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Observation of solar energetic particle (SEP) events associated with narrow CMEs

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Abstract. We report here on two proton energetic particle events observed by the Energetic and Relativistic Nuclei and Electron (ERNE) instrument on the Solar and Heliospherical Observatory (SOHO). Both events were impulsive (SEP) events with intensities of $> 10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}$ at an energy range of tens of MeVs and were associated with CMEs of angular widths $< 60°$ and linear speed of $> 800\,\mathrm{kms}^{-1}$. In one of the events there was no associated solar flare, which indicates that the first injected protons were completely due to the associated CME and in the second event the associated solar flare was an impulsive M1.1 class flare and the calculated first injection time for protons of energies ~ 36 MeV and propagating along 1.2 AU path length, was close to the liftoff time of the CME. These observations are inconsistent with the view presented in some studies that narrow fast CME are not associated with SEP events.

1 Introduction

Solar energetic particle (SEP) events are the most effective phenomena in solar physics, which have been taken into consideration in the discussion of the effect on spaceborn instruments and astronauts. The energy ranges in different classes of the SEP events are varying from some keV/nucl to some GeV, and they might have different sources such as solar flare in the low corona, coronal shock and interplanetary shocks driven by CMEs.

The role of CMEs and solar flares in accelerating the SEP has not been solved yet. There are different ideas about the roles of coronal and interplanetary shocks. On one hand, evidence achieved in the 20th century in several studies (e.g. Reames, 1990, 1995a, 1999; Cane, 1995; Kahler, 1992; Gosling, 1993; Dryer, 1994) suggested that energetic particles observed in large "gradual" SEP events are accelerated at shock waves driven out of the corona by CMEs. But on the other hand, Kallenrode (1996) suggested that a CME-driven shock may not itself accelerate significant numbers of particles out of the ambient solar wind to high energies, but it can confine and re-accelerate particles which were initially accelerated close to the sun. Between the two arguments, some recent studies indicate that SEPs may be produced also on the global corona scale between the impulsive flare and the interplanetary shock (Kocharov et al., 1999; Laitinen et al., 2000; Klein and Trottet, 2001).

SEP events associated with CMEs are well known to depend on the characteristics of the CMEs (Speed and angular width). Only when shock transit speeds exceed 500 km/s do SEP events become likely, while speeds of > 750 km/s always produce SEP events (Reames et al., 1997). Only the fastest $1-2\%$ of CMEs cause particle acceleration. Large and slow CMEs and magnetic clouds, even with the likelihood of substantial magnetic reconnection at the sun, do not produce SEPs, whereas fast CME-driven shocks do (Reames, 1999). For instance, the Earthward-directed CME on 6 January 1997 was studied widely and hence it was clear that this $< 500\,\mathrm{kms}^{-1}$ halo did not produce an SEP event (e.g. Wu et al., 1997; Cane et al., 1998; Torsti et al., 1998; Fox et al., 1998; Reiner et al., 1998; Webb et al., 1998; Sheeley et al., 1999). Torsti et al. (1998, 1999, 2001) suggest that shock waves on global coronal size scales (of about 1 solar radii) are necessary for particle acceleration associated with moderate speed CMEs. The maximum values of Coronal Alfvén speed VA are located between 2.5 and 3.0 solar radii, and the maximum values are between 650 and 750 km/s. The region where the Alfvén speed exceeds 600 km/s extends from 1.6 to 4.5 solar radii . Thus, CMEs with speeds in the range of less than 600 km/s may not be able to drive shocks at these distances (Vainio and Khan, 2004). No fast CMEs with widths less than 60° are associated with SEP events (Kahler and Reames, 2003). However, within the last 10 yr there is an increasing number of papers showing the presence of fast,

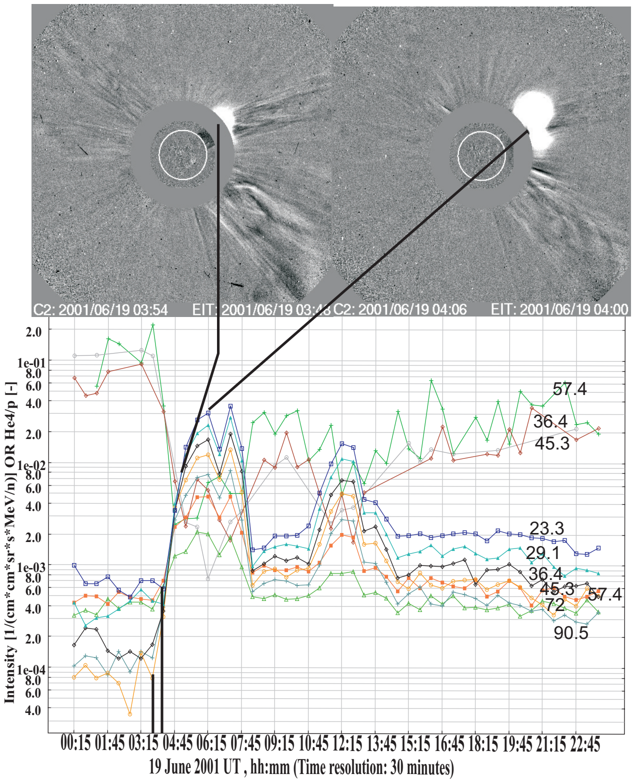

Fig. 1. Upper panel the Lasco C2 CME observed at two times interval. Second panel ERNE proton intensity-time profile and ^{4}He/p ratio. The 7 proton energy channels in MeV are: 23.3, 29.1, 36.4, 45.6, 57.4, 72 and 90.5. The 3 ^{4}He/p energy channels in MeV/nuc are: 36.4, 45.6 and 57.4.

narrow CMEs in a large number of impulsive SEP events (e.g. Kahler et al., 2001; Simnett et al., 2002; Wang et al., 2006).

2 Data analysis

In this study, we use the energetic proton observations from the SOHO/ERNE (Torsti et al., 1997) particle instrument, which consists of two particle telescopes, Low Energy Detector (LED) and High Energy Detector (HED). The identification of protons is based on an on-board algorithm, which provides intensities in the energy ranges $1.3-14$ MeV (LED), and $13-140$ MeV (HED), with a one minute time resolution. The particle data is accessible through the Erne Datafinder application, which can be found at http://www.srl.utu.fi/erne_data/.

Our data analysis is based on three combined methods to identify the real accelerator of the SEPs in the observed events. First, we employ the fixed path length method, where we use the same Archimedean spiral length for all events. For this method, we determined the injection time from the highest energy channel that was still consistent with the expected velocity dispersion. For the path length we used a value of 1.2 AU, which is often used in the event onset studies (e.g. Haggerty and Roelof, 2002; Cane, 2003). The value presumably originates from the path lengths of $1.1-1.3$ AU, obtained by Krucker and Lin (2000) for protons in the majority of their proton events, and for electrons in all their events. It should be noted that the Parker spiral length for a solar wind of velocity 400 km/s is below that value, at 1.14 AU. However, the three-dimensional structure of the magnetic field and fluctuations along the magnetic field may be expected to increase the path length, thus we find this difference explainable. In addition, the first observed particles have most likely already experienced some scattering, as the pre-event background prevents the distinction between the background and first event particles.

For the event (19 June 2001), we also determine the onset times for up to 20 Proton channels situated at energies (1.63, 1.97, 2.41, 2.98, 3.7, 4.61, 5.77, 7.24, 9.09, 11.4, 15.4, 18.9, 23.3, 29, 36.4, 45.6, 54.1, 67.5, 94 and 116) MeV, by using the same method as Huttunen-Heikinmaa et al. (2005). Assuming that particles with different energies are released simultaneously at or close to the Sun, the onset of the event at 1 AU should be observed earlier at higher energies than at lower ones. Assuming further that the energies of the particles remain unchanged through the passage in interplanetary space and that the path length does not depend on energy, it is possible to fit the release time of particles at the Sun and the path length travelled. This kind of analysis is called Velocity Dispersion Analysis (VDA), and it has been widely used (e.g. Debrunner et al., 1990, 1997).

Secondly, we use the ^{4}He/p analysis. Generally, it is believed that a different ratio of ^{4}He/p during specific period of SEP events indicates that we observe new injected SEPs from different source of seed population, or that we are entering a new magnetic field tube that contains a different ratio of species. The ratio of ^{4}He/p has been used to identify different classes of SEP events (e.g. Reames, 1990, 1993, 1995b; Reames et al., 1997; Kahler, 1992, 1994; Gosling, 1993; Cliver, 1996). Usually gradual events have a ^{4}He/p ratio of less than 10^{-2}. We used the ^{4}He/p measurements to identify the different period of cosmic background SEPs and injected SEPs. The tool of ^{4}He/p measurements can identify those cases if we join the results with other measurements such as velocity dispersion. Figure 1 shows the variation of the ^{4}He/p ratio, measured with high energy channels by HED in association with clear velocity dispersion.

3 Observation

We have selected 2 narrow CMEs among over 2000 CMEs during the solar cycle 23 which were associated with SEP events and had angular widths $< 60°$ and linear speed of $> 800\,\mathrm{km s^{-1}}$. A narrow CME is defined according to the angular width, being widest as a halo CME with 360° and decreasing until the less width $< 60°$, which is thought that CMEs with such width are not efficient for accelerating SEPs (Kahler and Reames, 2003). The angular width in this study has been taken from the LASCO measurements. Most of the narrow CMEs were occurring during multi-eruption SEP events with many powerful CMEs, which will result in masking the effect of the narrow CMEs, if there is such effect. Accordingly, we need a detailed study for the anisotropy flux for each multiple CME event.

We have carefully analyzed the event on 19 June 2001, since this event produced maximum intensity above $10^{-3}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}\,MeV^{-1}}$ on the > 90 MeV energy. On the 19 June 2001, onboard SOHO the Large Angle and Spectrometric Coronagraph (LASCO) observed a CME withan angular width of 58°, linear velocity of $817\,\mathrm{km\,s^{-1}}$ and acceleration of $-14\,\mathrm{km\,s^{-2}}$ at 03:54 UT at $2.7\,R_\odot$ from the northwest region of the solar disc at central position angle 292° (Upper panel Fig. 1). The CME liftoff time is 03:25 UT ±6 min taken as an average value for the extrapolation of both linear and quadratic fit. The onset of the energetic protons > 90 MeV was observed by SOHO/ERNE at 04:00 UT. The injection time calculated for the first, non-scattered protons traveling the nominal path length of 1.2 AU was at 03:44 UT ±8 min, based on the selectivity of the first rising protons for the 1 min resolution, when the leading edge of the CME was at $2.0 \pm 0.7\,R_\odot$. 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 03:46 UT ±9 min, with the protons having traveled through a path length of 1.5 ± 0.26 AU. At this time, the leading edge of the CME was at $2.2 \pm 0.8\,R_\odot$. The error of the estimated CME location is based on the error of the proton injection time and on the linear velocity and acceleration of the CME. Clear metric fundemental+harmonic type II radio burst lanes (Solar Geophysical Data listings (NGDC)), caused by a shock propagating away from the Sun, seem to start at 03:35 UT. The SOHO-observed protons were released well after the launch of the CME and after the associated shock formation. There was no soft X-ray observation during the SEP event time indicating no solar flare association and that the event is totaly due to the CME.

The maximum intensity was $3.00 \times 10^{-3}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}\,MeV^{-1}}$ on the > 90 MeV energy . Due to the difference in time-shifting between the real profile of the intensity and the observed one, the time of real maximum injection can not be fitted as the time of observed maximum intensity, although the time of maximum injection can not occur after the time of maximum intensity. Thus we consider the observed time of maximum intensity as the upper limit for the maximum injection. The upper limit for maximum intensity time for a fixed 1.2 AU path length was at 06:44 UT, while for VDA method was at 06:39 UT. This indicates that the ascending time from first injection to the maximum injection is about $3.00 - 2.88$ h respectively. The whole event duration was about 5 h taken according to > 90 MeV channel. The ^{4}He/p was determined for the 23 MeV/nuc channel with $1.14 \cdot 10^{-2}$. Various aspects of gradual and impulsive SEP events have been compared and described in a variety of review articles (e.g. Reames, 1990, 1993, 1995b; Reames et al., 1997; Kahler, 1992, 1994; Gosling, 1993; Cliver, 1996). We have considered the impulsive and gradual classification by using the ^{4}He/P ratio, SEP event duration, and the associated metric radio emission of type II, III and IV, as in previous studies. Accordingly, the event was classified as purely impulsive.

In the second event, on 1 May 2000, GOES detected an X-ray flare of class M1.1, which started at 10:16 UT and lasted for 18 min. Flare acceleration in low corona for SEPs have been suggested in many studies, showing that this event is ^{3}He-rich, heavy ion-rich, and shows energy-dependent heavy ion charge states, suggesting charge stripping during acceleration in a dense environment at low altitudes in the corona, much below 2 Rs (Mason et al., 2002; Klein and Posner, 2005; Kartavykh et al., 2007). However, later, LASCO observed a CME, with an angular width of 54°, linear velocity of $1360\,\mathrm{km\,s^{-1}}$ and acceleration of $-62.6\,\mathrm{km\,s^{-2}}$ at 10:54 UT at $5.58\,R_\odot$ at central position angle 323° from the same active region. The CME liftoff time according to a quadratic fit is 10:17 UT ±4 min. The onset of the energetic protons > 36 MeV was observed by SOHO/ERNE at 10:45 UT. The injection time calculated for the first, non-scattered protons traveling along the nominal path length of 1.2 AU was at 10:17 UT ±8 min, when the leading edge of the CME was below $2\,R_\odot$. Klein and Posner (2005) calculated the connection distance which the SEPs traveled along and found that it was 1.315 AU. Accordingly, the injection time calculated due to our onset observation would have been after the CME liftoff. Simnett et al. (2002) suggested that most of the near-relativistic electrons seen by ACE/EPAM were accelerated by a shock driven by a coronal transient, and were released at the radial distance around $2 - 3\,R_\odot$. The 1 May 2000 event was mentioned under this criteria in their list. This might indicate that the SEPs in this event were associated with both, the solar flare and the CME. The CME might have participated in the acceleration later than the flare.

4 Summary and conclusions

Two narrow CMEs with high velocity observed with SOHO/LASCO were accompanied by two impulsive SEP events registered by SOHO/ERNE. The absence of solar flare in the 19 June 2001, event indicates that the acceleration of the SEP was totally due to the narrow CME, while in the 1 May 2000 event where we find flare acceleration, the narrow CME could have contributed to the acceleration of > 36 MeV SEPs. It is rather a complicated task to identify the real effect of narrow CMEs since they normally occur in association with much more powerful CMEs. The examination of the intensity-time profile cannot identify the SEPs due to those narrow CMEs without careful analysis for the velocity dispersion and ratio of different species. We went through more than 2000 CMEs of angular width $< 60°$ observed by LASCO on board SOHO and found the following:

1 Most of the narrow CMEs cannot be investigated from the SEP events association point of view because they are mostly overwhelmed by the previous wide CMEs.

2 Fast narrow CMEs could accelerate SEPs in energy range of $> 90\,\text{MeV}$.

3 These two events are inconsistent with the view presented in some studies that narrow fast CMEs are not associated with SEP events.

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