DOI: 10.31401/WS.2024.proc.05

Investigation of Potential Sources of Solar Energetic Particles (SEPs)

Tirnakci M.[1], Asenovski S.[2], Kilcik A.[1]

[1]Department of Space Science and Technologies, Akdeniz University Faculty of Science, 07058, Antalya, Turkey, e-mail: meliketirnakci@gmail.com
[2]Space Research and Technology Institute BAS, Sofia, Bulgaria

Abstract

Solar Energetic Particles (SEPs) are one of the key components of space weather, and if they can be predicted; it may be easier to find ways to protect against their negative effects such as single event, satellite drag, communication, etc. SEPs mainly originate from solar flares and coronal mass ejections and it is known that solar flares are strongly related to sunspots. Therefore, first we investigated the solar proton event (SPE) production potential of sunspot groups based on the McIntosh classification system; we examined the solar proton production potential of the Zurich class, type of penumbra and the compactness of groups. Finally, we applied period analysis to SEPs to detect their periodic behavior. Obtained periodicities were compared with well-known solar activity periodicities. Our findings are as follows: i- Sunspot classes; class F has the highest SPE production potential (1.7%), while class B has the lowest potential (0.08%). Penumbra types; class k has the highest SPE production potential (2.02%), while r and x have the lowest (0.04%). Interior spot distribution; class c has the highest SPE production potential (2.32%), while class x has the lowest (0.06%). ii- The 25–34-day periods seen in SEPs show that SEPs are dependent on solar rotation. iii-51-63 days and 221-241 days periodicities were observed. The period of 51-63 days is known as solar flare periodicity, while the period of 221-241 days is known as coronal mass ejection (CME) periodicity.

Keywords: Solar energetic particles; Solar activity; Solar convection.

Introduction

Space weather has gained increasing importance with the development of technology in recent years, enabling more detailed research and a deeper understanding of this field. The most critical source for comprehending space weather is undoubtedly the Sun. Solar phenomena such as sunspots, solar flares, and CME have become better understood thanks to advancements in science and technology. Besides these phenomena, SEPs originating from solar flares and CMEs are an important component of space weather.

SEPs are referred to as accelerated protons, electrons and heavy nuclei, such as He and Fe, in the interplanetary medium and are caused by solar flares and CMEs (Malandraki and Crosby, 2018). There are two particle accelerators thought to be of solar origin in SEPs. One produces impulsive SEPs generated by magnetic reconnection during solar flares or jets, while the other is triggered by shock waves generated by fast CMEs that cause larger gradual SEP events, which produce the highest SEP intensities near Earth (Reames, 2013). High-energy (around 1 GeV) SEP events can result in increased proton fluxes even at ground level (Temmer, 2021). Thus, we can say that SEPs are mostly composed of protons. The main subclass of SEPs that focus only on protons are Solar Proton Events (SPEs) and are characterized by protons >10 MeV. These charged particles can affect the Earth's magnetosphere, ionosphere and life on Earth. These are important phenomena to be taken into account in space weather studies.

Understanding the behavior and origins of SEPs requires a closer look at solar activity, especially sunspots and sunspot groups. Sunspots are transient phenomena that appear as darker spots on the Sun's photosphere compared to the surrounding areas. These regions have strong magnetic fields that reduce the convective flow of plasma, making them cooler than their surroundings (Sahin, 2023). Occasionally, they may also appear in groups on the solar disc. Sunspot groups are defined as the sum of sunspots belonging to the same magnetic flux group. Such regions of strong magnetic field are closely linked to solar activity and have a significant influence on the formation of solar flares and CMEs. Historically, many classification methods have been used to classify sunspot groups such as Cortie, Mount Wilson, Zurich and McIntosh. The McIntosh classification, known as Zpc and Z is the Zurich classification, focuses on sunspot evolution, the parameter p describes the penumbra, and the parameter c indicates the complexity of the sunspot distribution inside a group. Marroquin et al. (2023) carried out research on active regions (ARs) and SEP. They discovered a significant correlation between SEP and several factors: the complexity of the magnetic field of ARs, the longitudinal position of the largest sunspot, the area of ARs, and the type of penumbra.

In this study, we investigated the relationship between SEP, SPE and sunspot groups. The study is organized into four sections: 1. Introduction, 2. Data and Method, 3. Results, and 4. Conclusion and Discussion.

Data and Methods

In this study, SEP, SPE and sunspot groups data of Solar Cycle 23 (SC23) and SC24 were used (1996-2020). As SEP data, the >10 MeV proton flux was used and 128 SPE events for the years 1996-2020 are taken from Space Weather Prediction Center (SWPC, https://www.swpc.noaa.gov/). Sunspot groups were also taken from SWPC and checked on the Solar Monitor webpage (https://www.solarmonitor.org/). All datasets were converted into daily and monthly versions for further analyses.

To fill gaps in the SEP data, we initially applied cubic spline interpolation for periods of less than three days. Next, we examined the temporal variations to compare daily SEP and SPE data and eliminated discontinuities by considering non-SPE days at minimum SPE energy. Then, we calculated cross-correlation coefficient. To further our understanding of SEP sources, we used the Multi-Taper Method (MTM) analysis on the continuous SEP data. The error for significant periods identified through MTM was calculated using the following equation developed by Lou et al. (2003):

$$\Delta P = -P\frac{\Delta\omega}{\omega}$$

where P represents the period, $\Delta\omega$ is the full width at half maximum of the corresponding peak, and ω denotes the frequency. Finally, we classified the sunspot groups from which SPEs originate, including solar flare, CME and filament eruption.

Results

As the first result of our study, the histogram of SEP and SPE is presented in Figure 1. As can be seen from this figure, both SEP and SPE clearly show the sunspot cyclic variation and a very high correlation (r=0.8) with each other.

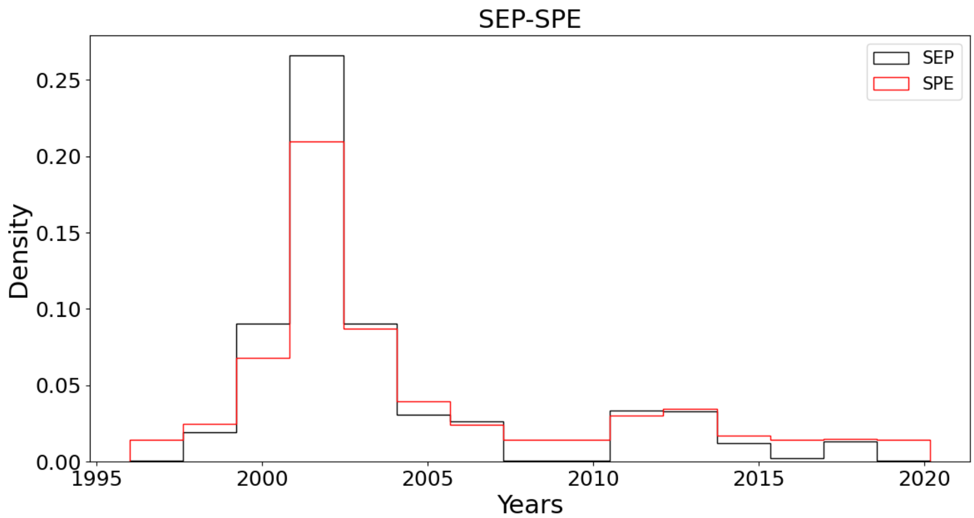

Figure 1. *Histogram plots of SEP and SPE*

However, SEP and SPE number density in SC23 is stronger than SC24. The study by Chandra et al. (2013) has a similar conclusion and suggests that higher density events in SC23 are associated with a higher level of solar activity in that cycle compared to SC24.

Figure 2 shows the MTM analysis result. As a result of the period analysis, significant periods and their significance levels are given in Table 1.

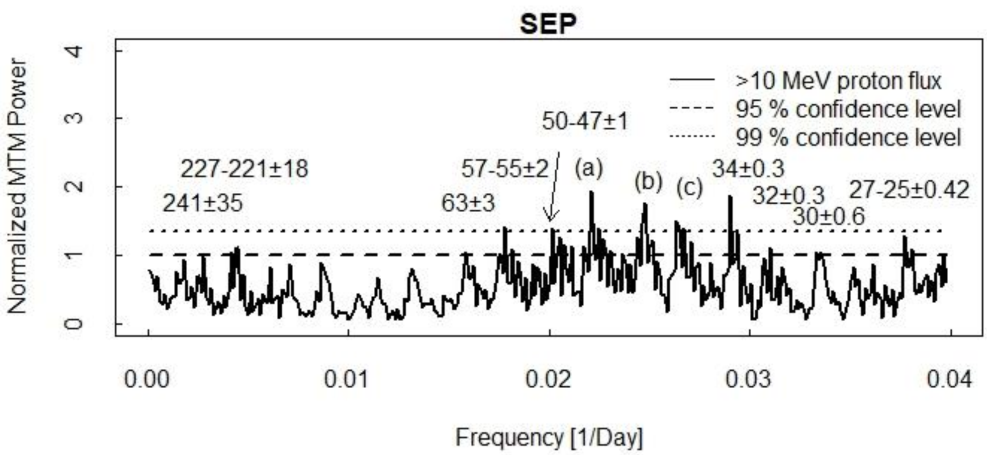

Figure 2. *MTM period analysis power spectrum of SEPs. In Figure;* ***a)*** *45±1;* ***b)*** *42±0.66;* ***c)*** *38-37±1*

Table1. Obtained significant periods and their significance levels.

Period (Days)	SEP
241 (1)	>95%
221-227 (1)	>95%
63 (2)	>95%
55-57 (2)	>99%
47-50 (2)	>99%
45	>99%

42	**>99%**
37-38	**>99%**
34 (3)	**>99%**
32 (3)	**>95%**
30 (3)	**>95%**
25-27 (3)	**>95%**

Specifically, periods 1 denote the CME periods, periods 2 represent the solar flare periods, and periods 3 correspond to the solar rotation periods. It is remarkable that the 356-day and 546-day periods in SEPs are significant at the 90% confidence level. These periods are also characterized by CME activities. However, for the purposes of this study, we have chosen to use a 95% confidence level.

In the final stage of the study, we categorized the SPEs according to the sunspot groups they originated from, as shown in Table 2. This table includes solar flares, CMEs and filament eruptions.

Table 2. Sunspot groups from which eruptive phenomena-induced SPEs originate

p and c parameter / Z parameter	**x**						**o**						**i**						**c**					
	x	**r**	**s**	**a**	**h**	**k**	**x**	**r**	**s**	**a**	**h**	**k**	**x**	**r**	**s**	**a**	**h**	**k**	**x**	**r**	**s**	**a**	**h**	**k**
A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	-	-	-	-	-	-	**2**	-	-	-	-	-	**1**	-	-	-	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	-	**1**	**3**	**5**	**1**	**1**	-	-	-	-	-	-	-	-	-	-	-	-
D	-	-	-	-	-	-	-	-	**3**	**5**	**1**	**4**	-	-	**1**	**4**	-	**9**	-	-	**2**	**1**	-	**7**
E	-	-	-	-	-	-	-	-	**1**	**2**	-	**1**	-	-	**1**	**3**	**1**	**9**	-	-	-	**2**	**1**	**10**
F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	-	**4**	-	-	-	-	**2**	**13**
H	-	-	**4**	**2**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

For instance, there are 13 SPEs originating from the Fkc sunspot group. However, it is important to note that not all proton events occur on the observable solar disk. Some events originate from regions behind the disk or from spotless active regions (see Table 3).

Table 3. SPEs from other sources

SPE Cause	**Number**
Events not associated with AR	**5**
Spotless AR	**1**
Behind	**7**
Unknown	**7**

In the SPE source shown in Table 2, especially the proton events seen behind the solar disc are numerous.

Discussion and Conclusion

In this study, we have investigated SEP, SPE and related sunspot groups. The findings of our study can be summarized as follows:

- Sunspot class F has the highest SPE production potential (1.7%), while classes B have the lowest potential (0.08%). According to penumbra type, class k has the highest SPE production potential (2.02%), while r and x have the lowest (0.04%). According to the compactness of the interior of the sunspot, class c has the highest SPE production potential (2.32%), while class x has the lowest (0.06%).
- The 25–34-day periods seen in SEPs show that SEPs are dependent on solar rotation.
- 51-63 days and 221-241 days periodicities were observed. The period of 51-63 days is known as solar flare periodicity, while the period of 221-241 days is known as coronal mass ejection (CME) periodicity.

SEPs will continue to be of interest in the coming years as they are an important component of space weather. As they are thought to originate from solar flares and CMEs, analyzing the sunspots from which SEPs originate will provide a better understanding of them. Although the 37-38, 42 and 45-day periods observed in SEPs are not fully explained in the literature, Kilcik et al. (2010) found 37-day periods in SC21 and 42-day periods in SC22 in the flare index data. Therefore, it would not be wrong to associate these periods with solar flare. Bronarska and Michalek's (2017) analyzed of 84 major SEP events revealed that these events typically originate from large bipolar structures (sunspot groups C, D, E, F in the McIntosh classification) and asymmetric sunspots, with the most energetic SEPs exclusively detected from active regions characterized by exceptionally large and complex penumbrae. Additionally, they found that active regions associated with eastern SEP events are larger than those linked to western SEP events, alongside a noted north-south asymmetry in SEPs.

Accurate predictions of such energetic particles will become more and more valuable. Therefore, it is important to extend the scope of the study and to include CMEs and solar flares.

References

Bronarska, K., & Michalek, G. (2017). Characteristics of active regions associated to large solar energetic proton events. Advances in Space Research, 59(1), 384-392.

Chandra, R., Gopalswamy, N., Mäkelä, P., Xie, H., Yashiro, S., Akiyama, S., ... & Nitta, N. V. (2013). Solar energetic particle events during the rise phases of solar cycles 23 and 24. Advances in Space Research, 52(12), 2102-2111.

Kilcik, A., Özgüç, A., Rozelot, J. P., & Ataç, T. (2010). Periodicities in solar flare index for cycles 21–23 revisited. Solar Physics, 264, 255-268.

Malandraki, O. E., & Crosby, N. B. (2018). Solar energetic particles and space weather: Science and applications. Solar particle radiation storms forecasting and analysis: the HESPERIA HORIZON 2020 project and beyond, 1-26.

Marroquin, R. D., Sadykov, V., Kosovichev, A., Kitiashvili, I. N., Oria, V., Nita, G. M., ... & Ali, A. (2023). Statistical study of the correlation between solar energetic particles and properties of active regions. The Astrophysical Journal, 952(2), 97.

Reames, D. V. (2013). The two sources of solar energetic particles. Space Science Reviews, 175, 53-92.

Sahin, S. (2023). An observational investigation of coronal rain in the quiescent and flaring solar corona (Doctoral dissertation, Northumbria University).

Temmer, M. (2021). Space weather: The solar perspective: An update to Schwenn (2006). Living Reviews in Solar Physics, 18(1), 4.