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Spectral analysis of SOHO/ERNE protons in solar cycles 23 and 24

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Abstract. We present first results on the spectral index analysis of solar energetic protons from SOHO/ERNE instrument. The log−log dependence between the peak proton intensity and proton energy is built using up to five energy channels, equidistantly distributed in the range 14−131 MeV and a power law dependence is assumed in order to deduce the proton spectral index. Finally, various distributions and statistical relationships between the calculated spectral indices and parameters of the solar eruptive phenomena are presented and discussed.

INTRODUCTION

Energetic electrons, protons and heavy ions of solar origin, so called solar energetic particles (SEPs) are one of the important aspects of space weather, together with the electromagnetic influences from solar flares and shock-driven waves due to coronal mass ejections (CMEs) [1, 2]. However, the effect of energetic particles is the remaining obstacle impeding human space travel mainly due to the danger of increased radiation dozes and the related health hazard, added to other negative effects on space instrumentation [3]. Presently, SEP-forecasting is a modern research trend in space weather studies with different models having different success in 'guessing' the SEPs occurrence, arrival time and/or peak intensity.

Nowadays, a number of catalogs of in situ observed protons are reported. Usually the events are observed at one or few specific (often given as averaged over the channel width) energies depending on the satellite/instrument. Some of the L1/near-Earth proton catalog are listed below:

- >10 MeV (GOES, https://umbra.nascom.nasa.gov/SEP/; [4]),
- >25 MeV (IMP-8, [5]),
- 25 MeV (Wind/EPACT, [6, 7]),
- 28 MeV (GOES, [6]),
- >30 MeV (GOES, [4]),
- 50 MeV (Wind/EPACT, [7]),
- >60 MeV (GOES, [4]),
- 68 MeV (SOHO/ERNE, [8, 9]),
- >100 MeV (GOES, [4]),
- >500 MeV (SOHO/EPHIN, [10]).

The only comprehensive multi-energy analysis [11] performed in solar cycle (SC) 23 aimed to investigate the energy dependence of statistical correlations between the proton peak intensity (and fluence) and the parameters of the SEP solar origin (usually in terms of flare class and CME speed). No event catalog at all used energies has been provided though.

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The proton spectral index is the slope of the dependence between the peak proton intensity and the mean energy of the proton channel. When in a given event a low value (in terms of absolute value) for the index is obtained (so-called hard spectral index), it is used as an evidence for a high-energy particle productivity and vice versa. Here, soft (steep) and hard (flat) spectral index (denoted with 'γ') are roughly separated by the value of >4 [12]. Earlier studies report proton spectral indices in the range from 2 to 4 calculated by the ratio of two energy channels [13], and few case studies were calculated using power law [12] with values around 4. In this work, we present much larger statistics on proton spectral indices (over 500 individual values are obtained, assuming power law distribution between the proton peak intensity and the proton energy) and using data sample covering a time period of nearly two SCs.

DATA AND ANALYSES

This study is based on the catalog[1] of proton events from SOHO/ERNE instrument [14] in the period 1996−2016. We used the available at present SOHO/ERNE science data level, however re-evaluation for some events is under way by the instrument team. The first identification of the proton enhancements and the procedure for their solar origin association are already reported elsewhere [15, 16, 17]. We use the first results obtained in five of the energy channels (in MeV) of the high energy detector, namely: 17−22, 26−32, 40−51, 64−80, 101−131. Based on the peak proton intensities calculated where enhancements are clearly seen, the log−log plot with the proton energy is built. The declining trend can be fitted using a power law giving a value for the slope (i.e., the spectral index). Most of the indices are calculated using the first two and three energy channels (i.e., the majority of the protons reach up to about 50 MeV). The most energetic proton cases are those with signal in the highest energy channel (101−131 MeV). In such cases, the single power law is often not an adequate fit and a broken power law better describes the event. Nevertheless, in this first approach a single power law is applied for all events.

RESULTS AND DISCUSSIONS

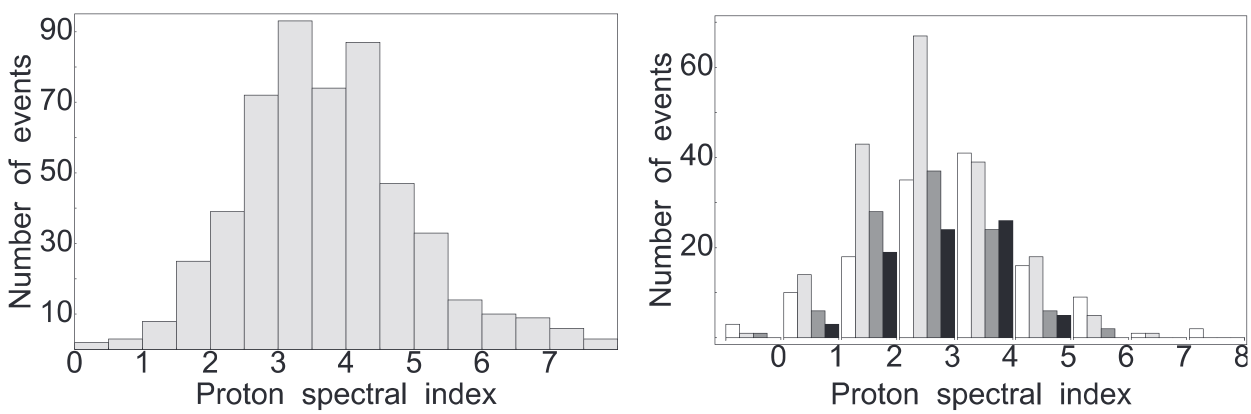

FIGURE 1. Proton spectral index for the entire sample (left) and as a bar chart (on the right) for spectral indices calculated by only two available channels (white color), three (light-gray), four (dark gray) and five energy channels (black).

The distribution of the spectral indices is shown in Figure 1. The histogram on the left is for the entire sample, and a peak at values for γ at about 3−4 is seen. Values below 2 and above 5−6 could be an artifact from the two-channel analysis. Depending on the number of energy channels used to calculate the index (right plot), we estimate spectral index calculated based on proton intensity from the first two channels (given in white color), by three channels (given in light-gray), by four-channels (in dark gray) and spectral index where all five energy channels are used (shown in

[1] The proton catalog is still in progress, with plans to include events during 2018 as well: http://newserver.stil.bas.bg/SEPcatalog

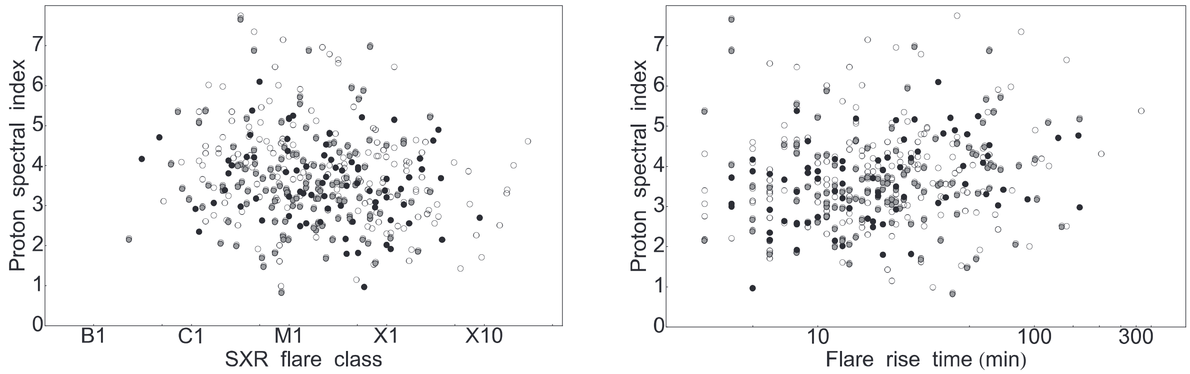

FIGURE 2. Scatter plot between the proton spectral index with the flare class (left) and with the flare rise time (on the right). Black color is for indices calculated by five channels, dark-gray – by four and white – by two and three energy channels.

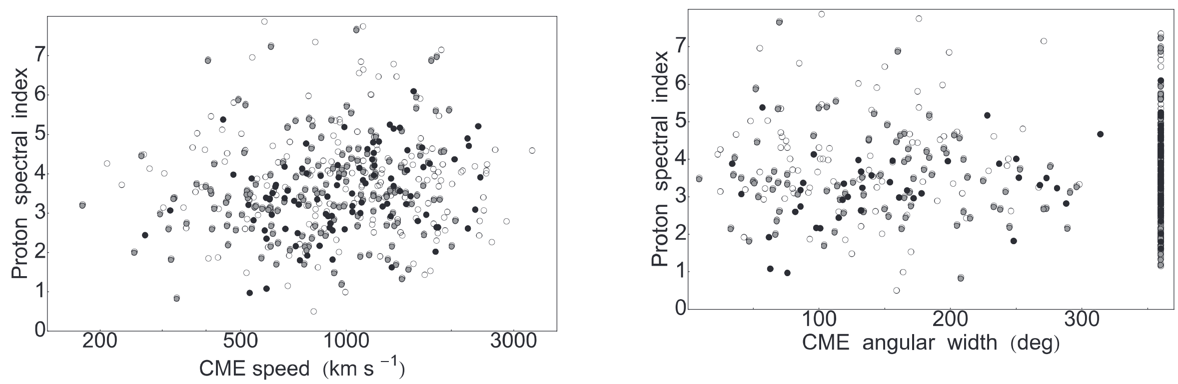

FIGURE 3. Scatter plot between the proton spectral index with the speed of the CME (left) and with CME angular width (on the right). The color code is as in Fig. 2.

black color). The maximum of the distribution is slightly shifted, from spectral index around 3 for the three- and four-channel sample to around 4 for the cases calculated by two channels. The high energy protons (five-channel γ-sample) have a rather flat distribution around 2–4.

Scatter plots between the γ and different parameters of the solar flares and CMEs are done in linear–$\log_{10}$ form. In Figure 2 are given the spectral index with the flare soft X-ray (SXR) class (on the left) and the onset-to-rise time (on the right). No trend is seen in either graph.

Similar linear–$\log_{10}$ scatter plots are completed between the γ and the reported CME speed and angular width are shown in Figure 3. As for the flare parameters, no clear positive/negative behavior between the pair of parameters is seen.

The scatter is noticed for spectral indices calculated using different number of proton energy channels (given with different color in Figure 2 and 3).

CONCLUSIONS

The majority of the proton events have intermediate spectral index, with a broad distribution peak at about 3–4 and longer tail to larger values.

The preliminary analysis shows that there is neither a clear, strong trend in the correlations between the proton spectral index with the parameters of the solar flares, nor with the coronal mass ejections. The scatter is large for spectral indices describing low (few energy channels) to high-energy proton events (all five energy channels). Note that a single parameter is adopted to characterize the solar eruptive phenomena and particle accelerators (e.g., flare class and CME speed). Such approximation does not seem to be adequate in describing the relationship between the spectra of the observed in situ proton events and the properties of the flares and CMEs. Other parameters need to be tested and/or additional (particle escape, transport and/or re-acceleration) effects may play a role.

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