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Solar proton events during the solar cycle 23 and their association with CME parameters ☆

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ABSTRACT

We have studied the solar proton events associated with the coronal mass ejections (CMEs) and flares during the solar cycle 23 (1997–2006) in order to determine what physical parameters of the solar eruptions might control the SPE intensity and time profile. For total 63 SPEs, we found that (1) SPE rise time, duration time and decrease times depend on a CME speed (cc=0.34, 0.48 and 0.48) and (2) a SPE peak intensity depends on an earthward direction parameter of a CME as well as the CME speed and x-ray flare intensity (cc=0.40, 0.31 and 0.37). The SPEs were divided into two groups according to the correlation between the CME earthward direction parameter and the SPE intensity. First group consists of large six SPEs (>10,000 pfu at >10 MeV proton channel of GOES satellite) and shows a very good correlation (cc=0.65) between the SPE peak intensity and the CME earthward direction parameter. Second group has a relatively weak SPE peak intensity and shows no correlation (cc=0.01) between the SPE peak intensity and the CME earthward direction parameter we found that the first group SPEs are associated with a very fast halo CME (>1400 km/s) and most of those are located at disk except for only one case. Especially, large six SPEs have a good correlation with their associated CME earthward direction parameters, implying that these events are produced by ICME-driven shocks. We also found that those six SPEs are associated with the preceding CMEs originated from the same solar source region and a nearby pre-existing helmet streamer. Thus, we speculate that the preceding CME and helmet streamer might provide seed particles for CME-driven shocks and cause a clear separation between two groups.

1. Introduction

Solar flares and coronal mass ejections (CMEs) are the most powerful events in the solar system. In tens of minutes they can convert in excess of 10^{32} ergs of magnetic energy into accelerated particles, heated plasma, and ejected solar material. In this paper, we chose the word of "Solar Proton Events (SPEs)" instead of "Solar Energetic Particles (SEPs)" as we analyzed only proton data. Some large SPEs had a rise time (from a threshold to the maximum intensity) within tens of minutes. This rapid rise time, coupled with the high intensity, means that if astronauts had been on EVA (Extra Vehicular Activity) on the Moon, there would be very little warning before the significant enhancement of the SPE flux. Events of this nature need to be taken into account in planning astronaut operations and shelters on the Moon and in interplanetary space, which is because the space radiation exposure to a human body and spacecraft can make severe

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radiation hazards. In addition, the rapid rise places extreme requirements on models that accelerate SPEs by CME-driven shocks, because protons with energies >1 GeV must have been accelerated within minutes in the very low corona.

There is a substantial evidence that gradual SPEs observed at 1 AU result from an acceleration at coronal and interplanetary shocks driven by fast CMEs [1,2]. CME speeds have been found to be correlated with the peak intensities of the associated SPEs, but there is a very broad scatter. This weak correlation indicates a complexity in the SPE shock acceleration process that has not been fully understood.

Recently, several attempts have been made to explore the effects that variation in the coronal magnetic and particle environment might have in the resulting SPE production by CME-driven shocks. Enhanced decametric–hectometric (DH) emission was observed during interactions of a fast CME with a preceding slower CME [3,4]. The enhanced DH emission was interpreted as evidence for strengthening of a pre-existing shock of the slower CME and for the formation of a new shock in the fast CME. The basic interpretation was that the efficiency of particle acceleration is somehow enhanced when the primary CME runs into regions of enhanced density due to preceding CMEs or streamers [5].

The first large statistical study of $E>20$ MeV SPEs was probably that of van Hollebeke et al. [6]. Using 185 20 MeV $<E<$ 80 MeV SPEs from the Interplanetary Monitoring Platform (IMP) spacecraft, they focused on the early phases of SEP events and plotted times ΔT, from event onsets to maxima, as a function of solar source longitude. The time ΔT reached a minimum value of about 2.5 h around W50° and increased for larger magnetic angular separations between the Earth and the solar source longitude. Cane et al. [7] surveyed a larger sample of 235 SEP events and plotted as a function of solar source longitude the delay times from associated Hα flare maxima to peak SEP intensities, some of which were peaks at 1 AU shock passages. In each of three proton energy ranges spanning $\sim$1–100 MeV, those plots showed a pattern of delay times increasing from W90° to E90° source longitudes. A similar result was found for 112 $E>10$ MeV proton events by Balch [8]. The decay phases of gradual SEP events are characterized by a spatial and temporal invariance of the energy spectra, whose onset is ordered by the location of the observer relative to the interplanetary shock [9,10]. Statistical analyses of $E>4$ MeV proton event decay phases show a tendency for event decay times to decrease with higher shock speeds and with steeper energy spectra [11], supporting the interpretation of adiabatic deceleration of SEPs quasi-trapped behind large-scale expanding shocks.

Since CMEs are the drivers of shocks that accelerate SEPs, we might expect that the characteristics of the SEP intensity–time profiles observed at 1 AU are determined by properties of the associated CMEs. For example, faster CMEs may drive shocks for longer periods of time, resulting in SEP events of longer duration or rise times, as may be the case with $E>300$ keV solar electrons [12]. Accelerations of CMEs have been the focus of considerable work since Sheeley et al. [13] described two classes of CME speed profiles observed in the range 2–30 $R_\odot$, those gradually accelerating to 400–600 km/s and those with nearly uniform speeds typically in excess of 750 km/s. The second class are candidate drivers of interplanetary shocks and hence important for SEP events [2]. Moon et al. [14] found that the second class is more likely associated with flares and shows decelerations slightly increasing with speeds. Kahler et al. [15] showed that rising time and duration time of SPEs are well correlated with the CME speed; it is consistent result with the shock model of the SPE production. Recently, a new geoeffective CME parameter, which is an earthward direction parameter representing the degree of symmetry of the CME front was suggested and its importance was demonstrated [14,19]. In this study, we examine the correlation between the CME direction parameter and the SPE flux. For this, we use most of the SPEs measured by NOAA's GOES satellites during solar cycle 23.

2. Data

We used SPEs (intensity >10 pfu, with 1 pfu = 1 proton/cm^2/s/sr) in the >10 MeV channel of the GOES instrument from 1997 to 2006. GOES data are available on line from NOAA Space Environment Center [16]. Of total 94 SPEs during this period, we studied 63 SPEs whose CME parameters are available. For an estimation of the CME direction parameter, we follow the method suggested by Moon et al. [14] using almost halo CMEs. Then our SPE dataset cover the 67% (63/94) of all the SPEs during solar cycle 23. We investigated LASCO CME catalog based on SOHO coronagraph [17] and flare list from NGDC website based on GOES SXI [18] to examine what physical parameters of solar eruptions might control the SPE intensity and time profile.

Fig. 1 shows the schematic diagram of typical gradual SPE time profile. The threshold of SPE (horizontal dashed line) indicates 10 pfu (particle flux unit) threshold at 10 MeV proton energy channel from GOES satellite. The SPE start time is the time of initially facing the threshold line, peak time is when the SPE intensity is on the peak

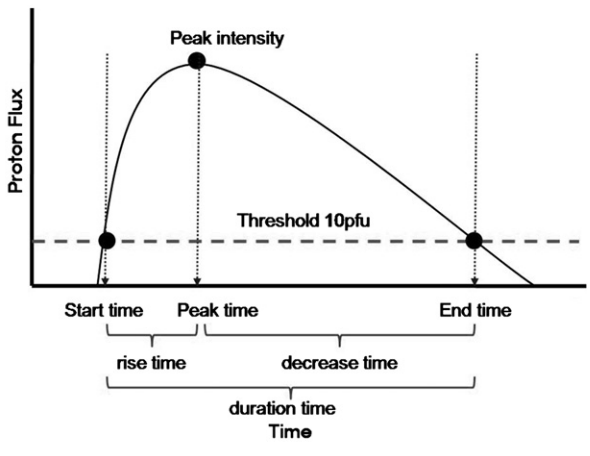

Fig. 1. Schematic diagram of a gradual SPE time profile.