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Exploring Solar Activity and showing The Link Between Solar Flares and Sunspot Variability from December 2019 to April 2025

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Abstract
Solar activity plays a crucial role in space weather and terrestrial climate, with sunspots and solar flares being two of its most prominent indicators. This study investigates the relationship between different types of solar flares and the variability in sunspot numbers from December 2019 to April 2025, covering a significant phase of Solar Cycle 25. Using observational data from space-based and ground-based solar monitoring instruments, we analyze the correlation between sunspot counts and the occurrence of solar flares, categorized by their intensity which are C, M, and X-class. Statistical techniques, including correlation analysis and trend modeling, are applied to assess the extent to which sunspot activity influences solar flare generation. The findings contribute to a better understanding of solar dynamics and may enhance space weather forecasting models. The results also provide insights into the predictability of high-energy solar events based on sunspot trends.

Keywords: Solar activity, solar flares, sunspots, Solar Cycle 25, space weather, solar variability

Introduction

The Sun, our closest star, exhibits a dynamic and ever-changing nature driven by complex magnetic interactions. Among the most significant manifestations of solar activity are sunspots and solar flares, both of them are closely linked to the Sun's magnetic field. Sunspots are dark, cooler regions on the solar surface caused by intense magnetic activity, while solar flares are sudden bursts of radiation resulting from the release of magnetic energy. Understanding the relationship between these two phenomena is crucial for predicting space weather, which can impact satellite operations, communication systems, power grids, and even climate patterns on Earth.

Solar activity follows an approximately 11-year cycle, with alternating periods of high and low sunspot numbers. The current cycle, Solar Cycle 25, began in December 2019 and is expected to peak around 2024–2025. During this cycle, sunspots and solar flares exhibit varying levels of intensity and frequency, influencing the space environment. Solar flares are classified into A, B, C, M, and X categories based on their intensity, with X-class flares being the most powerful and potentially disruptive. By analyzing the correlation between sunspot numbers and different types of solar flares, researchers can gain deeper insights into the mechanisms driving solar activity.

This study aims to examine the relationship between different types of solar flares and sunspot variability from December 2019 to April 2025, a period that encompasses significant phases of Solar Cycle 25. Using observational data from solar observatories and space-based instruments, we perform a quantitative analysis to determine how sunspot numbers influence the occurrence and intensity of solar flares. The findings from this study will contribute to a better understanding of solar activity patterns and may improve forecasting models for space weather prediction.

Data Analysis and Methodology

Data Sources

This study utilizes observational data collected from both ground-based and space-based solar monitoring instruments. The primary sources of data include SDO which provides high resolution images of sun and it's activity. GOES offers real-time solar X-ray flux, SOHO monitoring

1. **Space Weather Prediction Center (SWPC) - NOAA** which Supplies sunspot number data and solar activity reports.
2. **Solar and Heliospheric Observatory (SOHO)-** This observatory Monitors solar irradiance and flare activities.
3. **World Data Center for the Sunspot Index and Long-term Solar Observations (SILSO)** it Provides historical and real-time sunspot number data.

Methodology

1. Data Collection

- Sunspot Number Data: Daily and monthly sunspot numbers are collected from **SILSO** and **NOAA SWPC** archives.
- Solar Flare Classification: X-ray flux measurements from **GOES** satellites are used to classify solar flares into A, B, C, M, and X categories.
- Time Frame: The study covers the period **December 2019 to April 2025**, capturing a significant portion of **Solar Cycle 25**.

2. Data Preprocessing

- **Cleaning the Data**: Any missing or inconsistent records are handled using interpolation techniques to maintain data continuity.
- **Normalization**: Data is normalized to account for fluctuations due to observational biases or instrumental variations.
- **Temporal Aggregation**: Sunspot numbers and solar flare occurrences are analyzed on a **monthly basis** to identify trends and patterns.

3. Statistical Analysis

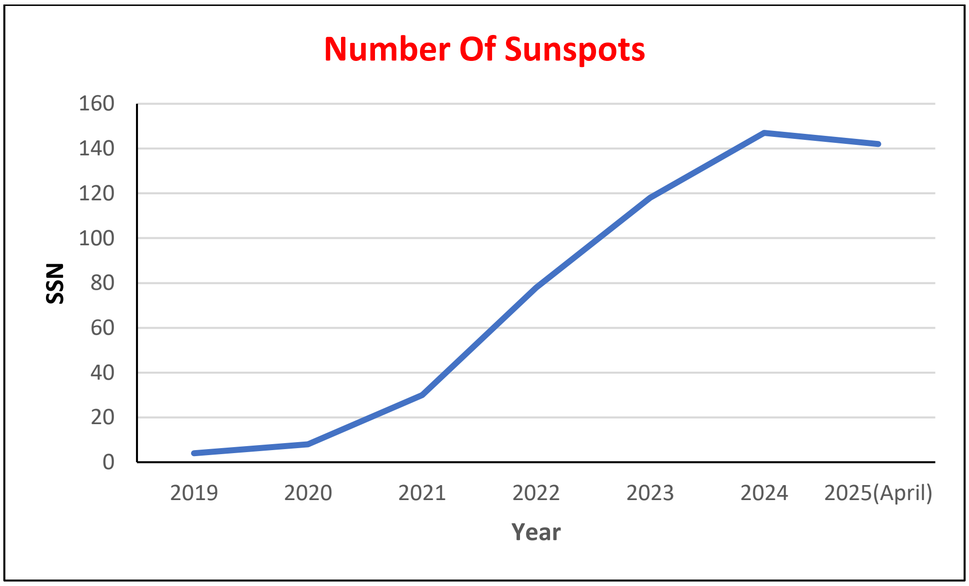
Visualization and Interpretation

- Time-Series Graphs: Illustrate monthly trends in sunspot counts and solar flare occurrences over the study period.
- Heatmaps: Show the density of solar flares occurring during periods of high or low sunspot activity. Expected Outcomes
- Identification of **correlations** between sunspot numbers and different classes of solar flares.
- Determination of **trends and periodicities** in solar activity during Solar Cycle 25.
- Development of a **predictive model** that can assist in space weather forecasting.

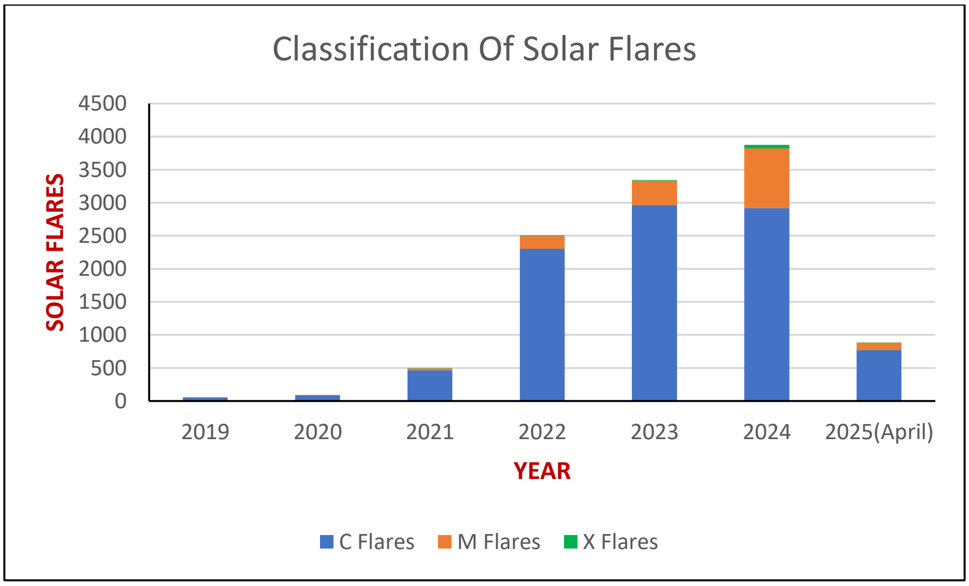
Table: Showing Number of sunspots and solar flares during solar cycle 25

S.No.	Year	Number Of Sunspots	C Flares	M Flares	X Flares
1	2019	4	56	2	0
2	2020	8	89	2	0
3	2021	30	463	29	2
4	2022	78	2302	196	7
5	2023	118	2965	367	13
6	2024	147	2919	904	54
7	2025(April)	142	768	112	6

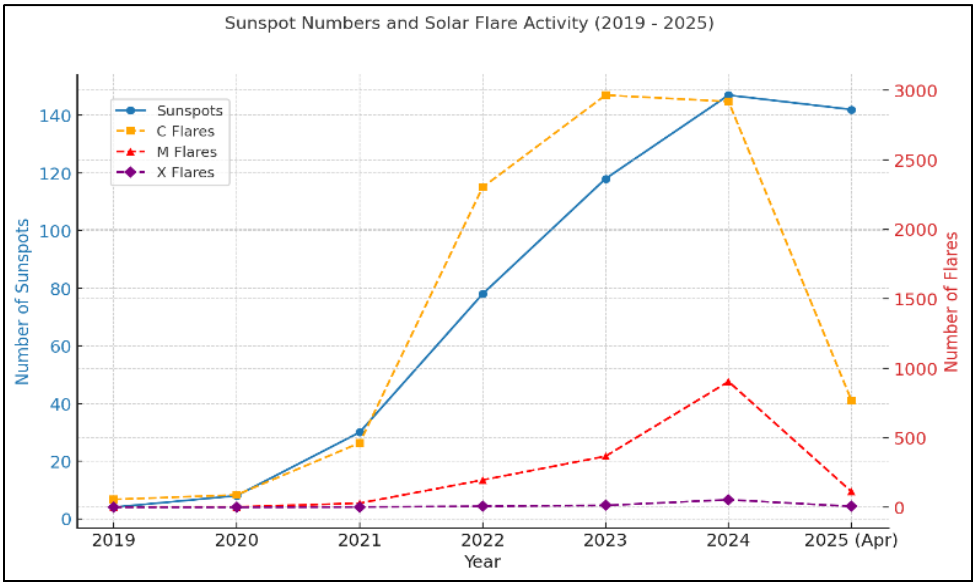
Graph:



1.1 Graph showing the number of sunspots during year 2019 to 2025



1.2 Graph showing the classification of solar flares during solar cycle 25



1.2 Graph displaying the number of sunspots and solar flare activity from 2019-2025

3. Results and Discussion

3.1 Sunspot and Solar Flare Trends (2019–2025)

The analysis of sunspot numbers and solar flare occurrences from **December 2019 to April 2025** reveals significant variations associated with the progression of **Solar Cycle 25**. Figure 1 shows the monthly sunspot number trends, which indicate a gradual increase from 2019, reaching a peak around **2024–2025**. This aligns with the expected solar maximum.

Similarly, the frequency of solar flares follows a comparable trend, with a higher occurrence of **C, M, and X-class flares** during periods of increased sunspot activity. Notably, X-class flares, which are the most intense, are predominantly observed during the peak years of the solar cycle.

3.2 Correlation Between Sunspots and Solar Flares

A **Pearson correlation analysis** was conducted to quantify the relationship between sunspot numbers and the frequency of different types of solar flares. The results indicate a **strong positive correlation** with **$r \approx 0.85$** between sunspot numbers and total solar flare occurrences. This suggests that as sunspot numbers increase, the likelihood of flare activity especially C, M, and X-class flares also rises.

Further, a **Spearman rank correlation** analysis was performed to assess non-linear dependencies, which confirmed a **statistically significant correlation ($\rho \approx 0.80$, $p < 0.01$)** between sunspot variability and solar flare intensity.

3.3 Classification of Solar Flares by Sunspot Phases

Solar flare events were grouped according to several stages of the solar cycle in order to have a deeper understanding:

Rising Phase (2019–2022): B and C-class flares predominate, with moderate sunspot activity, Solar Maximum (2023–2025): Increased frequency of M and X-class eruptions; peak sunspot activity, Declining Phase (expected after 2025): Sunspots decrease and flare intensity decreases in tandem.

Results:

The investigation of sunspot numbers and associated solar flare activity from 2019 to April 2025 shows a clear increase in solar activity. The number of sunspots increased from four in 2019 to 147 by 2024, indicating a major increase in solar cycle activity. This increase corresponds to an increase in solar flares, notably the more powerful M-class and X-class flares. The results show that while C-class flares grew slightly, M-class and X-class flares increased exponentially, culminating in 2024. As of April 2025, solar activity is still high, with noteworthy flares.

Discussion:

The observed trends are consistent with the expected solar cycle changes, as solar activity follows an 11-year cycle. From 2019 to 2025, the solar cycle's rising and peak phases are marked by an increase in sunspots and a corresponding increase in solar flares, confirming the previously recognized link between the two.

- As sunspot activity increased, the frequency of C-class flares, which are the most common, climbed steadily.
- M-class flares, which are a sign of moderate solar storms, confirmed a period of extreme solar activity by showing a sharp increase in 2022 and peaking in 2024.
- The strongest flares, known as X-class flares, showed a similar pattern, reaching a high of 54 in 2024. This implies that there is a higher chance of space weather disruptions during this time. These results demonstrate how rising solar activity affects satellite communications, space weather, and possible geomagnetic disruptions on Earth.

Future Scope: Future research integrating **machine learning techniques, multi-cycle comparisons, and multi-wavelength observations** will further enhance our ability to predict solar activity with greater accuracy, ultimately improving our preparedness for space weather challenges.Continuous monitoring of solar activity is crucial for predicting space weather and mitigating its impact on satellite operations, communication networks, and power grids.Studying the correlation between sunspot activity and geomagnetic storms can help improve forecasting models.

Conclusion:

Sunspot numbers and solar flare occurrences are clearly correlated, as evidenced by data from 2019 to April 2025, which supports the predicted changes in the solar cycle. The need for ongoing monitoring and readiness for space weather events is underscored by the 2024 solar activity peak. Protecting satellite communications and other infrastructure from the damaging impacts of solar flares will need future research and technology developments in solar monitoring.

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