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STATISTICAL STUDY OF CONFINED FILAMENT/PROMINENCE ERUPTIONS DURING SOLAR CYCLE 23

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Abstract

Filament/prominence eruptions can have a significant impact on Earth's upper atmosphere and space environment, and are the primary drivers of what is now called space weather. To distinguish the different types of filament eruptions we statistically examine them during the 23rd Solar cycle. In this study we use 159 filament eruptions using the List of interplanetary (IP) Shocks Observed during Solar Cycle 23 (May 1996 – January 2008) and their Source Information Environmental Satellites (GOES) X-ray plots (see GOPALSWAMY et al. [15]). It is found that 69% of the filament eruptions are *confined* eruptions, while 31% are *ejective* eruptions. *Confined eruptions* are 110 and 34 events (21%). They are due to *active filaments* and 76 events (48%) are due to *disappearing filaments*. The occurrences of active and disappearing filaments during the increasing phase of solar cycle 23 is found to be 80% while in the decreasing phase they are 13%. We have found that the dominant *X-ray flare energy* of confined eruptions is that of C class. The most common *filaments field extent* is located between 5 and 15 degrees. The most common flare duration is between 16 and 40 minutes.

Key words: filament, confined eruption, CMEs, flare, Solar Cycle 23

Introduction. Filament is a collection of many threads, forming an apparent gigantic loop of cool dense gas that arches up over the photosphere [1]. They

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are formed in magnetic flux tubes that hold relatively cool (5000–8000 K) and dense plasmas (10^{10}–10^{11} cm^{-3}). These plasmas are suspended in the hot (10^6 K) corona above the solar surface. Even if filaments and prominences refer to the same physical structures on the sun, different terms are used based on their location on the sun

The term "filament" is used when they are observed in Hα and appear as dark ribbons against chromosphere, while the term "prominence" is used when they appear on the limb and are seen as bright features. Some filaments and prominences end their existence by eruptions (filament disappearance). Filament/prominence eruptions, flares, and coronal mass ejections (CMEs) are the most important solar events in the domain of space weather effects, linking solar eruptions, major interplanetary disturbances, and geomagnetic storms [2–8].

WANG and ZHANG [9] examined X-class flares that associated with CME for both confined and ejective eruption, and they found that about 90% of X-class flares are eruptive, but the remaining 10% are confined. Also, they studied the magnetic properties of these events both in the photosphere and in the corona, and they found that:

a) the confined events tend to occur closer to the magnetic centre, while the eruptive events tend to occur close to the edge of active regions;

b) calculations of the coronal magnetic field show that the ratio of the magnetic flux in the low corona to that in the high corona is systematically larger for the eruptive events than for the confined events.

JING et al. [10] presented a statistical study of 106 filament eruptions for the period 1999–2003. They excluded eight events because they were not corresponding to the Large Angle and Spectrometric Coronagraph (LASCO) data and showed that 55 events out of the remnant 98 (56%) were associated with CMEs. They also found that active region filament eruptions had a considerably higher flare association (95%) than quiescent filament eruptions with only 27% association. On the other hand, quiescent filament eruptions (85 events) were more likely to be accompanied by CMEs than flares.

YAN et al. [11] carried out statistical studies of 120 events. They found that 115 out of 120 (about 96%) filament eruptions were associated with flares. Fifty-six out of 105 (about 53%) filament eruptions are found to be associated with CMEs except for 15 events without corresponding LASCO data. Also, the average speed of the associated CMEs of filament eruptions increases with X-ray flare size: it raises from 563.7 km^{-1} for C-class flares to 1506.6 km^{-1} for X-class flares [12].

Confined and ejective eruptions. Because of the importance of Filament/Prominence eruptions and their close relation with CMEs and flares, it is interesting to investigate whether a clear signature X-ray flare class could be associated with either confined or ejective eruptions or not. The classification of X-ray flare class uses the letters A, B, C, M or X according to the peak flux in watts per square meter (W/m^2). Also, some properties of CMEs (speed and angular width) have to be studied to check if these properties could be associated with either confined or ejective eruptions or not. So, the purpose of this statistical study is to try to identify the eruption precursors for each type of eruption separately.

We have thus created a list of Filament/Prominence eruptions and carried a statistical analysis. In order to better understand the conditions that occur before and after Filament/Prominence eruptions the list was divided according to the presence of CME and flares:

(a) **Confined eruptions** that occur when the filament becomes unstable and rises to reach a terminal height and the filament material returns back to the solar surface without a CME ejected.

(b) **Ejective eruptions** that occur when the filament erupts, leading to the formation of a CME [13].

Another division is made for both confined and ejective eruptions on the basis of the filament status – **active or disappearing** – in order to predict occurrence of CMEs and flares and avoid their hazard.

The occurrence frequency of CMEs and flares is strongly modulated by the Solar cycle. Flares of any given size are some 50 times more frequent at solar maximum than at minimum. Large coronal mass ejections occur on average a few times a day at solar maximum, down to one every few days at solar minimum. The size of these events themselves does not depend sensitively on the phase of the solar cycle. A case in point are the three large X-class flares that occurred in December 2006, very close to solar minimum [14]. An X9.0 flare on Dec 5 stands as one of the brightest on record. We obtained this from the website:

The Most Powerful Solar Flares ever Recorded (`spaceweather.com`)

`https://www.spaceweather.com/solarflares/topflares.html`

In this paper we investigate only *confined eruptions.*

Data set and method of research. The following data sources have been used:

Starting from the List of IP Shocks Observed during Solar Cycle 23 and their Source Information detected during Solar cycle 23 (Gopalswamy et al. [15]), we identified CMEs associated with soft X-ray flares, and the eruption locations on the solar disk.

The GOES daily flare lists represent the events registered by GOES satellite. Currently only X-Ray activity events are considered. From the GOES flare list we identified the start and end times of flares as well as their class and NOAA region. We obtained this list from the website `ftp://ftp.swpc.noaa.gov/pub/warehouse/`.

Finally, the associated filament or prominence can be identified by consulting NOAA and the National Geophysical Data Center (now NOAA National Centers for Environmental Information (NCEI)) events lists. We obtained this list from the website `https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-`

`features/prominences-filaments/filaments/pdf_tables/`.

The data collected includes 159 filament eruptions in the period 1998–2011. These Filament/Prominence eruptions were selected due to availability of full information and criteria of the following:

- Filaments extent field;
- Its location on the solar disk;
- The start and end time of the filament eruption.

We connected the selected data with Gopalswamy's list and GOES flare list, to have a complete list for the Filament/Prominence eruptions associated with flare and CME.

The selected associated flares and CMEs must lie within NOAA region and approximately near (±5 degrees) in location.

We studied the list and obtained different parameters that will be considered in detail in the next section:

- Flare class
- Flare duration
- CME speed
- Angular width of CMEs
- Filament field extent

The filament extent field according to NOAA Filament/Prominence list means the filament length. For limb events (prominences) it is the radial extent above the limb in hundredths of solar radius. For disk events (filaments) this is the heliographic extent in whole degrees. All the eruptive prominences selected in our list have no extent field. So, the unit of extent field (filament length) is considered in whole degrees.

Table 1

A. Distribution of filament/prominence eruptions

Type of eruption	Active filament	Disappearing filament	Total No. of observations
Confined eruptions	34 (21%)	76 (48%)	110 (69%)
Ejective eruptions	9 (6%)	40 (25%)	49 (31%)
Total No. of observations	43 (27%)	116 (73%)	159 (100%)

B. Distribution of the observations of active and disappearing filaments during the increasing (1998–2002) and decreasing (2002–2011) phase of Solar cycle 23

Solar cycle 23	Active filament	Disappearing filament	Total No. of observations
Increasing phase (1998–2002)	31 (19%)	96 (60%)	127 (80%)
Decreasing phase (2002–2011)	12 (0.8%)	20 (20%)	32 (13%)
Total No. of observations	43 (27%)	116 (73%)	159 (100%)

Filament eruption associations. Distribution of samples. Out of the 159 complete observations of the filament eruptions studied in this work, 69% were found to be confined eruptions while 31% were ejective eruptions. Table 1a shows the distribution of both confined and ejective filament/prominence eruptions:

• In the case of **confined** eruptions, there are 34 events (21%) due to **active** filaments and 76 events (48%) are due to **disappearing** filaments.

• In the case of **ejective** eruptions: 9 events (6%) are due to **active** filaments and 40 events (25%) are due to **disappearing** filaments.

We calculate the number of observations of active and disappearing filaments during the increasing phase of Solar cycle 23 (1998–2002) and during its decreasing phase (2002–2011) in order to compare them. The comparison is shown in Table 1B.

Figure 1 shows the annual distribution of confined and ejective filaments, respectively, for the period 1998–2011. It can be clearly seen that there are no ejective eruptions in the beginning of solar cycle 24 (2008 until 2020). This is probably because the sun is then at the minimum of its cycle phase.

Association between confined eruptions and flares. Here we investigate the confined filament eruptions, which are 69% of the 159 complete observations of filament eruptions we use.

The confined eruptions are divided into two categories:

1) Flares associated with active filaments.

2) Flares associated with disappearing filaments.

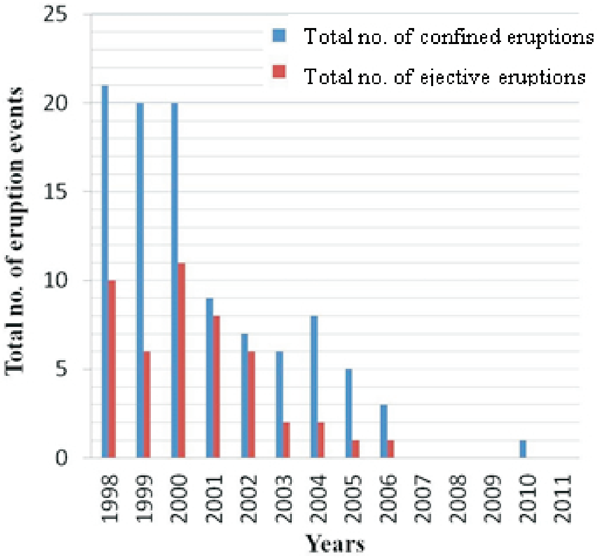

Fig. 1. Annual distribution of confined (blue) and ejective (red) filament eruptions in the period 1998–2011

Table 2

Summary of the number of the X-ray flares associated with active and disappearing confined filaments

X-ray flare classes	Association with active filaments	Association with disappearing filaments
A	0	0
B	4	8
C	23	52
M	7	13
X	0	3

Additionally, the number of X-ray flares in class B, C and M associated with disappearing filaments is always higher than the one associated with active filaments. On the other hand, A-class does not produce any associated filaments [16], while the energetic X-class only produces disappearing filaments.

Table 2 summarizes the X-ray flare classes associated with active and disappearing confined filaments. It was found that the dominant X-ray flare energy of confined eruptions is that of C class (75 events or 68.2% from 110 data selected).

Figure 2a displays the distribution of the filament field extent for confined eruptions. The distribution shows that the most common filaments field extent is located between 5 and 15 degrees. We can use filament length as a good predictor of a confined eruption, since the shorter the filament length on the solar disk, the higher the probability of a confined eruption.

Figure 2b displays the distribution of flare duration for confined flares. It shows that the most common flare duration is between 16 and 40 minutes. As the dominant type of flare for confined eruption in our list, was C class, it is probably the reason why the flare duration is relatively short.

Conclusion. Investigations of filament/prominence eruptions help to advance our knowledge on the physical processes in the solar corona, to reveal the pri-

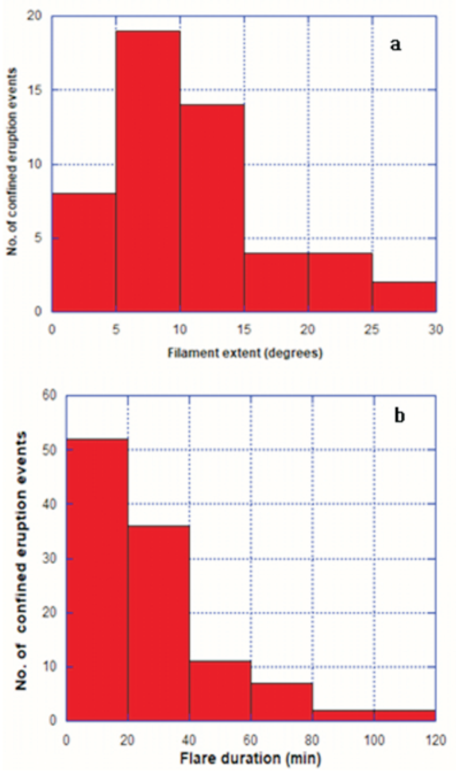

Fig. 2. a) Distribution of filament field extent for confined eruptions. b) Distribution of flare duration that results from confined eruptions

mary drivers of space weather. In this work we statistically examine confined filament eruptions during the 23rd Solar cycle (1996–2008):

1) We use 159 filament eruptions in the period 1998–2011; 69% of them are confined eruptions and the other 31% are ejective eruptions.
2) The total number of observations of active filaments is 43 (27%). It is less than the total number of observations of disappearing filaments 116 (73%).
3) We have found that due to the deep Solar cycle min (2008–2010), there are no ejective eruptions.
4) In the increasing phase of Solar cycle 23 (1998–2002), the total number of observations of the **active and disappearing filaments** is 127 (80%). This is higher than in the decreasing phase of the cycle (2003–2011) when the number reaches 32 (13%).
5) The total number of observations of **confined eruptions** is 110. Forty-eight percent of them are disappearing filaments (76) and 21% (34 events) are active filaments.
6) It was found that the dominant **X-ray flare energy of confined eruptions** is that of C class (75 events or 68.2% from 110 data selected).
7) The distribution shows that the most common **filaments field extent** is located between 5 and 15 degrees. We can use filament length as a good predictor of a confined eruption, since the shorter the filament length on the solar disk, the higher the probability of a confined eruption.
8) The most common **flare duration** is between 16 and 40 minutes.

It should be noted that besides filament/prominence eruptions, high-energy (relativistic) particles of solar and galactic origin, i.e. protons and heavier nuclei of galactic and solar cosmic rays are important for space weather and space climate [17,18]. They cause complex nuclear-electromagnetic-lepton cascades in the Earth's atmosphere, which leads to ionization of the surrounding air and entire environment. Cosmic ray-induced ionization is associated with effects on atmospheric chemistry and physics and is principal for radiation safety in spaceflight [19,20].

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