Probing successive coronal mass ejections using high-energy protons

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***Abstract*. We report on four multi-eruption solar energetic particle (SEP) events observed by Energetic and Relativistic Nuclei and Electron (ERNE) instrument on the Solar and Heliospheric Observatory (SOHO). All the events were gradual (SEP) events associated with two solar eruptions. One event was observed on 2001 October 19–21, in association with two X1.6/2B solar flares and halo coronal mass ejections (CMEs) separated by ∼15 hours. The event observed on 2000 April 04–06 was associated with two CMEs separated by ∼8 hours. The two other events were observed on 2000 February 17–19, in association with two CMEs separated by ∼13 hours, and on 2000 September 12–14, associated with two CMEs separated by ∼5 hours. We had analyzed the first two events in detail and found a second peak in 10–100 MeV protons associated with changes in proton flux anisotropy, energy spectrum and in He/p ratio. The observational data suggests that the second acceleration of 10–100 MeV protons occurred behind the first CME and the previous CME was not an obstacle for the new particles to directly access 1 AU in both events. The proton flux anisotropy data support the idea that the particle production significantly declined in about 10 hours after the first eruption, while the prolonged temporal profiles of the solar energetic particle events were due to a slow transport of previously accelerated particles in the interplanetary space.**

***Keywords*: acceleration of particles — Sun: coronal mass ejection**

I. INTRODUCTION

In a recent view of SEP events associated with CMEs, there are two phases of acceleration for high-energy particles. Firstly, when particles can escape the magnetic field in the beginning of the eruption after CME liftoff, and secondly by driven-shock created by a fast CME beyond 3 solar radii, which can lead to continuing acceleration (e.g., [13]). Gradual events combine both phases and thus have prolonged intensity-time profiles that last for days, which is thought to be due to continual shock acceleration as the shock is propagating in the interplanetary medium. There has been much debate over the role of each mechanism in the acceleration process, and to what particle energies each process is capable reaching. The most widely accepted mechanism for particle acceleration in gradual SEP events is diffusive shock acceleration in CME-driven shock waves in the solar corona and in IP space (e.g., [4], and references therein). Theoretical work suggests that protons could be accelerated by the shock to 1 GeV in tens of minutes [2]. On the other hand, it was suggested [9] that the CME may play the role of a trigger or even contribute to the buildup of magnetic stresses in the corona, but its bow shock is not the main accelerator of the high-energy protons.

Modeling [14] suggests that to accelerate protons to energies >10 MeV, starting from much lower energies, the parallel shock has to propagate into a medium with a very short scattering mean free path, while it may pose major problem for prompt particle access to 1 AU. This favors particle acceleration close to the Sun, where the shocks can be almost perpendicular, rather than in the solar wind, where one may expect shocks to propagate predominantly parallel to the ambient magnetic field. In a statistical study including 44 events associated with interplanetary shocks [15], it was found that in most events the shock acceleration efficiency decreases with increasing radial distance. Thus, most of the shocks are efficient accelerators close to the Sun, but there is a strong decrease in acceleration efficiency at few tenths of an AU.

In multi-eruption solar energetic particle (MESEP) events the order of the two types of acceleration might be inversed, since particle acceleration of shock wave of earlier CME might be followed by coronal acceleration of new CME or flare at the Sun. In such cases observation of coronal accelerated particles can be seen as a second peak in the intensity time profile, if it is not masked by the previous event. Even if the particle intensity related to shock acceleration masks the later accelerated solar particles, the changing in the anisotropy and abundance of compositions still can lead to the finding of new particle streaming from the Sun. In some cases the changing in the intensity-time profile might occur simultaneously with changing in anisotropy and abundance ratio. Observations of such events have been presented lately in [1] and [12], and it was concluded that shock acceleration of SEPs by the first CME above 0.2 AU was doubtful in these events, and the turbulent medium at CME bow shock became transparent for >10 MeV protons. Fast deceleration of a CME might be one reason for decaying of shock acceleration efficiency but still further investigations are needed. Coronal accelerated particles of a new eruption can not be observed from behind a previous CME unless the particles find a pass through the previous interplanetary shock or around it.

In this study we report on four double eruption events, all associated with two CMEs. Careful analysis for 2001 October 19–21 and 2000 April 4–6 SEP events by examining the SEP flux anisotropy, ^{4}He/p ratio, as well as the in-situ magnetic field, shows a new SEP acceleration due to second CMEs from behind the previous shock waves that has been later registered on board *SOHO*, *Wind* and *ACE*. Observation of such energetic particles which might have penetrated the interplanetary shock to reach the Earth can sample a new view of shock wave behavior during its propagation in the interplanetary medium.

II. Observations

On October 19, 2001, April 04, 2000, February 17, 2000 and September 12, 2000, the proton intensity on board SOHO/ERNE rose on up to tens of MeV energies over the cosmic ray back-ground in each event, indicating a clear SEP event that was related to eruptions at the Sun. In particular, the onset of the energetic protons >90 MeV was observed by *SOHO*/ERNE at 01:57 UT on October 19, 2001, and at 15:50–17:06 UT for proton energies 3.3–67 MeV, on April 04, 2000, (see Figs. 1 and 2). The timing of the onset is well associated with the CMEs, as shown in Table I.

All of the first CMEs (hereafter CME 1) were characterized as halo CMEs. The halos were all associated with solar flares and accompanied by radio emission. The high energy detector (HED) of the ERNE instrument is pointing to the nominal Parker spiral direction, θ=0°, ϕ=315° GSE, and its wide view cone (120°x120°) is divided into 241 directional bins, from which anisotropy of proton and helium fluxes can be measured (see also [8]). The lower left panel in Figs. 1 and 2 show the first anisotropic SEP event registered with *SOHO*/ERNE October 19, 2001, and April 04, 2000, and is clearly associated with the first solar eruption in both events.

All the CMEs 1 are associated with type II metric radio emission which indicates shock waves propagating in the solar corona. In addition to metric type II observation, the decametric type II, which is usually ascribed to shock wave driven ahead of CME piston (e.g., [18]), and the shock passage registered in each event, are more evidence that those halos were associated with shock waves. However, decaying anisotropy suggests that the acceleration by the CME 1 driven shock doesn't last very long.

The CMEs 1 in the October 19, 2001 and February 17, 2000 events seem to be decelerating according to the measurements of Large Angle and Spectrometric Coronagraph LASCO on board SOHO. The CMEs 1 in April 04, 2000 and September 12, 2000, are indicated as decelerating interplanetary CMEs by [16], where the propagation of the shock through the interplanetary

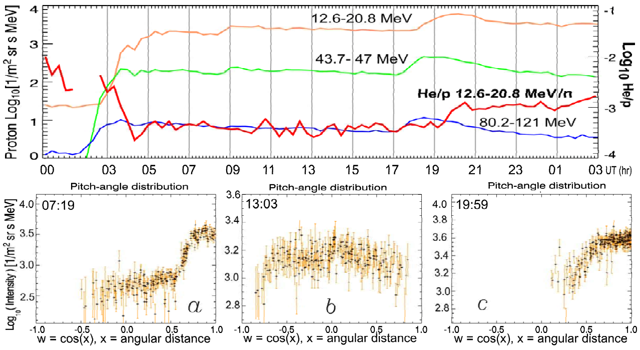

Fig. 1: In the upper panel, the intensity-time profile of protons and the ^{4}He/p ratio is shown for the event of 19 Oct 2001. In the lower panel, the anisotropy of 16.9-22.4 MeV protons at three distinct times is given, with time integration of 20 minutes. The 241 measuring points from the view cone of the HED instrument form the corresponding pitch angle distribution. The magnetic field direction, required for the determination of the pitch angle dirstribution, was obtained from the ACE/MAG instrument, using the 16 second magnetic field measurement integrated to the same time interval.

TABLE I: Characteristics of associated eruptions

CME 1	19.10.01	04.04.00	17.02.00	12.09.00
FC2AT[1]	01:27	16:32	21:30	11:54
CPA[2]	Halo	Halo	Halo	Halo
Width[3]	Halo	Halo	Halo	Halo
Speed[4]	558	1188	728	1550
Acc[5]	-25.6	12.8	-22.9	58.2
Flare[6]	00:47	15:12	20:17	11:31
Class	X1.6	C9.7	M1.3	M1
Hα	N16W18	N16W66	S29E07	S17W05
AR[7]	9661	8933	8827	–
Type II[8]	00:58	15:25	20:25	11:42
D-H II[9]	01:15	15:40	20:42	12:00
SPD[10]	21.10.01	06.04.00	20.02.00	15.09.00
SOHO[11]	16:05	16:01	20:56	04:15
ACE[11]	16:12	16:04	20:45	03:59
Wind[11]	16:40	16:27	21:00	04:28
CME 2	19.10.01	05.04.00	18.02.00	12.09.00
FC2AT[1]	16:50	00:06	09:54	17:30
CPA[2]	Halo	212°	268°	Halo
Width[3]	Halo	68°	118°	Halo
Speed[4]	901	898	890	1053
Acc[5]	-0.7	-2.0	-9.6	-17.3
Flare[6]	16:13	–	–	–
Class	X1.6	–	–	–
Hα	N15W29	–	–	–
AR[7]	9661	–	–	–
Type II[8]	16:24	No	09:13	No

[1]First LASCO/C2 Appearance Time [UT]
[2]Central Position Angle in degree
[3]Angular Width in degree
[4]Linear Speed of LASCO CME [km s^{-1}]
[5]Acceleration of LASCO CME [m s^{-2}]
[6]Starting time of soft X-ray emission [UT]
[7]NOAA Active Region
[8]Metric type II starting time [UT]
[9]Decametric–Hectometric type II starting time [UT]
[10]Shock Passage Date at 1 AU
[11]Shock passage time for a given spacecraft

medium was studied using the observations of the low frequency type II radio emission.

In the October 19, 2001 event, the proton intensity-time profile shows the first maximum and a decay, followed by a next enhancement and new maximum (Fig. 1) associated with CME 2 (Table I). At that time the difference in heliocentric location between the CME 1 and CME 2 was about $50R_{\odot}$ (see Table 2 in [17]). The starting of the second enhancement in the three energy channels of Fig. 1 shows a clear sign of velocity dispersion, as the enhancement starts in the three energy channels at 18:06 UT, 17:27 UT and 17:10 UT, respectively. Also the time of the second maximum follows the same pattern, with the maxima at 20:08 UT, 19:29 UT and 19:01 UT, respectively.

In the April 04, 2000 event, a new intensity rise was observed in SEPs in association with the CME 2 (Table I) when the CME 1 was at about 60 solar radii, extrapolating from the LASCO observations. The first SEP event masked the raising phase of the new particle event, so that a velocity dispersion in the second event can be found only in the maximum intensity time observed in the different energy channels (e.g., peak time of 6 MeV protons is at 08:06 UT $\pm$10 min, while at 24 MeV it is at 04:33 UT $\pm$10 min both on April 5, 2000).

While the onset determination of the second injection is complicated in these two events, its existence can be seen through other observations. New streaming of $\sim$20 MeV protons in both events was detected with ERNE/HED by the change in their pitch angle distribution (Figs. 1c and 2b). These new onsets were associated with changes also in the proton energy spectrum and in the He/p abundance ratio (upper panel in Figs. 1 and 2). It also seems that there are no special features in the interplanetary medium between Sun and Earth due to Interplanetary CME (ICME) according to [7], and [10], no effect of stream interaction region (SIR) according to [11], during the two events.

We conclude that the observed anisotropy, abundance changes and the observed velocity dispersion of the event, along with the lack of well-correlated local magnetic field changes, strongly suggests that the particles at the second rise originate from a second acceleration at the Sun, related to the X1.6 solar flare and the associated CME 2 driven shock in October 19, 2001, and the related CME 2 in April 05, 2000, respectively.

III. Discussion and Conclusion

We report four gradual SEP events detected by SOHO/ERNE, all associated with CMEs, flares and radio emission as expected (e.g., Table 2 in [5]). The current paradigm as formulated by Reames ([3], [4]) suggests that energetic particles in gradual events are continuously produced at CME bow shocks during their transit to the Earth's orbit.

The traditional view of an interplanetary CME consists of a flux-rope type structure, with rotating magnetic

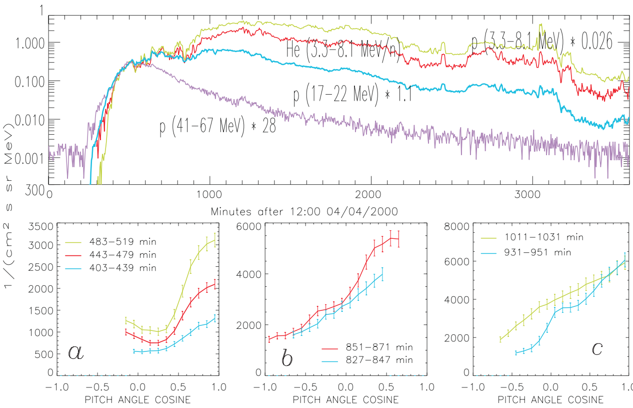

Fig. 2: Event of April 04-06, 2000. Upper panel shows re-normalized intensity-time profiles of SEPs observed with *SOHO*/ERNE, for three different energy channels and the ^{4}He/p ratio. Lower panels show the 17–22 MeV proton pitch angle distributions from the *SOHO*/ERNE/HED particle telescope for a few selected time intervals. Original 241 measuring points have been combined into wider bins

field, driving ahead of it a shock wave (see, e.g., [19], and references therein). Between the shock and the flux-rope, there is a sheath-region, which contains highly turbulent, shocked plasma. Thus, it would be difficult for particles from solar eruptions behind a previous CME to find access to the observing instruments near the earth. Should this take place, the particles would have to either find magnetic field lines around the flux rope or field lines through the flux rope, and subsequently propagate through the sheath turbulence. If the particles produced by CME 2 go around the flux rope of CME 1, they might be able to avoid the turbulent region completely. However, such a scenario implies that the 'observer' had lost magnetic connection to CME 1 before the CME 2 started, while we do not find any signatures of the disconnection in the SEP data.

The energetic protons after the second CME liftoff in October 19-21, 2001, and April 04-06, 2000, events were clearly anisotropic (Figs. 1c and 2b), although slightly less anisotropic than the primary event protons. The intensity of the protons from the second eruption is clearly higher than the intensity of the first eruption protons (at least in some energy channels), and a new peak in the intensity-time profile emerges. Thus, we experience here a masking of the rising phase of the second peak. On the other hand, this indicates that the acceleration of the particles in the second eruption is stronger than the interplanetary shock-accelerated component of the first eruption.

The escaping particles from the coronal shock of the second eruption have not been trapped behind the interplanetary shock of the first eruption. If the particles have access to magnetic field lines through the first CME-driven shock, the shock and the turbulence in the downstream of the shock should have weakened sufficiently to allow sufficiently easy access for the particles through to the spacecraft at 1 AU. As an alternative, the particles may have access to field lines that curve around the CME structure, which can not be ruled out in the September 12, 2000 event, where the CME 2 has possibly erupted from the NE while the CME 1 from SW, but further study is needed to confirm such assumption. One may also speculate that the spacecraft reaches a magnetic tube with new SEP population. The velocity dispersion and a lack of evidence in the magnetic field data, however, render this unlikely.

If the particles from the second particle enhancement do propagate around the first CME structure, this should be seen as an anomalously long pathlength for the first particles, as seen in, e.g., velocity dispersion analysis. The application of this method, however, is very difficult, as the onset of the second eruption is masked by the particles from the first eruption. On the other hand, careful analysis of the anisotropies and temporal behavior of the particle intensities may reveal whether the particles of the second particle enhancement have experienced stronger scattering, due to the very turbulent ICME sheath region. While the applicability of both of these approaches may prove difficult, the benefits of such studies are clear, as the particles that either penetrate through the ICME or go around it act as probes into the structure of the interplanetary CME. The proposed particle telescope LET on *Solar Orbiter* will allow investigating the SEP energy range 1.5–20 MeV nucleon^{-1} with 3-D anisotropy information both in and out of the ecliptic plane [6]. In situ observations of shocks and SEPs on *Solar Orbiter*, with its orbit perihelion at 0.23 AU, could refine the scenario inferred from the 1 AU data.

The new evidence that we found of an enhancement in those large SEP events from a second injection of new SEPs due to second eruption on the Sun leads us to conclude the following:

1) The decelerating shocks seem to be unable to accelerate > 10 MeV proton at distances > 0.2 AU from the Sun in these events
2) The particles accelerated at the second eruption most probably penetrate the interplanetary shock wave of the first eruption, since we observe particles related to this eruption near Earth. Further study is needed for understanding the transport of the particles in such events.
3) The paradigm of single shock continuing acceleration in gradual events up to 1 AU is inconsistent with those events, and thus the classification of SEP events has to be adjusted, since in multi-eruptions events several separate solar particle events can participate in forming one seemingly single intensity-time profile.
4) Participation of further enhancement in multi-eruption SEP events can be determined through careful analysis of anisotropy, ^{4}He/p ratio, local magnetic structures and velocity dispersion.
5) The particles interacting with an ICME before detection may reveal details of the ICME structure.

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