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Filaments Related to Solar Energetic Particles

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Abstract. We investigate the kinematics of 13 solar energetic particle (SEP) related eruptive prominences (EPs) and SEP spectral indices (using SOHO/ERNE proton data) for well observed set of events in the SDO era. From the height-time profiles of the EPs, we measured their average velocities and eruptive phase velocities. Relationships between proton spectral index γ and properties of the other associated solar phenomena (flare peak flux, CME speed, EPs speeds) are investigated.

INTRODUCTION

The highly dynamic processes in the magnetized coronal and interplanetary plasma are the reason of major acceleration of the charged particle populations [1]. Flares and/or coronal mass ejection (CME) shock waves are among the main accelerators of solar energetic particles (SEPs) [2]. In the past it was commonly understood that the acceleration of particles up to tens of MeV occurs only during flares in active regions (ARs) [3]. The paradigm changed in the early 1990s [4] with the realization that large SEP events may be driven by CME shock waves rather than by solar flares. It was considered that solar flares produce impulsive events, while CME shocks are responsible for gradual events [5]. Nowadays, it is accepted that these two different mechanisms both take part in producing SEP events and their role varies in the different events.

In most of the reported cases the solar origin of SEP events is linked with AR. However, there are a few studies that indicate that the presence of an AR on the Sun is not necessarily required [6, 7]. Moreover, some interplanetary particle events at 1 AU could originate from a disappearing filament instead of a large flare [6, 7, 8, 9, 10, 11].

As a part of a CME, eruptive prominences (EPs) are also often connected with gradual SEP events. Different studies reveal different values about this relationship. EPs associated with CMEs are 56% [12], more than 80% [13, 14] or even 92% [15]. The reverse association using Skylab observations found that 70% of the CMEs that could be associated with near-surface activity were linked with EPs or disappearing filaments [16] and while essentially all EPs that reach heights above $0.2R_{\odot}$ are connected with CMEs. Studying the connections of prominences with other solar activity phenomena is useful to distinguish them in different classes. The most common classification divides prominences in two groups – active and quiescent. We also rely on other division that differentiates EPs from active ones - if some or all of the prominence material escapes the solar gravitational field, the prominence is eruptive [17].

Typical prominence eruption consists of 3 phases: initial activation phase, eruptive phase with fast acceleration and eruptive phase with constant or gradually growing velocity. During the phase of activation the prominence rises slowly with almost constant velocity $v_{act} \approx 1-10$ km s^{-1}[18]. The beginning of the eruptive phase is accepted to be the moment of sudden acceleration when the prominence reaches certain critical height at about half of the distance between filament's feet. The rising velocity increases up to a few hundred km s^{-1}. While the activation phase is not always required, at least one manifestation of the eruptive phase is required. There are three possible scenarios for the end of the eruption: 1) rising with constant velocity; 2) constant velocity phase followed by phase with decreasing acceleration; 3) rising with increasing acceleration [19]. Both 1) and 3) assume ejecting the prominence material in solar corona, while 2) suggests falling of the material back to solar chromosphere.

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We previously inspected the relationship between SEPs and prominences and connected 92% of all SEPs registered between 2010 and 2016 with filaments [20]. In this paper, we report the properties of 13 EP-SEP pairs, comparing the energy spectra of SEP events with height-time profiles of prominence eruptions.

OBSERVATIONAL DATA AND ANALYSES

The current paper is based on our previous statistical study about the correlation between SEP events and prominences [20]. Starting with a list of 156 energetic proton events detected from SOHO/ERNE [21] 17-22 MeV energy channel in the period 2010-2016, we found prominences/filaments observed by SDO/AIA [22] in 143 cases. For the purpose of our study, we applied a selection criteria to filter only the EPs from our list. Since we had 67 on-disk filaments that are inappropriate for the current study, we classified the remaining cases: 11 quiescent prominences, 29 active prominences and 36 EPs. After removing the quick eruptions (the ones that lasted less than 15 minutes) as well as the thin or small ones or the prominences that show only horizontal motions instead of vertical ones, 13 SEP-related EPs remained to be explored. The properties of the explored events are summarized in Table 1. The provided information is collected from different catalogs: GOES event listing for associated solar flares and SOHO/LASCO CME Catalog [23].

TABLE 1. Table of selected EP-related SOHO/ERNE proton events and related solar events: onset for ~20 MeV protons; flares (class/onset/latitude and longitude), CMEs (time of first appearance/linear speed/angular width/measurement position angle – MPA), ARs, γ - proton spectral index calculated over the 14−131 MeV range, v_{avg}, v_{er} - average and eruptive phase velocities of the EP, respectively. Time is given in UT; speed - in km s^{-1}. Abbreviations: u: uncertain; N: no; Y: yes.

Event	Proton onset		Solar flare	CME	AR	γ	EPs	
No.	yyyy/mm/dd	hr	class/onset/location	time/speed/AW/MPA			v_{avg}	v_{er}
1	2011/03/07	22	M3.7/19:43/N30W48	20:00/2125/360/313	11164	5.20	40	190
2	2011/05/11	4	B8.1/02:23/N17W85	02:48/745/225/283	11203-11205	3.15	72	125
3	2011/06/11	13	u	12:00/522/9/58	N	3.40	8	8
4	2012/03/04	19	M2.0/10:29/N19E61	11:00/1306/360/52	11429	3.67	9	9
5	2012/10/07	16	u	07:36/663/149/207	N	5.83	7	7
6	2014/02/11	24	u	19:24/613/271/273	11975	2.47	86	86
7	2014/03/24	12	u	07:12/809/159/237	Y	6.08	11	13
8	2014/11/09	14	u	11:12/632/69/149	12207	2.95	21	40
9	2015/02/21	11	u	09:24/1120/360/215	N	4.03	178	285
10	2015/04/12	26	C6.4/23:24/S14W30	23:48/678/175/285	12320	3.52	10	13
11	2015/05/12	5	C2.6/02:15/S21W83	02:48/772/250/283	12335&12337	4.09	76	76
12	2015/06/18	4	M1.2/00:33/S16W81	01:26/1714/195/270	12365	4.31	69	69
13	2015/07/19	12	C2.1/09:22/S25W62	09:48/782/194/241	12384	4.21	28	60

RESULTS AND DISCUSSIONS

In our list we considered both flares and CMEs as a possible origin of proton events. However, in 6 of the cases no signs of flares could have been identified with certainty.

We obtained the height-time profiles of the eruptions of the EPs and measured the average velocities of the rising material for the whole eruption (v_{avg} – Table 1, column 8). If an eruption started with an activation phase (event No. 7, 8, 10 and 13), we separated the height-time profile and also measured the average velocity for the eruptive phase only (v_{er}). If the eruption consists of two eruptive phases without activation - rising with fast acceleration followed by constant or gradually growing velocity, we defined the speed of the phase with fast acceleration as v_{er} (event No. 1, 2 and 9), while if the whole eruption contains only one kind of eruptive phase, then $v_{avg} = v_{er}$ (event No. 3, 4, 5, 6, 11 and 12).

Most of the events from our list are connected with ARs (10 out of 13), but we also present 3 cases of SEP events, accompanied by EPs and CMEs without ARs (event No. 3, 5 and 9). This is a confirmation of a well-known fact shown in Ref. [6]. In all of these cases we have slow EPs ($v_{avg} < 15$ km s^{-1}) despite the fact that such velocities are also possible for active region prominence eruptions (e. g. event No. 4 and 10).

In order to produce SEP energy spectra, we used the data from the following SOHO/ERNE energy channels: 14-17, 17-22, 21-28, 26-32, 32-40, 40-51, 51-67, 64-80, 80-101 MeV. We also inspected 101-131 MeV channel, but none of the events has been detected with energy > 101 MeV. The produced spectra were fitted with power function (in the form $\frac{dN}{dE} = kE^{-\gamma}$, where N – energetic particle density, E – energy, k – a constant) to determine the spectral index γ. For the obtained results, see Table 1, column 7. Explored events tend to have spectral indices in the range $2.95 \leq \gamma \leq 6.08$, which coincides with the claim that $\gamma \geq 2$ stated in Ref. [6], but is wider interval than the one obtained in Ref. [11] – $4.15 \leq \gamma \leq 4.69$. It is probably due to the fact that we have larger study sample, more energy channels and not all of the SEP events originate out of AR. These values are shifted with respect to the range $2 < \gamma < 4.5$ in Ref. [24], but we have $\gamma > 4.5$ only in three cases (event No. 1, 5 and 7). In the first case we have a spectral break in the spectrum of the proton event, which may influence the value for γ, while in the remaining two cases, we have data only in 3 energy channels for each event.

We compared the γ-distributions of 4 parameters of the associated phenomena – v_{avg}, v_{er}, v_{CME} & flare peak flux – FPF (Figure 1). To analyze them we calculated Pearson product-moment correlation coefficient (r) for each plot. For the γ-distributions of v_{avg}, v_{er} and FPF we have low if any correlation with $r = -0.23; -0.04; 0, 33$, respectively, while v_{CME} shows high positive correlation with γ ($r = 0.70$). Moreover, the coefficient of determination between v_{CME} and γ is $r^2 = 0.49$, which shows that 49% of the variance in v_{CME} are associated with variance in γ. The flatter proton spectra (large values for γ) are related to faster CMEs. This result agrees with a statistical study [2] that low energy protons correlate better with CME speed.

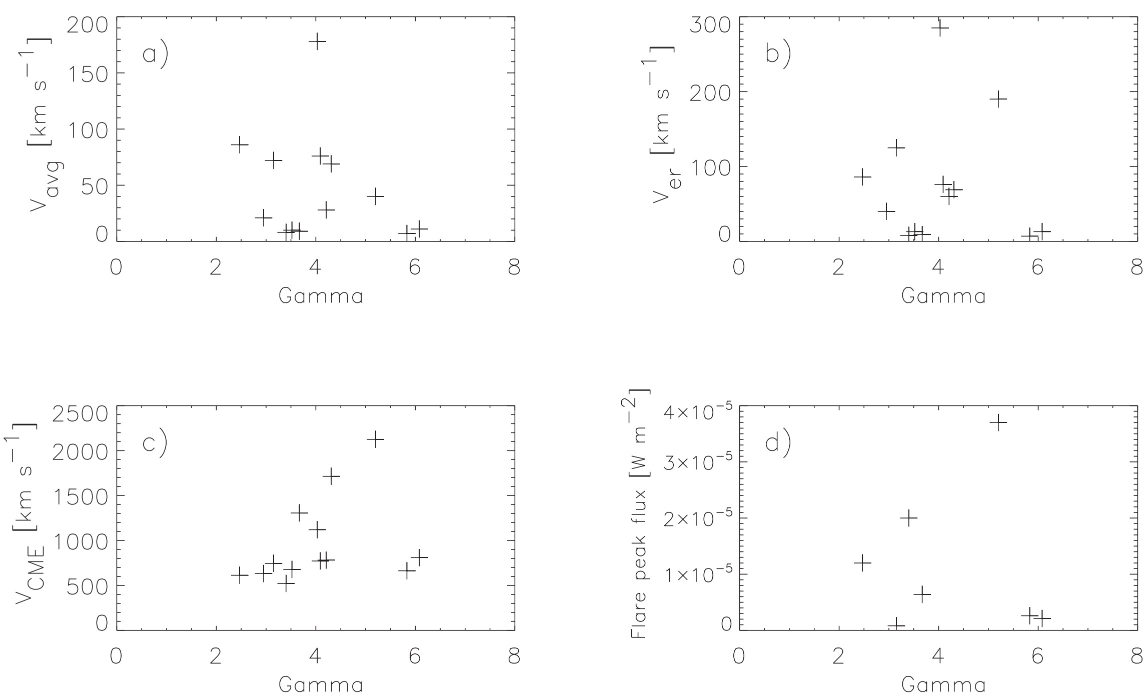

FIGURE 1. γ-distributions of: (a) EPs average velocities, (b) EPs eruptive phase velocities, (c) CMEs speeds and (d) flare peak flux.

We have a CME association with SEP events in all of the presented cases. The velocity distribution (Figure 2a) shows that the majority of SEP-related CMEs tend to have linear speeds $v_{CME} < 1000$ km s^{-1}, but none of them shows $v_{CME} < 500$ km s^{-1}. We have 2 out of 13 cases with $1000 < v_{CME} < 1500$ km s^{-1}, but the cases with $v_{CME} > 1500$ km s^{-1} are sporadic according to our results. This is in accordance with results obtained by [2].

The measured values for EPs speeds lie in the range $7 \leq v_{er} \leq 285$ km s^{-1} (Table 1, column 9) and cover the rising of the prominence on heights up to $0.5R_{\odot}$. If we take into account the distribution of v_{er} (Figure 2b) we can distinguish a variety of values that are lower than the defined as typical – 305 km s^{-1}[6] and ~ 275 km s^{-1}[11]. Only the eruption from 2015/02/21 (event No. 9) coincides with the cited velocities.

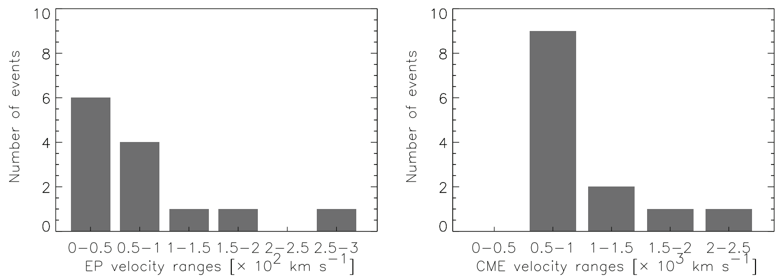

FIGURE 2. Distributions of (a) CME velocity and (b) EP eruptive phase velocity for the 13 SEP-related events sample.

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