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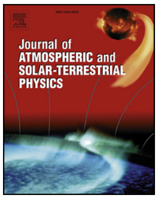

On the relationship between filaments and solar energetic particles

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ABSTRACT

In the current study the association rate between solar energetic particles (protons) and filaments and/or filament eruptions (FEs) is investigated using the largest reported event sample. Proton events observed in the period 2010–2016 are accompanied by filaments in 92% (143/156) of the cases. Due to the lack of comprehensive catalog of all filaments, a catalog of FEs is used for the reversed association. Only 5% of FEs have in situ proton signatures with larger peak intensity, compared to the median of the entire proton sample. Other solar activity phenomena (flares and coronal mass ejections) related to the proton events show differences in their distributions compared to the respective FE-samples. The indication for a shock wave formation using the type II radio signatures is also considered and discussed.

1. Introduction

For more than a century now, the different aspects of solar activity are considered to be undoubtedly connected. All of them owe their existence to the magnetic field and represent different ways in which solar plasma is responding to the underlying magnetic field evolution (Priest, 2014). Solar eruptions with their variety of signatures of energy release including prominences, solar flares, coronal mass ejections (CMEs), radio emissions, fluxes of solar energetic particles (SEPs) and global waves, play a significant role in generating space weather. Large eruptions can evolve into CMEs that can plow through the solar wind and ultimately impact the Earth's magnetosphere (Munro et al., 1979; Gosling, 1993). Many of these CMEs were claimed to originate from prominence eruptions (Gopalswamy et al., 2003). Regardless of their magnitude, eruptions are key elements in figuring out the structure and dynamics of the solar atmosphere (Hurlburt, 2015).

Solar eruptions demonstrate the solar activity – they might be a simple local brightening or the most powerful event in our solar system. The easiest to observe are the bright chromospheric eruptions. Typically, they are visible in H_α and are evidence of some deep-seated disturbance which may manifest itself at widely separated points on the Sun (Richardson, 1937b). Observations of solar eruptive events at radio frequencies started a few years after the first detection of radio waves from an astronomical object in 1932 by Karl Jansky and often the radio bursts are associated with chromospheric eruptions (Newton and Barton, 1937; Richardson, 1937a).

The occurrence of solar eruption often happens after a disparition brusque (DB) of a filament. DBs are events observed in H_α, first reported by Deslandres in 1889 (Tandberg-Hanssen, 1995). They are a kind of filament eruptions (FEs) and may be a final or a temporary change in shape and visibility of the prominence (Raadu, Malherbe, Schmieder, Mein). Despite the terms prominence/filament show the location where the phenomenon is observed (limb/on-disk, respectively), they are used interchangeably in the current article. Nearly half of low-latitude filaments are seen to suffer a DB at least once during their existence (D'Azambuja, 1948). Two types of DBs are known – thermal (DBt (Mouradian et al., 1986)) and dynamical (DBd (Demoulin and Vial, 1992)). DBds are classical eruptions of a quiescent filament when the prominence plasma is ejected in the corona and in the heliosphere. In most of the cases DBds are final stage of prominence lifetime. The DBts on the other hand happen due to heating of the cold prominence material because of rising energy flux to the body of the filament. It disappears in H_α line, but becomes visible in ultraviolet or X-rays. Often the prominence appears again in H_α in a few hours when cooling down. The DBds are more often associated with CMEs and intense geomagnetic storms (Taliashvili, Mouradian, Páez; Schmieder et al., 2000; Gopalswamy et al., 2003).

CMEs consist of large structures containing plasma and magnetic fields that are expelled from the Sun into the heliosphere with the apparent speeds of the leading edges of CMEs range from about 20 to >2500 km s^{-1}, or from well below the sound speed in the corona to well above the Alfvèn speed (Webb and Howard, 2012; Chen, 2011). White-light observations reveal the typical structure of a CME: a bright loop with a dark cavity below and a core (Illing and Hundhausen, 1986) – structures that can also appear in the quiet solar atmosphere (Saito and Tandberg-Hanssen, 1973; Gibson et al., 2006). Although it is still

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largely accepted that the CME core consists of a filament (House et al., 1981), some recent studies challenge this assumption and argue in favour of geometrical projection effects instead (Howard et al., 2017). Various studies explore the relation between different manifestations of solar activity. It was found that approximately half of active region (AR) FEs are associated with CMEs (Yan et al., 2011). Smaller eruptions may provide the ultimate source for the solar wind (Tian et al., 2014). As the FEs are claimed to be progenitors of mass ejections, different authors explore this relationship: 56% of eruptive prominences (EPs) are associated with CMEs by (Jing et al., 2004), or more than 80% by (Schmieder et al., 2012; Gopalswamy et al., 2003). CME-related are 92% of studied eruptive prominences by (Hori and Culhane, 2002), while the remaining 8% "show weak mass motions confined to nearby streamers".

While studying the relationship between different solar phenomena (Jing et al., 2004) divide FEs in two groups – active and quiescent. For a "solar flare" defined as the enhanced emission either in optical H_α or/and in GOES X-ray, 41% of all prominence eruptions are linked with flares by (Jing et al., 2004). AR FEs are more likely to be associated with flares (95%) compared to quiescent FEs (28%). Similar results are obtained using larger samples by (Yan et al., 2011), connecting 96% of FEs with flares.

No statistical relationship has been reported between FEs and SEP fluxes (above 10 MeV). Previous studies discuss only isolated cases, e.g., single event studies are shown in (Hyder, 1967; Kahler et al., 1986; Kahler, 2001) and a handful of events are analyzed by (Kahler et al., 2015; Gopalswamy et al., 2015). Overall, the authors claimed that AR and impulsive phase are not necessary for the occurrence of the SEP events that were characterized by a rather steep power-law energy spectral index ($\gtrsim$4). CME-driven shock acceleration scenario was favored there, supported by the observation of IP type II radio bursts (without metric type II or shock-signatures formed only in the high corona).

The aim of this study is to re-evaluate the association between filaments and SEP events using larger event samples than before and the best quality prominence observations possible to date. Thus, the analysis covers the time period of Solar Dynamics Observatory (SDO (Pesnell et al., 2012)) mission. In Section 3.1 we present a list of SEP events observed from 2010 to the end of 2016 cross-checked for the appearance of a prominence. Due to the lack of comprehensive catalog of all observed prominences in the explored period to make the reverse association and look for filament-related SEP events, in Section 3.2 we used a list of all reported SDO FEs (McCauley et al., 2015). The association rate and characteristics of the filaments are finally compared with the respective properties of all FEs.

2. Observations and data analysis

For the analysis performed in this study, several different types of data and catalogs are used. The main components of the work are the prominences and SEP (with a focus on the proton) events.

2.1. Observational data

Space-based observations by the Atmospheric Imaging Assembly (AIA; (Lemen et al., 2012)) aboard the SDO are the main source for the prominence data analysis. We analyzed images from HeII 304 Å channel taken with spatial resolution of $\sim 1.5^{\prime\prime}$ and a cadence of about 12 s. To check for possible association between the filaments and ARs we inspected images in AIA 1600 Å, 1700 Å and 4500 Å channels and the provided AR identification by https://solarmonitor.org.

In case we could not find associated filament in AIA observations, we checked H_α data archive from Big Bear Solar Observatory[1] or Kanzelhöhe Observatory.[2]

Observatoins from EUVI (Extreme Ultraviolet Imager) onboard STEREO (Solar TErrestrial RElations Observatory) A & B (Driesman et al., 2008) at the same wavelength (He II 304 Å) with spatial resolution of $\sim 1.6^{''}$ are used to ensure that behind the limb events not visible from AIA point of view are also considered.

Among the additional information relevant for the present study are the flare listing,[3],[4] radio burst identification (Miteva et al., 2018) and the SOHO/LASCO (Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph Experiment) CME Catalog[5] (Gopalswamy et al., 2009). Sunspot number data used for graphical representation of the solar cycle is taken from SILSO data archive, Royal Observatory of Belgium, Brussels.[6]

2.2. Selection of events

For the energetic proton events, data from the SOHO/ERNE[7] (Torsti et al., 1995) instrument is used. In the considered period (2010–2016), 186 proton events in the 17–22 MeV energy channel have been identified by visual inspection of the temporal profiles of the proton fluxes. A detailed report on the SOHO/ERNE 20 MeV catalog compilation is under way (for preliminary results see (Miteva et al., 2017)). Yearly distribution of all 186 SEP events is presented on Fig. 1.

Furthermore, we applied a temporal criteria for the association between the in situ proton event and the solar eruptive event, in terms of both solar flare and CME, where possible, similarly to the procedure summarized in (Miteva et al., 2018). For 111/186 (60%) of proton events both flare and CME could be identified, whereas for additional 45 proton cases only one of the eruptive event could be associated (due to data gaps, complex cases or high amount of uncertainty). For the remaining 30 proton cases, no solar origin association could be found and these events are not considered further in this study. Finally, a filament is sought at the time of onset of the solar flare/CME, regarded as the solar origin of the proton event.

In addition, a list of AIA/SDO FEs has already been compiled by (McCauley et al., 2015) and provided as online catalog[8] with $\gtrsim$900 entries over the period 2010–2014. Among all parameters listed in the catalog, relevant for our study are the onset and end times of the FE together with the related flare and CME. Based on these timings, we could associate the SOHO/ERNE proton event with the given FE.

The characteristics of the protons, filaments and related phenomena are summarized in Table 3 in the Appendix.

3. Results

3.1. Correlation analysis between solar proton events and filaments

Using the information for the proton-related flares and CMEs, we identified the presence or not of a filament (no distinction between eruptive or not). From our list, 143/156 SEP events were accompanied by prominences (92%), while in the remaining 13/156 cases (8%) could not be associated with any filaments.

The frequency of SEP occurrence increases around the solar maximum. (Fig. 1). The maximum of solar cycle 24 (as defined by sunspot number) reached in April 2014 coincides well with the maximum of registered proton events.

When evaluating the heliolocation of the proton origin, in addition to the information of the AR location taken from the proton-related

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[1] http://www.bbso.njit.edu/pub/archive/.

[2] http://cesar.kso.ac.at/halpha3a/.

[3] https://hesperia.gsfc.nasa.gov/goes/goes_event_listings/.

[4] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SGD_PDFversion/.

[5] https://cdaw.gsfc.nasa.gov/CME_list/.

[6] http://sidc.be/silso/datafiles.

[7] https://srl.utu.fi/erne_data/.

[8] http://aia.cfa.harvard.edu/filament/.