Observation of maximum injection upper limit for energetic proton events according to SOHO/ERNE measurements

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We analyzed 25 solar energetic particle events, with energies $\sim 1 - 100$ MeV, observed with ERNE instrument onboard Solar and Heliospheric Observatory (SOHO) and found that all of the solar energetic particlse were associated with coronal mass ejections, observed with LASCO/SOHO. The observational data suggests that the associated coronal mass ejections were located at lower heliocentric altitudes during the time of maximum intensity of the high energy protons than those during the time of maximum intensity of lower energy protons. This might indicate that the upper limit of maximum acceleration by the shock waves decreases earlier as we go higher in the proton energy level.

Introduction

The Sun contributes enormously to the energetic particle population in the heliosphere through various processes: from solar flare in the low corona, coronal shocks [2, 6, 22] and interplanetary shocks driven by coronal mass ejections (CME) [23]. Solar Energetic Particles (SEP) are believed to be accelerated in the lift-off phase of CMEs, which could include either acceleration in flaring processes [3], acceleration in coronal/interplanetary shocks ([21] and refs. therein), or in both [11, 12, 13]. Recently, the role of CME interaction in SEP production has also been discussed (see [4, 9, 29] and refs. therein). One of the difficulties in determining the relevant processes lies in the uncertainties of timing. SEPs are typically released no earlier than the maxima of the flare impulsive phases [8], yet at the time of SEP release the altitude of the associated CME can vary from one to over ten solar radii [5, 8, 15]. It has also been observed that different particle species can be released non-simultaneously [5, 15, 17].

It was suggested in [28] that a strong kind of eruptive processs is necessary to generate shock waves capable of particle acceleration in the solar corona. Knowing the role of injection of high energy protons, whether it is associated to coronal or interplanetary shocks, or both, has given a great insight into understanding the location of the responsible eruption on the heliocentric distances. Injection profiles are most easily inferred for SEPs of the highest energy, which propagate to 1 AU with the longest mean free paths [7]. In [8] the proton onset times at > 10 MeV were analysed and conclusions were made that the proton releasing near the Sun occurs not earlier than the maximum of the flare impulsive phase and that the peak of the injection profile occurs when the associated CME reaches altitudes of $5 - 15\ R_{\odot}$, which corresponds to the time scale of several hours. The observations of the first non-scattered relativistic particles [27] is one of the tools to establish the connection between sudden rise in the intensity-time profile for many particle species which occur after flares or CMEs. It has long been assumed that the first observed SEPs of all energies of transient events at 1 AU arrive after traversing common spiral field lines over distances of 1.2 AU with little scattering. At the same time the SEP onsets show the velocity dispersions expected from impulsive releases of the solar particles of all observed energies. The standard technique to deduce the onsets of SEP solar injection times is to plot the times of the first arriving particles ($T0$) against c/v where v is the speed of the particles [10]. The intercept of the plot at the time axis gives the inferred solar onset time of injection.

Simulations [16, 24] with various assumptions of scattering have shown that, although the particle onset times usually align close to a straight line as a function of c/v, the estimated injection times and path lengths can deviate significantly from actual values. However, the proton flux development at different energies during the onset and maximum phase of the event has not yet been investigated. Events typically start with a sudden rise in the intensity over the cosmic ray background due to an eruption launched on the

Sun and the majority of the SEPs start to be injected in the corona at altitudess below $2\ R_\odot$[13]. The bulk of ions of any energy is accelerated by the bow shock of the CME while it travels through the high corona $> 5\ R_\odot$[8].

In this study we examined the onset and the maximum of the intensity-time profile for a chosen SEP events and the possibly associated CMEs in order to determine the CME altitudes during the first and maximum upper limit injection time for both high and low energy channels. This will allow us to approach the shock wave acceleration at both large and small distances from the Sun and possibly the efficiency of acceleration for low and high energy SEPs.

Data analysis

In this study, we use the energetic proton data from the SOHO Energetic and Relativistic Nuclei and Electron (ERNE) [26] 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 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/`.

Firstly, for the proton events, we determined the onset times for up to 20 energy channels (ten LED channels and ten HED channels), by using the same method as in [5]. 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 during 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 traveled. This kind of analysis is called Velocity Dispersion Analysis (VDA). The fixed path length method ([27]) was also employed for all the events. We calculated the flight time of the non-scattered protons along the Archimedean field line of nominal length 1.2 AU, and subtracted it from the observed time on ERNE.

Secondly, we compared the injection time of the first protons to the lift-off time on the SOHO/LASCO catalog at `http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/` to determine the closest CMEs to those events.

Thirdly, we applied the injection time to the quadratic fit of the LASCO catalog to estimate the heliocentric location of CME for the first injected protons and at the maximum intensity. As the error limit has not been calculated for the LASCO CME height-time, we calculated the error limit for the quadratic fit. Note that tracking the CME's altitude below $2\ R_\odot$ is not a trivial task. The C1 coronagraph is not available after 1998, thus we depend on fitting the altitude-time for the CME on C2 and C3. In this case the observational data below $2\ R_\odot$ were missing and we calculated the approximate value for the altitude-time of CME. It should be noted that while the assumption of scatter-free propagation can to some extent be justified for the propagation length of the first particles, it cannot be applied to the subsequent particles. The turbulence of the plasma causes the particles to scatter in the corona and interplanetary space, with mean free paths for the scattering process typically ranging from ∼ 0.01 to ∼1 AU [18]. Thus, e.g., the maximum injection time cannot be obtained from the observed intensity profile without first deconvolving the transport effects from the observations. While such methods exist (e.g., [25]), they are beyond the needs of this study. We can, however, conclude that the maximum injection at the Sun must take place before the time of the observed maximum at 1 AU, subtracting the travel time of the particle from the Sun to the Earth on the VDA-fitted or the fixed path length. We considered this parameter, the upper limit for the injection maximum, as one of the parameters in our study.

It means that we subtract the time the the proton takes to travel to Earth according to the assumption that the proton travels either on 1.2 AU or as the path length calculated by the VDA method.

Results

The observation of onset obtained through analysis of different energies in the intensity-time profile for SEP event might give a clearer picture about when and where the first injection/acceleration of such particles has started. The sources of SEPs from the Sun have been connected to two major phenomena, the solar flares and CMEs. The participation of each in the production of SEP has been debated for many decades. The observed SEP events in our case are related mostly to CMEs. There is no doubt about the role of the shock waves resulted from CME as a generator of accelerated SEPs observed on the Earth. The controversial

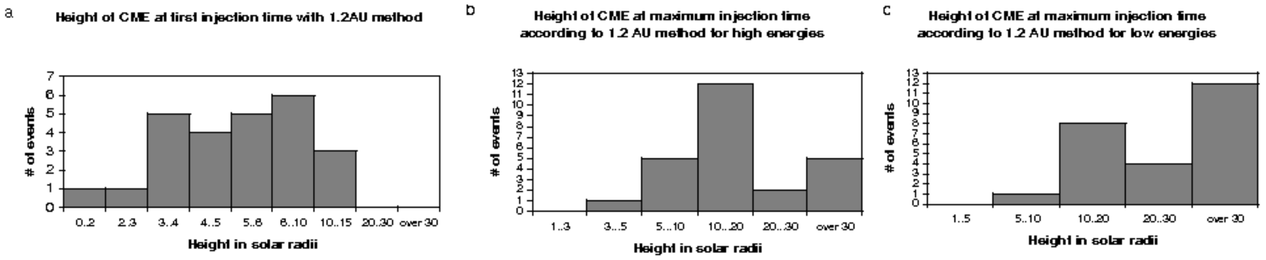

Figure 1: Heliocentric location for CMEs according to 1.2 AU method, a) at first injection time, b) at upper limit of maximum injection time for high energies and c) at the upper limit of maximum injection time for low energies.

issue regarding SEP production is whether the bulk of the acceleration takes place in the solar corona, say below a few $R_\odot$, or whether it occurs in traveling interplanetary shocks associated with CME [19]. Following the CME from near the corona up to the interplanetary medium simultaneously with the rise in the SEP intensity-time profile over the cosmic ray background up to the maximum might answer such question.

Some studies indicate that the majority of the SEPs start to be injected in the corona at altitudes below $\sim$2 $R_\odot$[13], while others indicate that the bulk of ions with any energy is accelerated by the bow shock of the CME while it travels through the upper layers of corona (>5 $R_\odot$[8]). Our results indicate that the CMEs were located at heliocentric altitudes below 5 $R_\odot$ at first proton injection time (44% for the 1.2 method and 76% for the VDA method) (see Fig. 1a, 2a).

The current paradigm formulated in [20, 21] suggests that energetic particles in gradual events are produced continously at CME bow shocks during their transit to the orbit of the Earth. Recently in [1, 14] it was proved that the acceleration of $>$ 10 MeV by interplanetary bow shock may cease beyond 0.2 AU. Our study shows that in 72% of our events, the upper limit for maximum injection, measured by 1.2 AU and VDA methods, may occur while the leading edge of the associated CME is below 20 $R_\odot$(see Fig. 1b, 2b). While for the low energy channels the leading edge of the associated CME is over 20 $R_\odot$in 64%–68% of the events measured by 1.2 AU and VDA methods correspondingly (Fig. 1c, 2c).

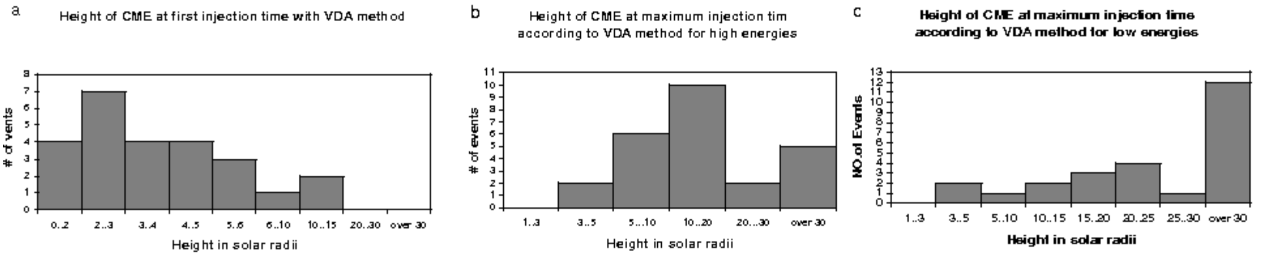

Figure 2: Heliocentric location of CMEs according to VDA method, a) at first injection time, b) at upper limit of maximum injection time for high energies and c) at upper limit of maximum injection time for low energies.

Conclusions

We went through the SEP events intensity-time profiles for the solar cycle 23 using the `ERNE Datafinder` application. A set of 25 SEP events was chosen by taking the widest possible energy range starting from 1 MeV up to 116 MeV to estimate the associated CME altitude at the obtained SEP first and maximum injection time and we found the following:

1. All the events were associated with CMEs and those CMEs were the main accelerator for the energetic protons up to 116 MeV.
2. In most of the events the first protons seem to be injected while the leading edge of the CME is located at about 5 solar radii according to the 1.2 AU pathlength method and about 4 solar radii for the VDA method.

3. The approximate upper limit for the maximum high energy protons seems to be injected while the leading edge of the CME is at about $21-23$ solar radii for both methods.

4. The approximate limit for the maximum high energy protons seems to be injected while the leading edge of the CME is at about $21-23$ solar radii for both methods. These results indicate that the shock acceleration of the high energy protons has a shorter time to reach its maximum and then decay much earlier than in accelerating low energy protons.

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