Investigation of the Relationship between Solar Flares and Sunspot Groups

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Abstract: We studied the relationship between X-Ray flare numbers (C, M, and, X class flares) and sunspot counts in four categories (Simple (A + B), Medium (C), Large (D + E + F), and End (H)). All data sets cover the whole Solar Cycle 23 and the ascending and maximum phases of Cycle 24 (1996-2014). Pearson correlation analysis method was used to investigate the degree of relationship between monthly solar flare numbers and sunspot counts observed in different sunspot categories. We found that the C, M, and X class flares have highest correlation with the large group sunspot counts, while the small category does not any meaningful correlation. Obtained correlation coefficients between large groups and C, M, and X class flare numbers are 0.79, 0.74, and 0.4, respectively. Thus, we conclude that the main sources of X-Ray solar flares are the complex/large sunspot groups.

Keywords: sunspots, flares, geomagnetic indices, solar activity

1. Introduction

Sunspots are the product of intense magnetic field consisting interior of the Sun deriving extends to the surface. They are temporary phenomenon which lives from a few days to a few months. Sunspots have two parts: First, the umbra, which is the darkest part in the center, where the magnetic field is vertical to the Sun's surface. Second, the penumbra, which is lighter than umbra, where the magnetic field is more inclined. Sunspots have been observed and recorded regularly since the invention of the telescope in 1610 (Vaquero, 2007). They classified in several ways according to various parameters as follows: morphology, evolution, spot size, longitudinal extension of the group, sunspot distribution inside the group, the presence or absence of penumbra in the group, complexity, etc. They were first classified by Cortie (1901) according to their shapes. Later to describe sunspot morphology and evolution Waldmeier (1938; 1955) introduced the Zurich classification schema. Finally, to better describe the sunspot and flare activity McIntosh (1990) modified Zurich classification schema, which is used today. This classification schema is fundamentally based on three parameters: The first one is describing the morphology and evolution of a group, the second parameter is clarifying the shape of the biggest spot in the group and the third one is defining the distribution of spots inside a group. According to the first parameter of this classification, sunspot groups divided into seven classes:

A: Unipolar group with no penumbra, representing either the formative original stage of evolution in a spot group.

B: Bipolar group without penumbra on any spot.

C: Bipolar group with penumbra on one end of the group, in most cases surrounding the largest of the leader umbrae.

D: Bipolar group with penumbra on spots at both ends of the group and the longitudinal extension of the group is smaller than 10 degrees (longitudinal extension ≤ 10°).

E: Bipolar group with penumbra on spots at both ends of the group and with length defined as: 10° < longitudinal extension ≤ 15°.

F: Bipolar group with penumbra on spots at both ends of the group and longitudinal extension > 15°.

G: Unipolar group with penumbra. The principal spot is usually the leader spot remaining from a pre-existing bipolar group.

A solar flare is a result from the release of free magnetic energy near the sunspots that sudden flash of brightness observed on the solar surface. Radiation is emitted across virtually the entire electromagnetic spectrum, from the long radio wavelength, through optical emission to X-rays and gamma rays at the short wavelength. The energy released during a flare is typically on the order of 10^{27} ergs per second. Large flares can emit up to 10^{32} ergs of energy (Fletcher et al. 2011). They affect the photosphere, chromosphere and corona, as well as the near space environment and the Earth. Solar flares are classified in two different ways as follows: the first one is Hα and the second is X-ray classification. Solar flares classified as A, B, C, M or X in X-rays according to their peak flux (W/m^2) of 1 to 8 Angstrom. The first solar flare was observed in a white light by Carrington (1859) and Hodgson (1859). This flare caused the largest geomagnetic storm (1760 nT) and damaged to the terrestrial telegram system (Loomis 1861; Tsurutani et al 2003). Lee et al. (2012) classified sunspot groups into two categories according to their areas as large and small. They classified these two categories into three sub-categories according to their area changes: decreasing, steadying, and increasing. They found that flare occurrence rate and probability in these categories increase with sunspot group area. The flare energy release to magnetic reconnection that occurs in arouse of coronal mass ejections (Moore et al 2001; Priest & Forbes 2002). CMEs are the major drivers for space weather and Earths environment. In addition to this, solar flares effect the solar energetic particles (SEP), flare-related irradiance enhancements and geomagnetic storms. Geomagnetic storms are measured by different indices such as: *Ap* (Bartels et al. 1939), *Dst* (Sugiura 1964), etc.

Kilcik et al. (2011a) analyzed the sunspot classification data in two categories as small (A+B+C+H) and large (D+E+F) from cycle 20 to cycle 23 (1966-2008). They found that the large group numbers correlate better with solar and geomagnetic activities. Later Kilcik et al. (2014) analyzed the sunspot classification data by further dividing them into four categories as "small" (A+B), "medium" (C), "large" (D+E+F) and "end" (H). They found that the temporal behaviors of these four categories are not the same.

The aim of this study is the investigation of the relationship between X-ray solar flares (C, M, and X), sunspot counts in four categories (small, medium, large and end) and geomagnetic indices (*Ap* and *Dst*). For this purpose, we used the sunspot counts in four categories as mentioned above, the X-Ray flares and the *Ap/Dst* geomagnetic indices data for the 1996-2014 time intervals.

In the next section (Section 2) we described data sets, presented their comparisons and obtained results. The discussion and conclusions are given in Section 3.

2. Data, Comparison, and Results

We used the solar flare data 1996 and 2014 obtained from http://www.solarmonitor.org/data/. The sunspot group data were taken from https://www.ngdc.noaa.gov/. The Ap data are taken from https://www.ngdc.noaa.gov/ and the Dst data are taken from the World Data Center for Geomagnetism at Kyoto University. Then, the monthly average values calculated for each type of X-Ray flares, sunspot counts for each category, and for geomagnetic indices. First, we investigated the temporal variation of the X-Ray flare numbers in different classes (C, M, X) and the sunspot counts in four sunspot categories during the investigated time period (see Figure 1). Then, the geomagnetic Ap/Dst indices and X-Ray flare numbers were compared (See Figure 2).

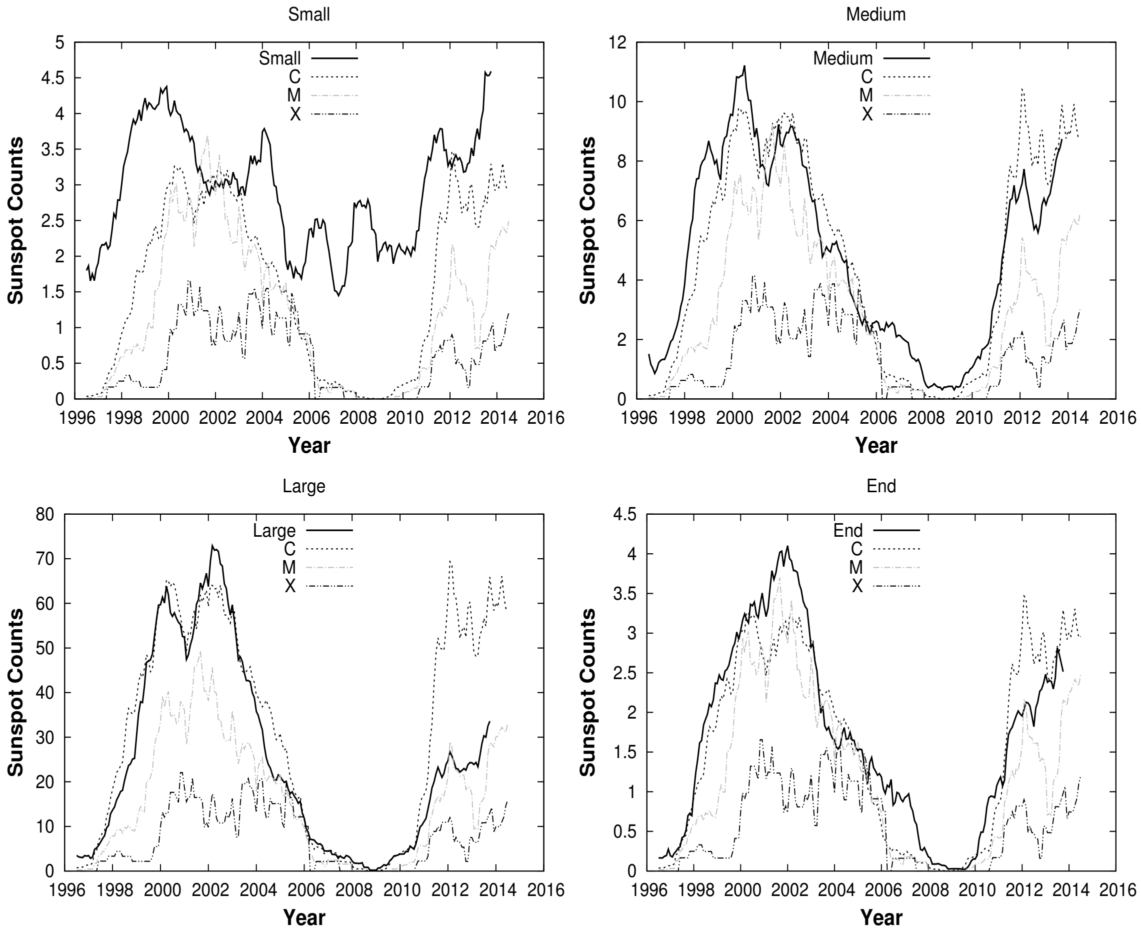

Figure 1. Comparisons of monthly mean flare numbers observed for different flare classes (C, M, and X) and sunspot counts in four sunspot group categories. To remove short term fluctuations and reveal the long term variations all data sets were smoothed with a 12 step running average filter. All flare data were rescaled for display purposes.

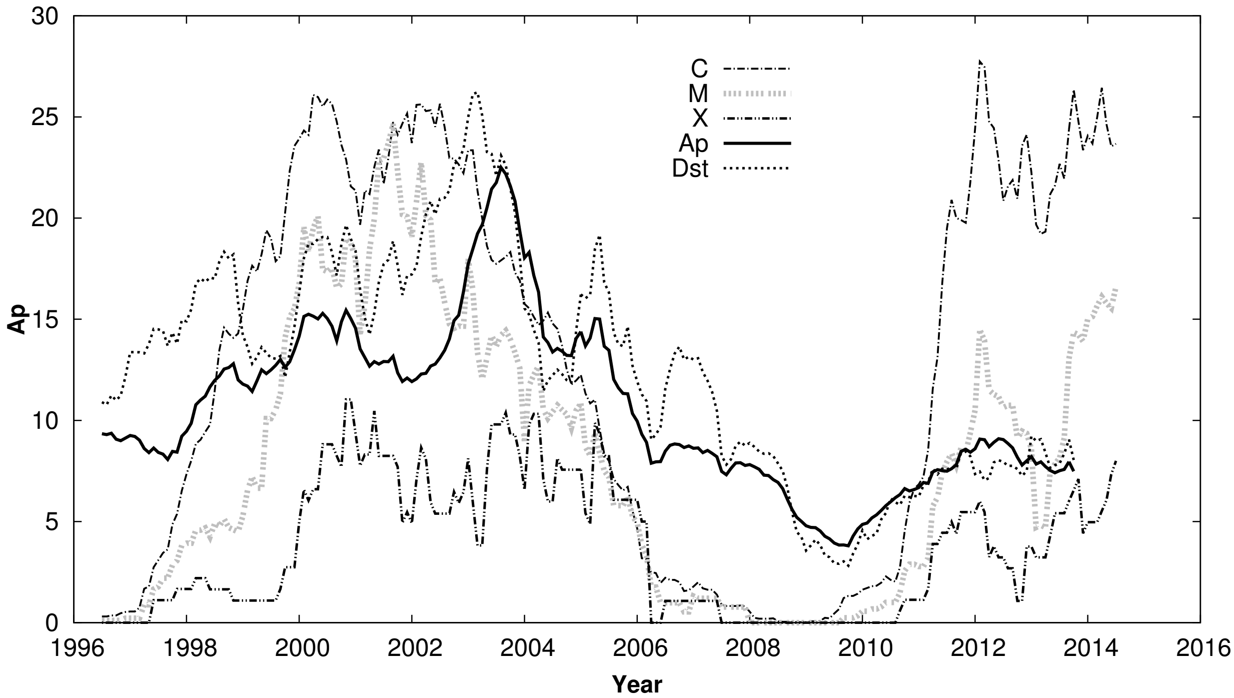

Figure 2. Temporal variation of geomagnetic indices (*Ap*, *Dst*) and each class X-Ray flare numbers (C, M, and X). Similar to Figure 1 all data sets were smoothed with a 12 step running average filter. For display purposes the sign of *Dst* index was reversed and all X-Ray flare numbers multiplied by 8, 40, and 200, respectively.

To obtain the degree of relationship between flare classes (C, M, X and Total) and sunspot counts in different categories we applied Pearson correlation analysis method. To obtain the significance limit Fisher's test were applied. We found that sunspot counts in large groups show the best correlation with flare classes (see Table 1), while there is no any meaningful correlation with sunspot counts in small category.

Table 1. The Degree of Relationship between Sunspot Groups and Different Flare Classes

Class	Small	Medium	Large	End
C	0.33 ± 0.14	0.70 ±0.08	0.79 ± 0.05	0.65 ± 0.08
M	0.10 ± 0.13	0.46 ±0.11	0.74 ± 0.07	0.49 ± 0.11
X	0.04 ± 0.13	0.23 ±0.13	0.40 ± 0.12	0.24 ± 0.13
Total (C+M+X)	0.31 ± 0.12	0.68 ±0.08	0.81 ±0.05	0.65 ± 0.08

There are some interesting points in these plots that we would like to mention: 1) Temporal variations of sunspot counts in different categories show big deviation during Solar Cycle 23, while they behave similarly during the current Solar Cycle 24. 2) Simple category sunspot counts and the number of X class flares have similar peaks during the descending phase of Solar Cycle 23 (around 2004). 3) Sunspot counts in medium and end categories and the number of M class flares show similar trend during the descending phase of Solar Cycle 23. In Cycle 24, all data sets show very good agreement. 4) Large category sunspot counts have double peak during the investigated cycles. 5) The C, M, and X class flares best correlate with the sunspot counts in large category. 6) The X class flare numbers have better correlation with geomagnetic indices (r = 0.53, *r* = -0.40 for Ap and Dst, respectively) compared to other ones.

3. Discussion and Conclusion

In this study, the relationship between X-Ray flare numbers for all classes and four categories of sunspot groups were analyzed. The main findings of this study are as follows:

1. Temporal variations of different class flares were different during Solar Cycle 23, while they behave similarly during the current Solar Cycle 24.
2. The C, M, and X class flares best correlate with the sunspot counts in large categories.
3. The temporal variations of Ap, Dst indices and all class flares show similar trends during the investigated time period (1996-2014), except the descending phase of Solar Cycle 23.
4. Geomagnetic Ap and Dst indices and the number of both M and X class flares decreased strongly during the Solar Cycle 24 compared to previous Solar Cycle 23.

Lee et al. (2012) found that the mean flare occurrence rates and flare probabilities noticeably increase with sunspot group area for all sunspot groups. In this study, we used the same categorization for the sunspot groups by Kilcik et al. (2014) and investigated the relationship between X-Ray solar flare numbers for different flare classes and sunspot counts in these categories. We confirm Lee et al. (2012) result and found that that the sunspot counts in large category show better relation with flare numbers (see

Table 1) and flare numbers increase with the spot complexity and size.

Recently, Javaraiah (2016) used sunspot group data from two different stations for 1874-2015 time periods. Author also analyzed sunspot groups for northern and southern hemispheres, and then classified the sunspot groups in three main categories according to their maximum areas and life times as “small”, “large” and “very large”. He reported that on the average ratio of the number of large to the number of small sunspot groups is larger in the ascending phases of Solar Cycles 24 than the same phase of Solar Cycle 23. We found that the number of C flares is comparable during the ascending phase of Cycle 23 and 24. Contrary the number of strong flares (M and X classes) decreased seriously in the same phases of this cycles. Thus, we may speculate that most of the large groups produced C flares during ascending phase of Solar Cycle 24.

Kilcik et al. (2011b) introduced the Maximum CME Speed Index (MCMESI) which is the measure of the linear speed of the fastest CME for a day. They compared this new index with geomagnetic *Ap* and *Dst* indices and found that this new index (MCMESI) shows higher correlation with geomagnetic activity indices (Ap, Dst) than International Sunspot Number (ISSN) during Solar Cycle 23 (see Table 1 in their paper). Later, Kilpua et al. (2014) analyzed geomagnetic *Dst* and *AE* indices during two periods around the last two solar minima and rising phases (1995-1999 and 2006-2012) and reported very low geomagnetic activity during the current solar cycle (Cycle 24). During the same year, Kilcik et al. (2014) compared monthly sunspot counts in four categories with ISSN. They found that both ISSN and large categories sunspot counts show significant decrease during the same solar cycle. Here, we compared monthly flare numbers with geomagnetic Ap and Dst indices and found that the number of M and X class flares decreased strongly during the solar cycle 24 compared to previous cycle (Cycle 23). Thus, we may conclude that the main source of powerful solar flares (M and X classes) are the large/complex sunspot groups (D, E, and F) and also these flares strongly related to geomagnetic Ap and Dst indices.

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