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LETTER TO THE EDITOR

Observation of a solar energetic particle event behind previous coronal mass ejection

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ABSTRACT

On 2001 October 19–21 the Energetic and Relativistic Nuclei and Electron (ERNE) instrument on the *Solar and Heliospheric Observatory* (*SOHO*) observed two gradual solar energetic particle (SEP) events separated by 15 h, in association with two X1.6/2B solar flares and halo coronal mass ejections (CMEs). The observational data suggest that the second acceleration of ~10−100 MeV protons occurred behind the first CME and the previous CME was not an obstacle for new particles to directly reach 1 AU. The proton flux anisotropy data support the idea that the particle production significantly declined in about 10 h after the shock wave started, while the prolonged temporal profile of the solar energetic particle event was due to a slow transport of previously accelerated particles in the interplanetary space. These observations call into question the view that in all gradual events high-energy particles are continuously produced at a CME bow shock as it travels from near the Sun to beyond 1 AU.

Key words. acceleration of particles – Sun: coronal mass ejections (CMEs)

1. Introduction

The widely accepted impulsive-gradual paradigm of solar energetic particle (SEP) events is an empirical classification system developed step-by-step by combining SEP data, solar flare observations in the X-ray and radio bands, and more recently observations of coronal mass ejections (CMEs) (Lin 1974; Van Hollebeke 1975; Pallavicini et al. 1977; Kocharov et al. 1983; Cane et al. 1986; Reames et al. 1990; Kallenrode et al. 1999; Lin 1994; Reames 1995; Cliver 1996). A refined formulation by Reames (1995) suggests that impulsive SEP events are short (hours) and have high abundance ratios of ^{4}He/p and ^{3}He/^{4}He, while gradual events are prolonged (days), with low values of both helium abundance ratios and are associated with CMEs and interplanetary shocks. The current paradigm suggests that gradual SEP events originate from the continual acceleration of particles at the CME-driven bow shocks in the solar wind. However, there is increasing evidence that the current paradigm is significantly oversimplified (Cane et al. 2002, 2003, 2006; Klein & Trottet 2001; Simnett 2006)

Fast CMEs with velocity >500 km s^{-1} are expected to form bow shocks at ~3−5 solar radii from the Sun and the CME-driven shocks in interplanetary space are thought to be a source of accelerated particles in the gradual SEP events (Reames 1999). In front of the CME bow shock, in its upstream region, the accelerated protons may excite MHD waves to form a turbulent sheath. Within the turbulent sheath, with its fluctuating magnetic field components, the energetic particle scattering mean free path, λ, is small and the diffusive shock acceleration of the particles is rapid (e.g., Toptygin 1985). Behind the bow shock, the shock downstream region is also turbulent. There the upstream turbulence is compressed and enhanced by the shock. At small values of the mean free path the particle diffusion through the sheath is slow and the shock can accelerate particles to high energies. Such a regime is typically assumed for the SEP-productive shocks. At large values of λ the shock turbulent sheath is transparent for SEPs and the diffusive shock acceleration is not significant.

Multi-peak SEP events are occasionally observed in space, but the secondary peaks typically do not attract much attention, partially due to masking of the onset of particle injection from a later eruption by the previous one. Some secondary peaks appear simultaneously in all energy channels, indicative of the spatial structures encountered by a spacecraft. However, in some events, the SEP abundance changes, flux anisotropy and velocity dispersion can give strong evidence of freshly-accelerated solar energetic particles (Al-Sawad et al. 2006). There have been a few studies of the effect of multiple eruptions on SEPs. Higher SEP intensity has been observed in events where a CME is preceded by another wide CME from the same source region, even with long time differences between them (Gopalswamy et al. 2004).

For the present study we selected a double-eruption SEP event on October 19−21, 2001 observed with the particle instrument *SOHO*/ERNE, and examine the SEP flux anisotropy, ^{4}He/p ratio, the in-situ magnetic field, and the two associated solar flares and CMEs that occurred more than half a day separated from each other. Particles of a second eruption can sample the interplanetary structures disturbed by the previous CME and hence can carry information not only on their source near the Sun, but also on the previous CME-shock complex responsible for the first SEP event. This will help us place new limitations on the sources of gradual solar energetic particle events.

2. Data analysis

Figure 1 shows the SEP, solar wind and X-ray profiles of the October 19−21, 2001 event. On October 19, *GOES* detected in

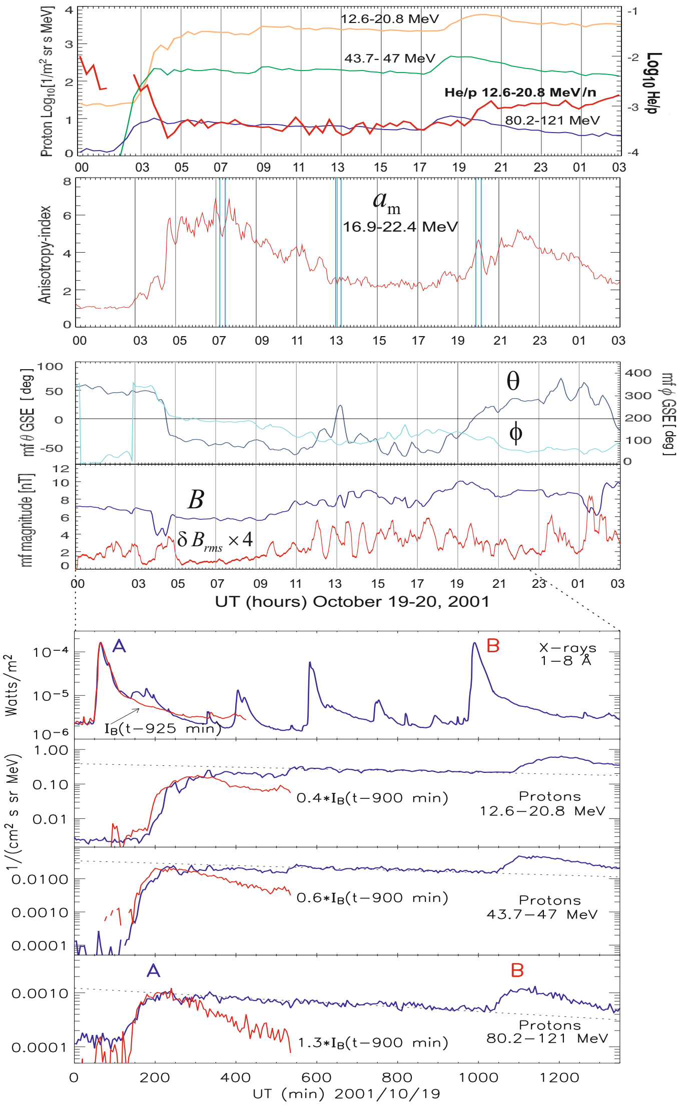

Fig. 1. Two upper panels show the proton intensity-time profiles in three energy channels of ERNE/HED, ^{4}He/p-abundance ratio and proton flux-anisotropy index, a_m. The pairs of vertical lines in the second panel indicate the time periods from which proton angular distributions are presented in Fig. 2. *Middle panels* shows the magnetic field direction angles in the GSE coordinates, θ and ϕ, the magnetic field intensity, B, and its 20-min-running-average root-mean-square fluctuation, δB_rms, observed with *ACE*/MFI. *Lower panels* shows the soft X-ray profile observed with *GOES-8* and the high-energy protons observed in association with X-ray flares A and B. *Red* curves additionally show profiles of the event B shifted to the time of event A. An overall similarity between the events as well as some differences and time shifts are clearly seen. The proton profiles of the event B in all energy channels are similarly shifted in time, while the energy trend of the re-normalization factor indicates a softer spectrum of event B compared to event A.

Hα at the location N16W18 from NOAA active region 9661 a X-ray flare of class X1.6, which started at 00:47 UT and lasted for 26 min. Later, onboard *SOHO* the Large Angle and Spectrometric Coronagraph (LASCO) observed a halo CME, of a linear velocity of 558 km s^{-1}, with brightness asymmetry at 01:27 UT at 2.86 $R_\odot$ from the same active region. The CME liftoff time according to a quadratic fit is 00:44 UT ± 18 min. The onset of the energetic protons >90 MeV was observed by *SOHO*/ERNE at 01:57 UT. the injection time calculated for the first, non-scattered protons traveling on of nominal path length of 1.2 AU was at 01:44 UT ± 8 min, when the leading edge of the CME was at 4.0 ± 0.7 $R_\odot$. As an alternative method to analyze the onset time, we used a velocity dispersion analysis. The injection time of the protons by this method is at 01:23 UT ± 6 min, with the protons having traveled through a path length of 2.2 ± 0.19 AU. At this time, the leading edge of the CME was at 2.5 ± 0.6 $R_\odot$. A metric type II radio burst, caused by a shock propagating away from the Sun, seems to start at 00:58 UT, preceded by a type IV burst. A decametric type II burst was observed by *Wind*/WAVES starting at 01:15 UT. The SOHO-observed protons were released well after the launch of the halo CME and after the associated shock formation. On October 21, 2001, the shock passage was registered near the Earth's orbit, by SOHO, ACE and Wind spacecrafts at 16:05, 16:12 and 16:40 UT, respectively.

The high energy detector (HED) of the ERNE instrument is capable of measuring anisotropy with very high accuracy within its wide viewcone of 120° × 120° around the nominal interplanetary magnetic field direction (e.g., Torsti et al. 2004). Using its 241 directional bins, we define a proton flux anisotropy index, a_m, within the instrument's view cone as the difference between the five highest and the lowest thirty intensities in the directional bins divided by a proper mean deviance. A pitch-angle distribution can be found with respect to the current magnetic field direction. *SOHO* does not have a magnetometer on board, but a likely magnetic field direction can be found by fitting an axially-symmetric function to the SEP pitch-angle distribution (Torsti et al. 2006) or alternatively the magnetic field direction can be taken from the *ACE*. The direction of the SEP symmetry axis is indicated in Fig. 2 upper panels with a white square and the deflection angles of 5°, 30°, 60° and 90° are marked with circles. The symmetry axis directions were used when creating the pitch angle distributions in the lower panels of Fig. 2. With triangles we show the direction along the interplanetary magnetic field line towards the Sun, as measured by *ACE*. We show the anisotropy index for these events in the second panel of Fig. 1. The upper panels in Fig. 2 show the directional distributions at time intervals indicated by the vertical paired lines in the second panel of Fig. 1 for protons from the energy range 16.9−22.4 MeV. The pitch angle distributions for these periods are shown in the lower panels of Fig. 2.

The first anisotropic SEP event was registered with *SOHO*/ERNE at around 2 UT on October 19, 2001, and is clearly associated with the first solar eruption. The anisotropy index (Fig. 1) reaches its maximum 4 h later, and decays into low anisotropy 12 h after the first SEP event onset. By this time, the CME has reached a height of 0.16 AU, assuming a linear CME velocity of 558 km s^{-1} (the SOHO/LASCO observation).

A series of M-class flares followed the first X1.6 flare and halo CME, from different positions on the solar disc. At 16:13 UT *GOES* detected another X1.6 solar flare from the same active region while the Hα location had changed, mainly due to solar rotation, to N15W29. The soft X-ray emission lasted for 30 min, reaching its maximum at 16:30 UT. The LASCO coronagraph detected a new halo CME, with a linear velocity of 901 km s^{-1}, also with brightness asymmetry at 16:50 UT at a heliocentric location 2.78 $R_\odot$ from the same active region associated with the flare. Between 16:24 and 17:00 UT, several metric type IIs and type IVs were observed, suggesting again the existence of CME-associated shocks. The difference in heliocentric location between the first CME and the new one at that time was 46.9 $R_\odot$ (see Table 2 in Gopalswamy et al. 2004).

The start of the second SEP enhancement in the three energy channels of Fig. 1, 12.6−20.8 MeV, 43.7−47 MeV, and

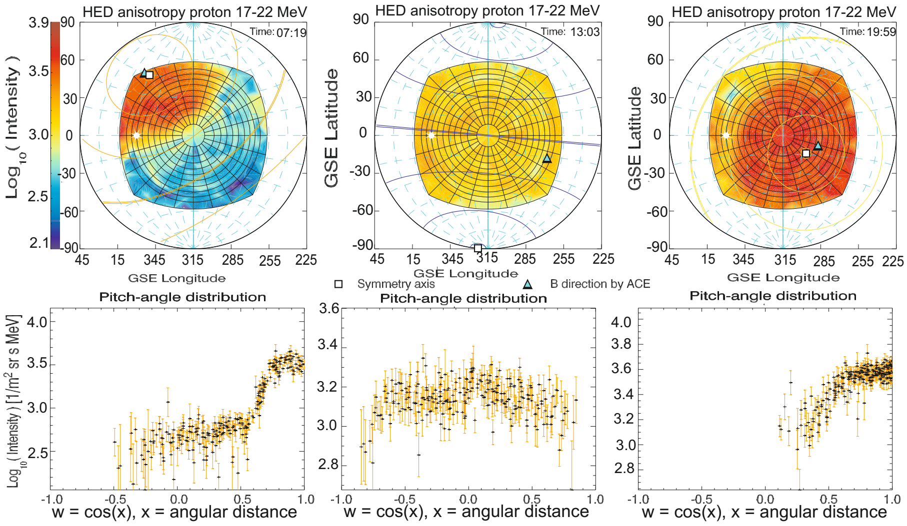

Fig. 2. Angular distribution of the 16.9−22.4 MeV proton flux measured by the ERNE/HED instrument at three distinct 20-min intervals indicated in the second panel of Fig. 1. *Upper panels* show the instrument's view cone in the GSE coordinates. The direction of the Sun is indicated with a star left of the view cone center. The full circle area with coordinate lines is the hemisphere which ERNE is pointing, and the semi-rectangular borders indicate the borders of the view cone. The 241 data points, corresponding to the 241 segments of the view cone, form the pitch angle distributions in *the lower panels*.

80.2−121 MeV, shows a clear sign of velocity dispersion, that is, the higher energy particles reach the spacecraft before lower energy ones, as the enhancement starts in the three energy channels at 18:06 UT, 17:27 UT and 17:10 UT, respectively. 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. The anisotropy index increases again, related to this intensity rise. The ^{4}He/p abundance ratio (Fig. 1) reveals significant differences between the two events, while the ratios in both events are well within the characteristic range of gradual SEP events, $^4\mathrm{He/p} \ll 0.1$. It is thus clear that the new SEP enhancement is related to the second X1.6 flare and halo CME.

3. Discussion and conclusions

Two X1.6/2B solar flares on October 19, 2001, peaking at 01:05 UT and 16:30 UT from AR 9661 at N16W18 and N15W29, respectively, were accompanied by two SEP events registered by *SOHO*/ERNE. Both eruptions produced halo CMEs and shock waves observed with *Wind*/WAVES. The lower panel block of Fig. 1 illustrates the remarkable similarity of those eruptions in terms of X-ray emission and high-energy protons at 1 AU. In Fig. 1 we have shifted the X-ray profile of the second flare (flare B) by 925 min to visualize its similarity to the profile of the first flare (flare A). In a similar manner we have also shifted the proton intensity profiles of the eruption B to get them close to the corresponding profiles of eruption A, with the pre-event-B "background" subtracted (the subtracted part is shown with the dotted line) and with re-normalization by an energy-dependent factor ~1. The time shift between the proton events is 25 min shorter than the time shift between the flares, which means that the B-event protons arrived at *SOHO* 25 min earlier with respect to the flare B than the A-event protons did with respect to their flare. The energy spectrum of the ~10−100 MeV protons in event B was slightly softer than in event A, and the ^{4}He/p abundance ratios of the two events were different. The differences may be a pattern of rotational stereoscopy in SEPs, i.e., they may be caused by the difference in the angular distance between the Earth-connected longitude and the eruption center, which in turn is due to the solar rotation between the flares A and B.

The current paradigm formulated by Reames (1995, 1999) suggests that energetic particles in gradual events are continuously produced at CME bow shocks during their transit to the Earth's orbit. The classic interplanetary CME consists of a flux-rope-type structure driving ahead of it a shock wave, with a highly turbulent sheath region between the flux rope and the shock (see, e.g., and Zurbuchen & Richardson 2006, references therein). Particles can be accelerated to high energies in a turbulent medium at the CME bow shock, which is thought to be a moving source of SEPs in gradual events. Our event A has an extremely high p/^{4}He ratio and a prolonged intensity-time profile (Fig. 1). It is associated with a halo CME and a shock wave observed near the Sun with *Wind*/WAVES and at 1 AU with *SOHO*/CELIAS, which suggests that the shock transit speed is 650 km s^{-1}. Considering event A without SEP anisotropy data and without event B, a straightforward interpretation would be a gradual SEP event being continuously produced by the CME bow shock, with *SOHO* continuously staying on magnetic field lines connected to the shock.

This event, however, presents severe challenges for such an interpretation. We prove the conflict with the current paradigm by the rule of contraries. Indeed, there were no dropouts observed in the SEP intensity. If continual acceleration at the CME bow shock on open magnetic field lines was the source of all energetic particles, as the current paradigm suggests, one has to conclude that there was a continual magnetic connection to the shock driven by the first CME. Hence, one has to conclude that the onset of the second SEP event was observed on the magnetic field line connected to the shock of the first CME. A free penetration of the second-event particles through the shock acceleration region of the first CME seems inconsistent with our understanding of the turbulent sheath near the SEP-productive shock. Besides, a prolonged production of SEPs on standard, Archimedean magnetic field lines suggests a prolonged anisotropy of the particle flux from the source, while in this event the anisotropy vanishes almost completely within 12 h, and increases again only at the start of the second event (B). Thus, the traditional scenario does not explain the features of the observed events.

As a plausible alternative, we propose that the relatively slow shock of eruption A was SEP-productive only near the Sun, while a temporal trapping of SEPs in a possible solar wind structure with a bottleneck behind the Earth's orbit (e.g., Bieber et al. 2002) resulted in extended intensity-time profiles with low values of the SEP flux anisotropy. At distances >0.2 AU from the Sun, as suggested by the vanishing anisotropy, shock A became unable to accelerate high-energy protons, possibly by becoming quasiparallel and surrounded by not very turbulent plasma, or even by decaying completely on the Earth-connected magnetic field lines. Thus the CME-driven compression became transparent for the >10 MeV protons and the solar-accelerated protons of the event B were able to reach *SOHO* without significant attenuation by the interplanetary shock wave of eruption A.

The SEP anisotropy may be affected by different interplanetary magnetic field structures. We have looked for the possibility that *SOHO* might be inside a magnetic cloud caused by an interplanetary CME (ICME). Two statistical studies, by Cane & Richardson (2003) and Jian et al. (2006a), have produced ICME lists for solar cycle 23, but no ICME was reported during these SEP events. As another alternative of a local disturbance, we also checked the stream interaction region list by Jian et al. (2006b), and, again, no such structure was detected during the day of the events (see also the middle panel of Fig. 1). However, there were several eastern CMEs a few days before the eruption A, which could result in magnetic compressions (magnetic mirrors) at the Earth-connected magnetic field lines behind the Earth, forming a large scale magnetic trap for the SEPs produced near the Sun on October 19. A candidate for this is a partial halo CME observed at 06:06 UT on October 16 with a central phase angle 105°, final speed 752 km s^{-1} and mass $\sim 10^{16}$ g (*SOHO*/LASCO observations). An increase in the magnetic turbulence level after 09:30 UT October 19 (Fig. 1) can also contribute to the SEP isotropization and slowing down of their transport.

We focus on the deca-MeV range, where the *SOHO*/ERNE instrument provides high-quality proton flux anisotropy data, while the instrument's range extends down to ≈1 MeV. We note that the arrival of the shock at *SOHO* on October 21 was accompanied by an energetic storm particle event in the MeV range, while no enhancement was observed at >5 MeV.

The new evidence that we found of an enhancement in the of the October 19–21, 2001 events from a second injection of new SEPs due to a second eruption on the Sun, and the SEP flux anisotropy data of *SOHO*/ERNE, lead us to conclude the following:

1. The data call into question the view that in all gradual events the >10 MeV protons are continuously accelerated at a CME bow shock as it travels from near the Sun to 1 AU.
2. The data support the idea that in the 2001 October 19–21 events the high-energy particles were accelerated within 0.2 AU from the Sun and then temporarily confined in the interplanetary space.
3. The SEP flux anisotropy data are needed in each particular event and energy range to ascertain the particle source and to model the observed event.

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