Filament Eruptions Associated with Flares, Coronal Mass Ejections and Solar Energetic Particle Events

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Abstract

We present analysis of three cases of filament eruptions (FEs) that occurred on 04 Aug 2011, 09 Nov 2011 and 05 Apr 2012 and their associations with flares as sources of solar energetic particles (SEPs) and coronal mass ejections. The associated FEs and SEP-related solar flares were selected by simultaneous observations in X-ray, EUV and radio wavelengths.

Introduction

The aim of this work is to investigate the various pre- and eruptive signatures that were observed during three complex events, including filament eruptions (FEs), solar energetic particles (SEPs) related solar flares, coronal waves (CWs) and coronal mass ejections (CMEs). We focus on the filament helical morphology and kinematic evolution (heights, velocities, accelerations) in order to determine their eruption mechanisms and the rate of their connections with the associated flares, CMEs and SEPs, as well.

Data

We used data from AIA/SDO (Lemen, et al. 2012) in He II 304 Å channel to study the eruptions kinematics.

The analyzed events were observed in hard X-ray (HXR), extreme ultraviolet (EUV) and radio wavelengths, and had associated SEP fluxes observed at 1 AU.

We used data from RHESSI (Lin et al. 2002) to trace the flare properties in HXRs.

High-energy particles related to the studied events are analyzed in different energy channels using proton data from SoHO/ERNE instrument (Torsti et al. 1995) and electron data from ACE/EPAM DE (Gold et al. 1998).

In order to search for a possible association with CMEs, data from SoHO/LASCO CME catalog (https://cdaw.gsfc.nasa.gov/CME_list/) and STEREO (Wuelser et al. 2004) were also used.

Results

\textbf{a) The event from 4 Aug 2011:}

The filament eruption was observed on 4 Aug 2011 close to the AR 11261 with heliographic coordinates N16W51. The eruption started at about 03:30 UT in the AIA field-of-view (FOV) and lasted about 5h. It was an asymmetric full type eruption with well pronounced twist. Its evolution is shown in base-difference images in Figure 1 (a).

The eruption clearly showed two evolution phases: The initial phase lasted about 44 min. During this phase the velocity rose from 10.4 km/s to 49.4 km/s with a constant acceleration of 23.2 m/s\textsuperscript{2}. During the second phase the filament rose with a constant velocity of about $v = 65.1$ km/s. The height-time profile of prominence evolution and eruption velocities and acceleration are shown in Figure 1 (b).
The eruption was followed by a M9.3 GOES class SEP-related solar flare. The flare started at 03:41 UT, about 11 min after the eruption onset. In Figure 2 (plot made using http://server.sepserver.eu/) the proton and electron intensities from SoHO/ERNE and ACE/EPAM DE are presented, respectively.

In Figure 3 as an example of SEP event on 04 Aug 2011 are shown the proton intensities in three GOES energy channels (>10, >50, and >100 MeV), the CME height-time plot and the soft X-ray flare light curves in two energy channels. The flare phase is indicated with dashed lines.
Fig. 3 The time variation of SEP intensity in three energy channels (first panel); the CME height-time plot (second panel); and the soft X-ray flare light curves in two energy channels (third panel). The vertical dashed lines outline the flare phase.

The event was associated with a fast halo CME, which first appearance in LASCO C2 was at 04:12 UT. The filament material could be traced in the corona in STEREO (A and B) coronagraph C1 FOV more than 3 hours after the eruption onset (Fig. 4).

b) The event from 9 Nov 2011

The filament eruption was observed on 09 Nov 2011 close to the east limb with heliographic coordinates N18E20. The filament was situated along the polarity inversion line (PIL) in AR 11342 with magnetic configuration of type $\beta\gamma\delta/\beta\gamma\delta$. In this event two consecutive eruptions was observed, here named FE1 and FE2. The eruptions were linked to a two ribbon solar flare of M1.1 GOES class, which start and peak time was at 13:04 UT and 13:35 UT, respectively.
The FE1 started about 30 min before the flare peak at 12:05 UT. The eruption showed two phases: initial phase with velocities from 0.4 km/s to 154 km/s at increasing acceleration from 0.5 m/s\(^2\) to 820 m/s\(^2\) and second phase with velocity of 166.8 km/s. The FE2 started at 14:05 UT, 30 min after the flare peak. This eruption had a linear height-time profile and velocity of 131 km/s. The height-time evolution FE1 and FE2 and corresponding velocities and acceleration are shown in Fig. 5a.

![Height-time profile of FE1 and FE2 evolution (top) and eruption velocities and acceleration (bottom) (a). Time-slice diagram used for height determination (b).](image)

The event on 9 Nov 2011 was associated with a fast halo CME with a linear speed of 907 km/s, which first appearance in LASCO/C2 was at 13:36 UT (Fig.6).

![The CME associated with 9 Nov 2011 event in the STEREO COR2 FOV.](image)

c) The event from 5 Apr 2012

The filament eruption on 5 Apr 2012 was observed close to the AR 11450 (N17W33). The eruption was followed by a two ribbon solar flare of C1.5 GOES class, which started at 20:49 UT. The filament eruption began at 21:10 UT and lasted about 2h. This time coincides with the time of flare peak intensity. No apparent filament twist was observed during the eruption.

During the FE the velocity increased from 20 km/s to 224 km/s and then decreased in the final stage to 214 km/s. Acceleration changed from 330 m/s\(^2\) to 19.6 m/s\(^2\), then it became negative, which suggest plasma returning during the final stage.
Fig. 7. Height-time profile for the event of 5 Apr 2012 (top) and relevant velocities and acceleration (bottom).

This eruption was also associated with a halo CME with linear speed of 828 km/s, whose first C2 appearance was at 21:25 UT. The prominence material was well visible as the CME bright core and could be traced in the STEREO A/COR1 FOV up to 21:55 UT.

Summary
Time lines for solar activity involved in each of the studied events are presented in Fig. 8. The duration of activities from the onset to the end are indicated by solid lines: flares - orange, filament eruption (FEs) - dark blue, coronal waves (CWs) - green, CMEs - purple (in LASCO C2 FOV), hard X-ray - violet and electron and proton intensities enhancement - light blue and cyan. The peak's times of the GOES SXR flux are also indicated with green arrows.

In the event from 4 Aug 2011 the FE preceded the flare start. In this case the reconnection process between the erupting filament and surrounding magnetic field could be regarded as a trigger of the two ribbon solar flare.

During the event from 9 Nov 2011 two consecutive FEs were observed: one before and one after the flare start. This sequence of events may be interpreted as the so-called “sympathetic events” (Moon et al. 2002; Wang et al. 2007; Joshi et al. 2016), i.e. successive eruptions and flares occurring within a short time interval and physically linked.

In the event on 5 Apr 2012 the flare start was followed by FE, which started at the time of flare intensity peak. In this event filament destabilization was probably due to magnetic field reconstruction during the solar flare.

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Fig. 8. Time lines for solar activities involved in each of 3 events. The time of 150 minutes before the flares onset is selected as a start point.

References