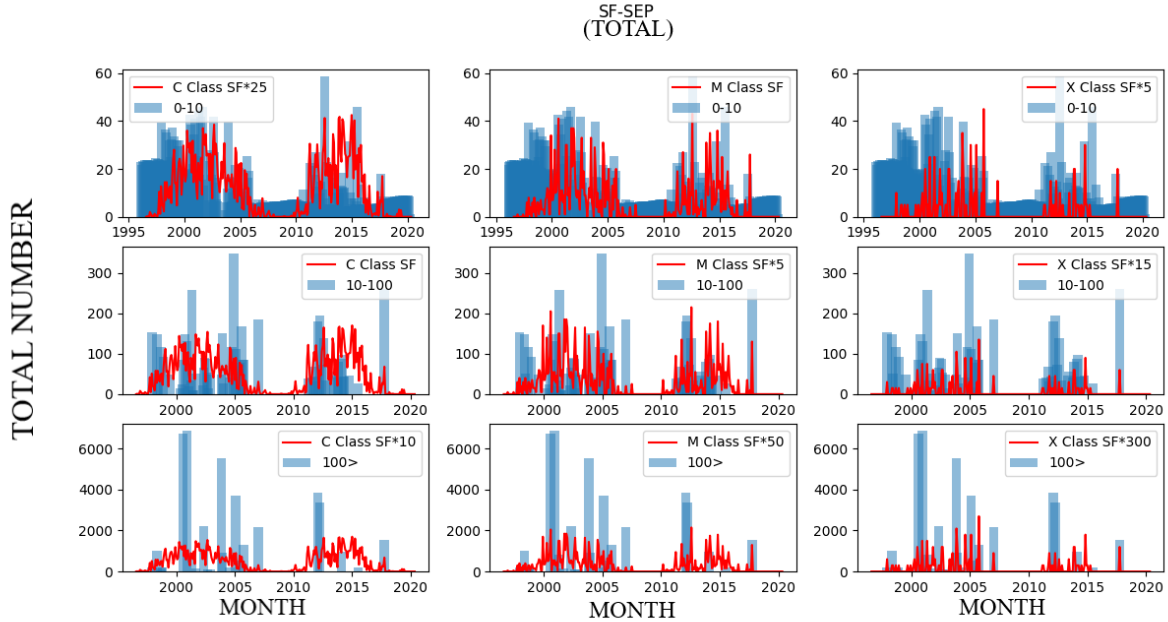

Figure1. Temporal variation plots of different class X-ray SFS and different categories of SEP events

Figure 2 plots the cross-correlation analysis results between different X-ray SFs and different SEP groups used in this study. The detailed results of the correlation analysis are given in Table 2.

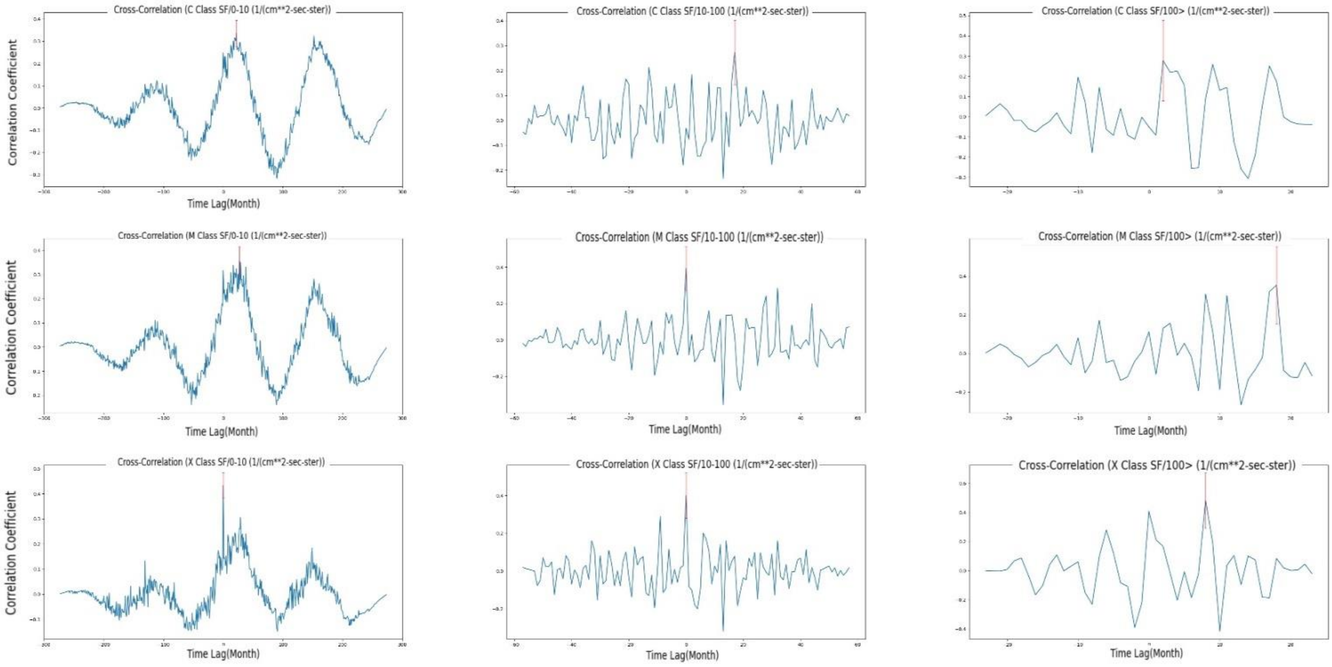

Figure2. Cross correlation analyses results between different X-ray SFS and SEP groups

The maximum peak in each graph represents the cross-correlation coefficient. The red line seen at the maximum correlation coefficient is the error bar. The error bars show the amount of standard errors.

Table1. Cross correlation coefficient and time delays

Cross correlation coefficient	0-10 pfu	Time Delay (Month)	10-100 pfu	Time Delay (Month)	100> pfu	Time Delay (Month)
C Class SFs	0.33±0.06	22	0.27±0.13	17	0.28±0.2	2
MClass SFs	0.37±0.06	27	0.39±0.12	0	0.35±0.2	18
X Class SFs	0.43±0.05	0	0.40±0.12	0	0.48±0.19	8

Based on Figure 2 and Table 1, we can conclude that X-class SFs are a source that influences all SEP groups.

In Figure 3, we compared the temporal variation of total SFs, SSN and SEPs. Here, it can be observed that both SFs and SSN are in good agreement with SEPs. The results of cross-correlation analysis can be found in Figure 4 and Table 2 for these data sets.

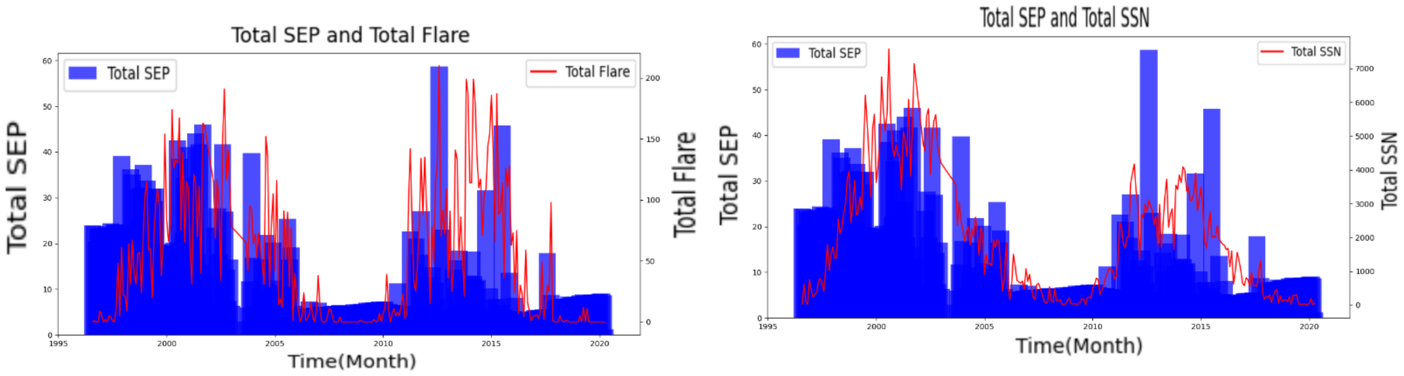

Figure3. Temporal variation plots (left: monthly total SEP and X-ray flare numbers, right: monthly total SEP and SSN)

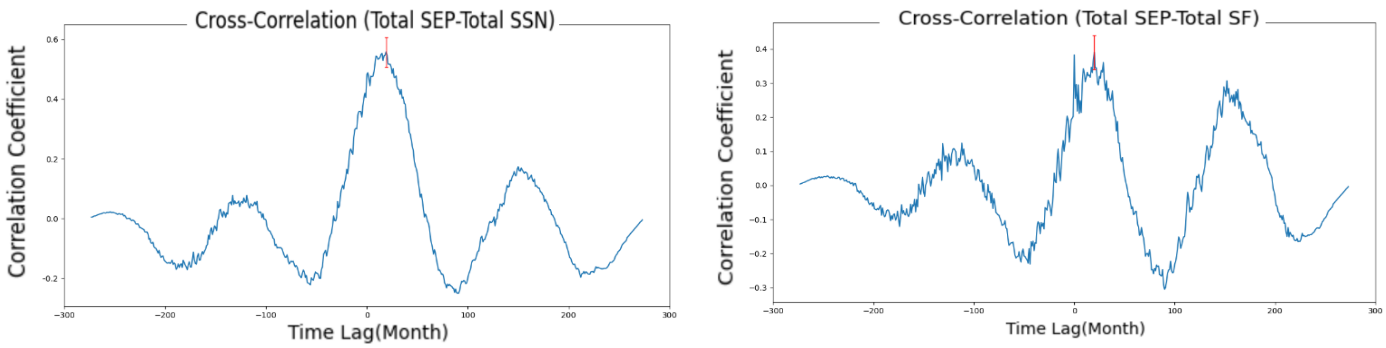

Figure4. Cross correlation analyses results (left: monthly total SEP and X-ray flare numbers, right: monthly total SEP and SSN)

Table2. Cross correlation coefficient and time delays

Cross correlation coefficient	**SFs**	**Time Delay (Month)**	**SSN**	**Time Delay (Month)**
SEP	0.39±0.06	20	0.56±0.05	19

When comparing Figure 4 and Table 2, there is a noticeable anomaly. However, this is not within the scope of this study. It will be explained in a follow-up study in the future.

4. Discussion and Conclusion

In this study, we have investigated SEP events and various X-ray Solar Flare classes. The findings of our study can be summarized as follows:

- All datasets used in the study follow the average 11-year Solar Cycle (Schwabe cycle).
- ii) iii) iv) as shown in Figure 1 there is an agreement between all SF groups and SEP groups. The correlation coefficient between SFS and SEP were also significant during the investigated time period (1996-2020).
- It can be clearly stated that all three categorized SEPs are particularly influenced by X-class SFs. The resulting time delays indicate that SEP events occur after the flares. While SSN data show a higher correlation than the X-ray SFs, this correlation mainly results from the 11-year cyclic trend. However, further examination of this relationship will be conducted in the forthcoming article.

As stated in Section 1, the primary sources of SEP events are CMEs and SFs. During times of high solar activity, there is a stronger correlation between the energies of CMEs and the X-ray flux of the flares they are associated (Youssef, 2012). Dierckxsens et al. (2015) found that events connected to large X-class flares, western solar longitudes, CMEs with high velocities, and halo CMEs typically have significantly higher possibilities of causing SEPs. In light of the influence of CMEs, we intend to expand this research in the future by introducing supplementary analyses, thus creating a follow-up to this paper. By doing so, we are planning to enhance the scope of our study considering the effects of CMEs.

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