Observation of the Multi-Eruption Solar Energetic Particle (MESEP) event of September 12, 2000

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Abstract: On 2000 September 12-14 the Energetic and Relativistic Nuclei and Electron (ERNE) instrument on the Solar and Heliospheric Observatory (SOHO) observed a gradual solar energetic particle (SEP) event associated with Halo CME and M class solar flare from the South West hemisphere. Production of 20-90 MeV protons lasted for 160-137 hr respectively. The analysis of the intensity-time profile, ^{4}He/p- Fe/O ratios and anisotropy flux suggested that this event is combined with a second eruption associated with a Halo CME from the North East hemisphere and that the shock wave of the first CME was an efficient accelerator for$\sim$20 MeV protons during only the first 8 hr after the launch. According to our calculation of the angle Θ_{Bn} between the shock normal and the direction of the upstream magnetic field, shock parameters such as speed, compression ratio and Mach number, this shock seems to be gradually slowed down, weakened, and became transparent for the protons produced by the second eruption behind the previous CME or the protons of the second CME may have access to field lines that curve around the first CME structure

Keywords: Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: acceleration of particles – Sun: shock wave – Sun: Multi-Eruption Solar Energetic Particle (MESEP) events

1 Introduction

A definition for the phenomenon of Multi-Eruption Solar Energetic Particle (MESEP) events, has been introduced for the first time by [1] as a combination of many SEP events each one associated with a single eruption can create one complex intensity-time profile that will result in masking the observation of the first injected particles detected near Earth for each participated eruption. The same study suggested that the investigation of the participation of each eruption (CME or flare) in injecting or accelerating particles are possibly accomplished if we use the Velocity Dispersion Analysis (VDA), $^4He/P$ ratio and anisotropy analysis. Each eruption in the MESEP event might be CME-flare associated. In such case the SEP event is consisting of both a flare-accelerated component and a particle component accelerated at the shock in front of the CME. Particle acceleration at collisionless shock can be observed best at planetary bow shocks and travelling interplanetary shocks. There are different physical mechanisms involved in the particle acceleration at interplanetary shocks (i) The shock drift acceleration (SDA), sometimes also called scatter-free acceleration, in the electric induction field in the shock front.(ii) The diffusive shock acceleration due to repeated reflections in the plasmas converging at the front.(iii) The stochastic acceleration in the turbulence behind the shock front[3].

Two separate energy bands could discuss the energetic particles accelerated at interplanetary shocks (a) a low-energy component with ion energies up to a few hundred keV/nucl and electron energies up to some tens of KeV; and (b) a high -energy component with ion energies in the MeV and tens of MeV/nucl range and electron energies in the hundreds of KeV to MeV range. One reason for such a separation is the break in the ion spectrum [3, 4].

The shock analysis based on one spacecraft observation is in general be tested by satisfying the Rankine-Hugoniot (R-H) relations. The well-known method is the magnetic coplanarity theorem [5]. One can determine shock normal only with up- and down-stream averaged magnetic fields. This theorem is very frequently used. A mixed data method called velocity-magnetic field coplanarity was proposed by [6] and also [7]. This method requires up- and down-stream magnetic fields and velocities to determine the shock normal. Therefore the shock normal, magnetic fields, and velocity difference lie on the same plane, called a coplanar plane. These two methods can be reliable if the data are accurate. The velocity-magnetic field should more reliable than the magnetic coplanarity theorem if the data have more or less errors.

Shock normal can also be determined by least squares minimization. A well-known method is minimum variance method (MVA), which is based on the conservation of the normal component of the magnetic field across the shock layer, that applied mainly to tangential and rotational discontinuities [8, 9]. [10, 11]suggested that the MVA is much less reliable than has been previously assumed. When applied to shock waves, it is well-known that the eigenvector degeneracy of the MVA causes that the method is not useful for finding the normal of the shock. In order to remedy this difficulty, [16] proposed a novel scheme called Coplanarity Variance Analysis (CVA), which in search for an accurate geometry exploits the eigenvalue degeneracy in M-VA, at planar structures, to enforce coplanarity. It is found that CVA is much better than MVA at finding the shock normal.

In the MESEP events the coronal and IP shock acceleration can occur simultaneously and observed in continues intensity-time profile that fit under gradual SEP event. As the current paradigm proposed by [4], the particle acceleration in gradual SEP events is due to diffusive shock acceleration in CME-driven shock waves in the solar corona and in IP space. The CME 1 in the MESEP event will be travelling in the IP space while CME2 erupt at Sun. If both CMEs accelerate SEPs then we will have a combination of coronal and IP accelerated particles. Observation of coronal accelerated particles during IP acceleration has been introduced by [13, 14, 15]. However, coronal accelerated particles can not be observed from behind a previous CME unless the particles find a pass through the previous interplanetary shock or around it. In those studies the V-DA, SEP flux anisotropy and $^4He/P$ ratio have been used to achieve the results. They concluded that shock acceleration of SEP after >0.2 AU is doubtful and the turbulent medium at CME bow shock became transparent for >10 MeV protons and that fast decelerating of CME might be one reason for decaying of shock acceleration efficiency but still further investigations are needed.

In this study we added the mentioned shock wave parameters calculations to determine the (deceleration or acceleration) of the shock wave propagated in the IP due to CME1. We also added the Fe/O ratio measurement for separation of coronal and interplanetary SEP compositions.

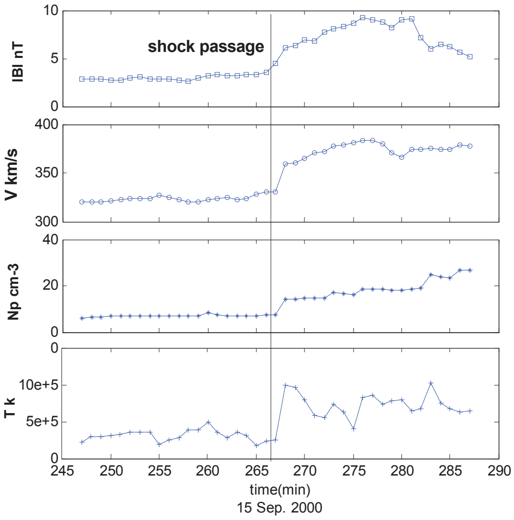

Fig. 1: : Magnetic field intensity ($|B|$), proton speed (V), proton density (Np), proton temperature (T) of IP shocks observed by WIND for 15 September 2000.WIND magnetic field and plasma data are plotted at resolution 1 minute.

2 Observations

On the 12th of September 2000, *SOHO*/ERNE detected an SEP event onset for proton energies 13.8-67.3 MeV at 13:04 UT. The ≈90 MeV proton injection time (time at the Sun plus 8.3 minutes) calculated for the first, nonscattered particles traveling on a nominal path length of 1.2 AU was at 12:42 UT ±8 minutes. A similar timing at 12:40 UT ±3 can be obtained with a velocity dispersion analysis with particles traveling on a path length of 1.30±0.08 AU. *GOES* observed a gradual X-ray flare of class M1.0, which started at 11:31 UT and peaked at 12:13 UT and ended at 13:13, with Hα at location S17W09. The Large Angle and Spectrometric Coronagraph (LASCO) on *SOHO* observed a halo CME starting at 11:54 UT at heliocentric location of 2.83 $R_\odot$ (hereafter CME 1) from the same active region with linear plane-of-sky velocity of 1550 Km/s. The extrapolated CME-liftoff time is 11:42 UT ±5 minutes.

A clear delay can be seen between liftoff time of the CME and injection time of SEPs. CME's heliocentric location at injection time was at (8.1±1,7.9±0.6)$R_\odot$ with both methods respectively, which means that the first injection time was delayed from the CME's liftoff time for the whole range of the proton energies. The CME, originating from S17W09, is, however, clearly asymmetric towards the southern hemisphere, and thus the delay may be due to the delayed access of the particles to the earth-connected field lines. There might be an association CME interaction with an earlier transient took place at ∼13:00 UT, close to the injection time at 12:42 UT.

A metric type II radio burst, caused by a shock propagating in solar corona, seems to start at 11:33 UT, two minutes after the start of the long-duration M1 soft X-ray flare and about 10 minutes before the liftoff time of the CME. There were also later type II bursts, one starting at 11:42 UT, exactly simultaneously with the liftoff time of the CME, and at 12:07 UT, close to the time of maximum soft X-ray emission.

The shock on 15.09.2000 was observed at ∼ 04:27 UT at(32,-230.1,-9.12) R_E in the GSE coordinate , *WIND*/MFI and *WIND*/SWE instruments were used for the measured magnetic field and plasma data. Magnetic- and Velocity coplanarity methods used to estimate the shock normal. The data used in the present analysis are obtained from *Coordinate Data Analysis Web* (CDAWeb). The data has a time resolution of 1 min. The IP shock is the result of the deference between the propagating structure (upstream) and the medium (downstream) speeds. The selected up- and downstream with time intervals of (10 min) for the magnetic fields, plasma densities and plasma velocities are shown in (Fig.1) to get the shock parameters for *WIND* observation. The associated CME-driven shock with this event arrived at *WIND*, *ACE*, and *SOHO* spacecrafts on 15 September 2000, at about (04:27, 04:00 and 04:15) UT respectively. The transit time from liftoff on the Sun to arrival at the spacecrafts were (60.5,60,and 60.3) hr, implying an average transit speed of (640, 648 and 647) Km/s. Comparison of the transit speed with the plane of sky CME speed 1550 Km/s near the Sun indicate that the CME must have decelerated during the propagation from the Sun to 1AU. To calculate the shock parameters we used [16] method to solve the Rankine-Hugoniot equations. The shock normal was (0.929, -0.35, 0.11), and was quasi-perpendicular (Θ_{Bn} =69.2), with Mach no. (=2.18). The shock speed calculated was 351.78 Km/s, and compression ratio (=2.62). The transit shock velocity was 640Km/s. The CME 1 in September 12, 2000, was indicated as decelerating interplanetary CME by [17], where the propagation of the shock through the interplanetary medium was studied using the observations of the low frequency type II radio emission. Shock speed calculated by this method was 310 Km/s, with transit speed of 646 Km/s very close to the result obtained by our calculation.

While CME1 propagating in the IP medium and after ∼04:35 hr when the leading edge was at ∼53 $R_\odot$, (LASCO) observed another halo CME at 17:35 UT at heliocentric location of 4.83 $R_\odot$ (hereafter CME 2) from the North East hemisphere with linear plane-of-sky velocity of 1053 Km/s. The extrapolated CME-liftoff time is 16:46 UT ±4 minutes.

a simultaneous changing in both ^{4}He/p- Fe/O ratios at

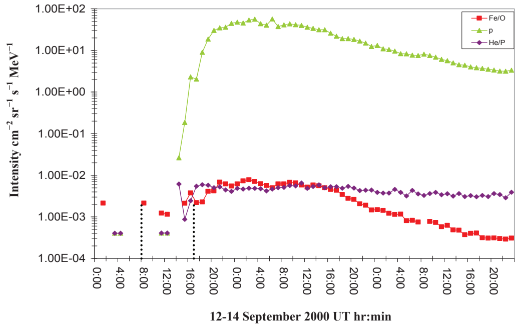

Fig. 2: :High Energy Detector (HED)/ERNE proton intensity (green), ^{4}He/p ratio (blue) and *ACE* Fe/O ratio (red). Dotted lines, first before the event, second in association with CME2

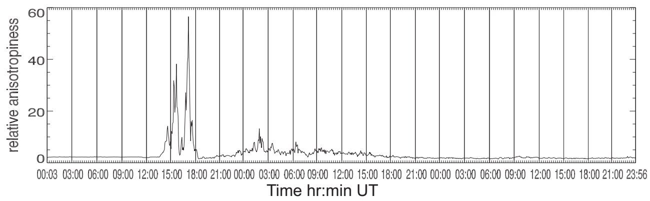

Fig. 3: :High Energy Detector (HED)/ERNE Anisotropy proton 16.85-18.05 MeV for the period 12.09.2000 00:03-14.09.2000 23:56 UT.

$\sim$17:00 (Fig.2) and the distinctly two peaks seen at the beginning of the event (seemingly corresponding to the two CMEs identified) in Fig.3, were (Relative anisotropiness) obtained by calculating the greatest difference of the logarithmic values, and divided it by the mean deviation, and then brought it back to linear (10^x). Therefore the value indicates how much stronger the maximum intensity is relative to the minimum.

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 [18]). Fig.4 shows selected measurements of anisotropy flux and pitch-angle distribution at 14:08, 14:40, 16:16, 17:20 and 18:40 respectively (from upper to lower panels). There is apparent isotropiness between the peaks and then anisotrpiness after the liftoff time of CME2. Production of 20-90 MeV protons lasted for 160-137 hr respectively. Continuity of production confirms a continuation of streaming particles from the Sun as the magnetic field lines connecting to the root of the eruption and further more after the propagation in the IP medium. This will result in a clear masking for the rising phase of the second accelerated particles from the CME 2.

3 Discussion and Conclusions

The efficiency of CME-driven shocks as particle accelerators varies with time (as the shock travels away from the Sun) and with longitude (as the observer establishes magnetic connection to different regions of the shock front). Whereas shocks are believed to be able to accelerate protons to GeV energies when they are close to the Sun (at 3-5 $R_\odot$), when they reach 1 AU they hardly accelerate ions above 20 MeV/n. The angle Θ_{Bn} between the shock normal and the direction of the upstream magnetic field plays an essential role in determining the mechanism of particle acceleration at shocks.

There are two factors that lead to decreasing energetic particles acceleration by the interplanetary shock wave. First, there is continuous leak of particles from the ejected material through the diffusive acceleration of the energetic particles during the propagation in the interplanetary medium. Second, there is continuing expansion in the volume of the ejecta. Both facts probably contribute to thinning of the turbulent sheath of the shock wave and thus lead to decrease ability in acceleration of more energetic particles. 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). We looked at the ICME list presented by [19] and we found no ICME reported during the SEP event. The shock parameters were calculated to test it for understanding the ability of accelerated solar protons from CME 2 to penetrate through the shock of CME1 without strong scattering.

The new evidence that we found of an enhancement in the large SEP event of the September 12–14, 2000 from a second injection of new SEPs due to second eruption on the Sun and the SEP flux anisotropy data of *SOHO*/ERNE and the parameters of the shock wave due to CME 1 lead us to conclude the following:

1. Interplanetary accelerating of $>$ 10 MeV protons by the decelerating shock wave associated to CME 1, has decreased at distances $>$ 0.1 AU from the Sun. The shock and the turbulence in the downstream of the shock should have weakened sufficiently to allow sufficiently easy access for the particles accelerated by the coronal shock associated to CME 2 through to the spacecraft at 1 AU.

2. The protons of the second CME may have access to field lines that curve around the first CME structure. 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 but 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 4 hours, and increases again only at the start of the CME 2.

3. This results suggested that the gradual MESEP event is not completely due to the particle acceleration at CME bow shock in solar wind, and present an evidence that coronal processes could also contribute to SEP production in such events.

High-energy ions in some gradual SEP events can be accelerated mainly during the first few hours after the CME liftoff. Such an acceleration could be caused by oblique CME-associated shocks near the Sun and followed by the SEP confinement in different magnetic field structures. In the case of the 2000 September 12–14 event the CME-bow-shock's ability to accelerate protons seems significantly reduced at distances > 0.1 AU and energies > 10 MeV. The residual acceleration rate could be quantitatively estimated only after a numerical modeling.

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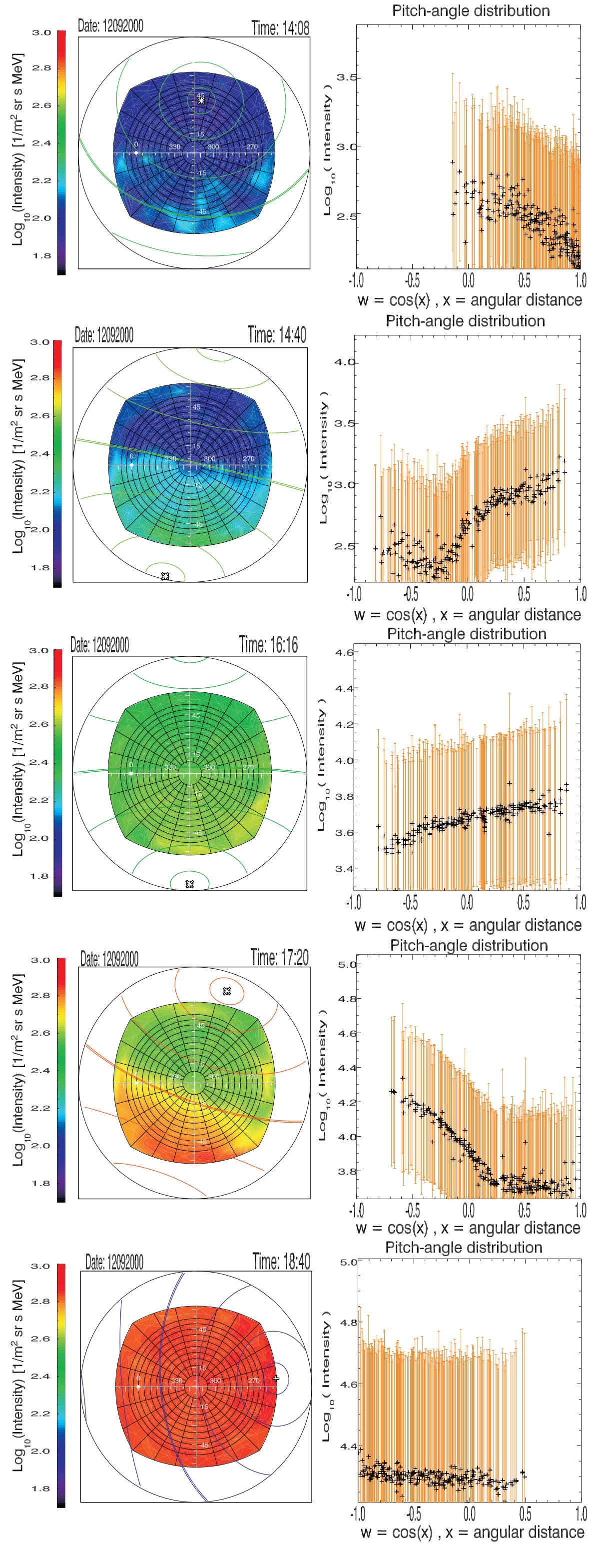

Fig. 4: Angular distribution of the 16.85–18.05 MeV proton flux measured by the ERNE/HED instrument at five distinct 16-min intervals. Left panels show the instrument's view cone in the GSE coordinates. The direction of the Sun is indicated with a star left of the view cone center. The full circle area 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 right panels.