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Dependence of 100 MeV solar proton events on the solar activities: flares and coronal mass ejections

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To investigate the possible solar origin for high energy (E≥100 MeV) solar protons, the correlation coefficients (CCs) between the peak intensities of E≥100 MeV solar proton events (SPEs), I_{100}, and the speeds of coronal mass ejections (CMEs), and CCs between I_{100} and the soft X-ray (SXR) emission of solar flares are calculated. Data analysis show that I_{100} has a moderate correlation with the CME speed for the SPEs with source location in the well connected region(W20°-W70°) , however, I_{100} has good correlation with the SXR emission of solar flares. The results suggest that both the CME-driven shock acceleration and flare-acceleration contribute to E≥100 MeV protons. However, the flare-acceleration contribute much more to E≥100 MeV protons than CME-driven shock acceleration in the large gradual SEP events. The solar flares either contribute directly to the production of the high-energy particles or provide superthermal particles for the further acceleration by the CME-driven shocks.

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1. Introduction

Large gradual solar energetic particle (SEP) events are often accompanied with flares and coronal mass ejections (CMEs) concomitantly, and both of them are capable of accelerating charged particles. The main controversy focuses on which process plays a key role in producing high-energy particles. One way to distinguish this controversy is to derive the particle release time and compare it with the associated solar eruptions (refer to some recent studies, e. g.,Kahler et al. [17] ; Miroshnichenko et al. [34] ;Simmnet [46]; Le et al. [24]; Masson et al. [32]; Reames [42], [43]; Aschwanden [2] ; Gopalswamy et al. [14]; Li, et al. [30]). However, the methods applied are different from each other, therefore leading to different conclusions even for a same SEP event. For example, the release time of relativistic solar protons that occurred on 28 October 2003 calculated by Miroshnichenko et al. [34] was different from the one calculated by Reames [42].

Combing particle energy spectra, elemental abundances, and multi-wavelength solar observations, a number of studies have been designed to identify the acceleration sources and/or mechanisms of large gradual SEP events (Cane et al. [5], [6] ; Tylka et al. [48] [49] ; McCracken et al. [33] ; Li et al. [27] [28] [29];Grechnev, et al. [15] ;Bazilevskaya [3] ;Perez-Peraza et al. [40] ; Andriopoulou et al. [1] ;Firoz et al. [9] ; Vashenyuk et al. [50] ;Kahler et al. [19] ;Moraal et al. [36] ;Mewaldt et al. [35] ;Nitta et al. [37] ;Veselovsky et al. [51] ;Ko et al. [22]). Different researchers have different interpretations on the same phenomena associated with SEP events. For example, (Cane et al. [5] [6]) suggested that the high Fe/O at the early phase of a SEP event was directly from the flare acceleration. In the contrast, (Tylka et al. [48] [49]) related the high Fe/O to the CME driven shock, the flare accelerated particles provide as seed particles.

A number of researchers suggested that large, fast CMEs overtake the ones emit previously from the same or nearby active regions and then interact with each other. The CME-interaction is probably a key factor determining the SEP production (Kahler [16] [18] ; Gopalswamy et al. [11] [12] ; Ding et al. [8]). However,Richardson et al. [45] argued that the interaction between two CMEs is not a key factor controlling the SEP intensity.Kahler and Vourlidas [20] suggested that the relevance of CME interactions for larger SEP event intensities remains unclear.

Statistical correlations between large gradual SEP events and the associated flares and CMEs can provide us another clue to distinguish the role of flares and/or CMEs in producing SEPs. Park et al. [38] [39] investigated the correlation between the peak intensities of SPEs and the parameters of flares and CMEs. They found that the SPE fluxes have a good correlation with the CME speeds rather than the solar flare emission. To be noticed that their calculation of the peak intensities of SPEs is based on the temporal profiles of E$\geq$10 MeV protons. As we will discuss in the following section that the relatively low-energy protons in many cases reach peak intensities when the CME-driven interplanetary (IP) shocks arrive the near-Earth space. Therefore, the conclusions of Park et al. [38] [39] can be consequently predicted.

Both flares and CME-driven shocks can accelerate SEPs. However, it is still in question whether flare or CME is more important for the large gradual SEP. Cane et al., [7] suggested that the solar flares and CMEs are likely to coexist and the evolution of any event depends on relative importance of the processes. This is also consistent with the statement (Firoz, K. A., et al. [9]) that the type III and type II bursts are successive evolutions and it is difficult to separate them. Trottet et al. [47] investigated the statistical relationships between SEP peak intensities of the 15-40 MeV protons and near-relativistic electrons and characteristic quantities of the associated solar activity. Their statistical evidence suggested that both flare acceleration and CME shock acceleration contribute to the 15-40 MeV proton and near-relativistic electron populations in large SEP events.

To investigate the possible solar origin for high energy protons (E$\geq$100 MeV), we calculate the correlation coefficients (CCs) between the peak intensity of E$\geq$100 MeV protons and the SXR emission of solar flares or CME speed. This is the motivation of the study. Section 2 presents data analysis. Summary and discussion are given in Section 3.

2. Data analysis

For each SEP event that occurred in solar cycle 23, the eruptive solar activity is characterized by parameters of the associated SXR flare and the CME with a linear speed VCME, which can be obtained from the CME catalogue (Yashiro et al., [52] , `http://cdaw.gsfc.nasa.gov/CME_list/`) of Solar and Heliospheric Observatory/Large Angle Spectroscopic Coronagraph (SOHO/LASCO; Brueckner et al., [4]). The peak flux of SXR emission and the SXR fluence associated with each SEP event that occurred during solar cycle 23 can be obtained from the NOAA GOES X-ray solar flare catalogue (available at `ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/`). The peak intensity of E$\geq$100 MeV protons observed by the Geostationary Operational Environmental Satellites (GOES) were download several years ago from the website (refer to `http://spidr.ngdc.noaa.gov/spidr/`). Consequentially, 48 SPEs that occurred in solar cycle 23 were picked out. Among them, 17 SPEs were originated in the region around the solar disk center (E30°-W20°), and 20 SPEs were distributed in the well-connected region (W20°-W70°). The speed of the CME associated with the SPE that occurred on 20 January 2005 was derived to be 3242 km/s (Gopalswamy et al. [13]), which will be used in this paper.

According to the fact that the SPEs with peak intensity $\geq$20000 pfu for E>10 MeV protons were distributed in the longitudinal area from E28° to W18° (Le, et al. 2014), while the strongest ground level enhancements (GLEs) were distributed in the well-connected region (Le, et al. [25]), we calculate the correlation coefficients between I_{100} and the parameters of the solar eruptions for all the events, the events distributed in the longitudinal area from E30° to W20°, and the events distributed in the well-connected regions (W20°-W70°) respectively.

We use CC (X, Y) to indicate the correlation coefficient between the parameters X and Y. Figure 1 shows the correlation between I_{100} and the linear speed of the CMEs, VCME. For the all SPEs, CC (I_{100}, VCME) is derived to be 0.37. For the SEP events distributed in the region around the solar disk center and the SEP events distributed in the well-connected region (W20°-W70°), the CC (I_{100}, VCME) is 0.27 and 0.56, respectively. Under the assumption of CME-driven shock acceleration, when CME source locations were distributed in the well-connected regions, the shock noses of CMEs are well-connected with the Earth. This may be the reason why CC (I_{100}, VCME) is longitudinal dependent.

Figure 2 shows the correlation between flare intensity (FI) of SXR emission and I_{100}. For the all E$\geq$100 MeV SPEs, the CC (I_{100}, log FI) is derived to be 0.49. For the events with the sources distributed around solar disk center and in the well-connected region (W20°-W70°), the CC (I_{100},

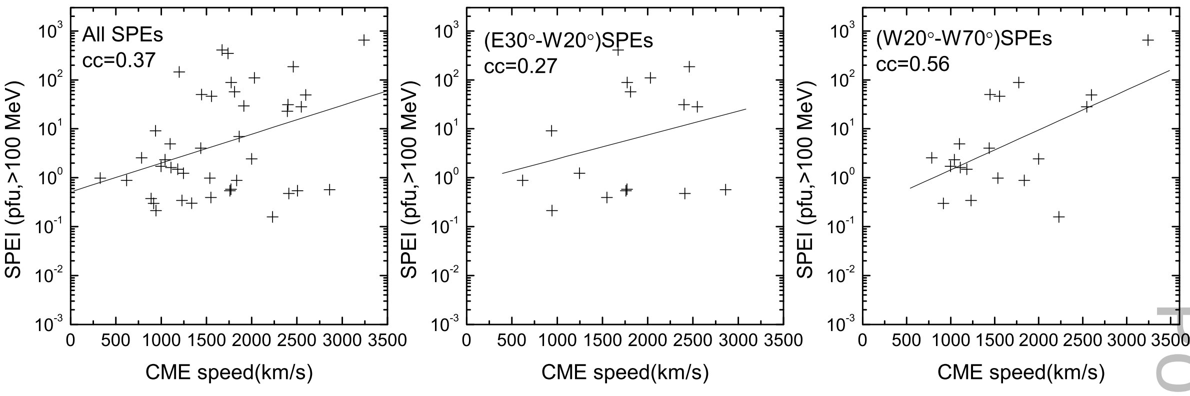

Figure 1: Correlation coefficients (CCs) between CME speed and the peak intensity of SPEs for E≥100 MeV protons. From left to right, showing CCs for all events, the events distributed in the longitudinal area from E30°-W20°, and in the longitudes at W20°-W70°).

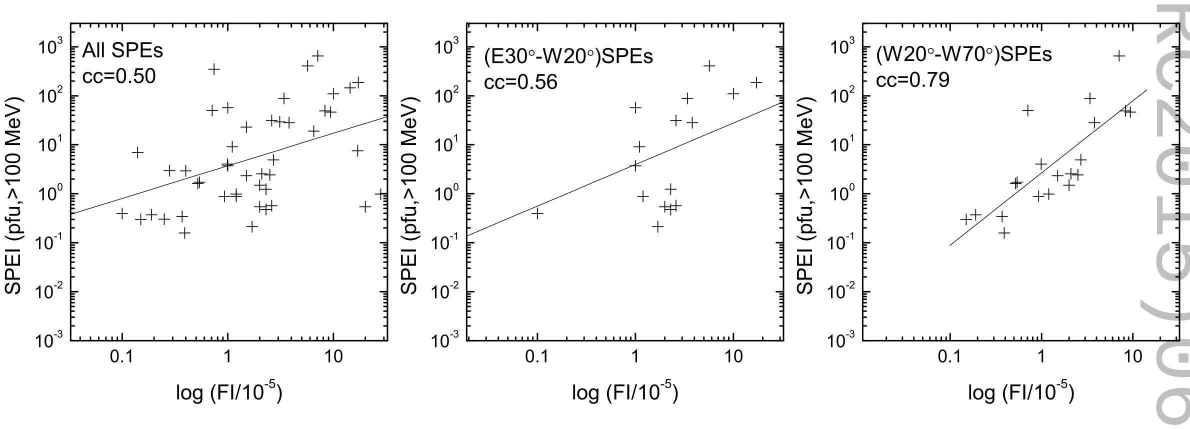

Figure 2: Correlation coefficients (CCs) between flare intensity of SXR emission and the peak intensity of SPEs for E≥100 MeV protons. From left to right, showing CCs for all events, the events distributed in the longitudinal area from E30°-W20°, and in the longitudes atW20°-W70°).

log FI) is 0.52 and 0.79, respectively. This also reveals a clear longitudinal dependence of CC (I_{100}, log FI).

Kubo & Akioka [23] suggested that SXR fluence can be used to forecast the occurence of solar proton events. How is the relationship between the SXR fluence and 100 MeV SPEs? Figure 3 shows the correlation between the SXR fluence (Φ_x) and I_{100}. It is obviously that CC(I_{100}, log Φ_x) is larger than CC(I_{100}, log FI) for the SPEs distributed the same source region. This suggests that SXR fluence has closer relationship with I_{100} than the peak intensity of SXR emission.

3. Summary and Discussion

For the well-connected 100 MeV SPEs, the CC (I_{100}, VCME) is 0.56 with confidence significance above 95%, suggesting that the contribution of CME-driven shock acceleration to E≥100

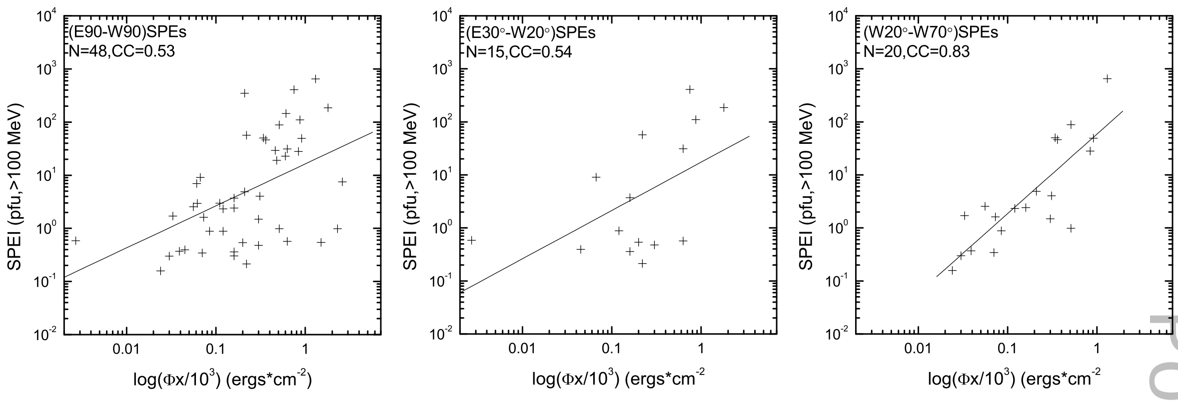

Figure 3: Correlation coefficients (CCs) between the SXR fluence and the peak intensity of 100 MeV SPEs. From left to right, showing CCs for all events, the events distributed in the longitudinal area from E30°-W20°, and in the longitudes at W20°-W70°.

MeV protons can not be ignored. The CC (I_{100}, log FI) and CC(I_{100}, log ęţx) are 0.79 and 0.83 respectively for the well-connected SPEs, suggesting that SXR fluence has closer relationship with I_{100} than the peak intensity of SXR emission. The results of the paper suggests that flare acceleration appears to have a close relationship with the production of high-energy protons. According to the results of the paper, we conclude that both CME-driven shock acceleration and solar flare acceleration contribute to the E≥100 MeV protons, namely that 100 MeV SPEs are mixed or hybrid events. However, the solar flare acceleration may contribute much more to E≥100 MeV protons than CME-driven shock acceleration. The solar flares either contribute directly to the production of the high-energy particles or provide superthermal particles for the further acceleration by the CME-driven shocks.

To be noticed that strong flares are, in some cases, not accompanied by SEP events if the flares are not accompanied by fast CMEs. Klein et al. [21] suggested that the flare-accelerated particles might be trapped in the flare site if the radio emission at decimeter and longer wavelength are absent. In other words, the flare is confined (not accompanied by a CME). If the solar flare is eruptive, the CMEs can open quite amount of magnetic configuration above the solar active region and make it easier for the escape of flare-accelerated particles. The CME-driven shock can further accelerate particles in high coronal site and in interplanetary space.

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