PROCEEDINGS OF SCIENCE

Analysis of multi-eruption solar energetic particle events (MESEP) on March 17-18, 2003

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On March 17-18, 2003 the Energetic and Relativistic Nuclei and Electrons (ERNE) instrument on board the Solar and Heliospheric Observatory (SOHO) spacecraft observed three solar energetic particle (SEP) events in rapid succession (within ∼26 hours) from the same active region. The first event was weak and proton intensity enhancement was observed only below ∼25 MeV. No coincident coronal mass ejection (CME) was found, but the event can be associated with an impulsive Hα flare starting at 10:09 UT on March 17 at location S16W33 and with type III radio burst. The second particle event was associated with an X1.5-class X-ray flare starting on March 17 at 18:50 UT and a fast and wide (1020 km/s, 96°) CME. The CME has been reported to be radio quiet. Enhanced proton intensities reached up to 60 MeV. The third SEP event occurred about 18 hours later on the tail of the second one, reached proton energies up to ∼60 MeV, and lasted for roughly 2 days at energies >10 MeV. The event was associated with another X1.5-class flare, fast and wide (1601 km/s, 206°) CME, and decametric-hectometric type II radio burst. This last event was associated with a shock observed at the Advanced Composition Explorer (ACE) spacecraft on March 19. We analyse these particle events based on the velocity dispersion of the particles, helium-to-proton ratio, and the observed anisotropy of the particle intensities.
Keywords: Coronal mass ejections, type II radio bursts, solar energetic particle events.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

*Speaker.

PoS(ICRC2015)084

1. Introduction

Solar energetic particle (SEP) events are produced by solar eruptions, coronal mass ejections and solar flares. These particles are thought to be accelerated by the shocks ahead of CMEs [1] or by the magnetic reconnection processes in solar flares [2]. Large gradual SEP events are accelerated by coronal and interplanetary (IP) shocks driven by fast CMEs [3, 4, 5, 6, 7, 8, 9]. The SEPs produced in gradual events are continually generated at the CME bow shocks during their travel to the Earth orbit.

Some events have complex intensity time profiles, with peaks separated by varying time intervals, and wide energy ranges. In cases when the two peaks are separated by 1-3 hours these events can be seen in GOES particle detectors and in the data of ground-based neutron monitors [10]. When the time interval between the two peaks exceeds 24 hours, the relative contribution of different SEP components is a function of heliolongitude of the source region [3]. Another study suggested that the first peak with high Fe/O abundance ratio is associated with a flare and the second peak with low Fe/O ratio is due to shock passage [11].

Recent studies [12, 13] showed that multi eruption intensity-time profiles with a time difference of 3-24 hours between the peaks were due to separate coronal accelerations. The specific feature of multi eruption solar energetic particle (MESEP) events is that, each SEP enhancement in each peak is accelerated by a single, separate solar eruption (CME or flare). In this report we analyse a series of events with three peaks in the intensity-time profiles within a time interval of $\sim$26 hours observed by ERNE on board SOHO. We study the release time, ^{4}He/P ratio and the flux anisotropy in order to distinguish between possible coronal and interplanetary accelerations.

2. Multi eruption event on 17-18 March 2003

2.1 First solar event on 17 Mar 2003

On 17 March 2003, GOES detected a two-ribbon Hα flare with heliocentric coordinates S16W33. The flare started at 10:09 UT, peaked at 10:14 UT and ended at 10:18 UT in NOAA active regio 10314. WIND/WAVES observed type III radio burst without type II association (Figure 1). No CME was observed and no shock wave was recorded by ACE, WIND or SOHO, which could be associated with this eruption. From the summary plot of RHESSI at 10:10 UT we can see that the flare is also associated with a hard X-ray flare (the second top panel in the summary plot of Figure 1) at the same location of the Hα flare. There is also another flare at 11:05 UT which has the same intensity as the 10:10 UT flare in hard X-rays. This flare does not have type III radio burst association. Still another Hα flare started at 11:47 UT, peaked at 11:52 UT and ended at 11:56 UT without any CMEs at that time, but was associated with type III burts. Since accelerated particles are visible in hard X-rays and because type IIIs indicates open field lines, then both 10:10 UT and 11:47 UT flares can be possible accelerators of the particles observed by ERNE.

2.2 Second solar event on 17 Mar 2003

On 17 March 2003, an Hα solar flare located at S14W39 started at 18:50 UT, peaked at 19:05 UT and ended at 19:16 UT in AR10314. GOES observed soft X-ray flux starting to rise seven minutes later at 18:57 UT, peaking at X1.5 at 19:02 UT and ending at 20:10 UT. This flare

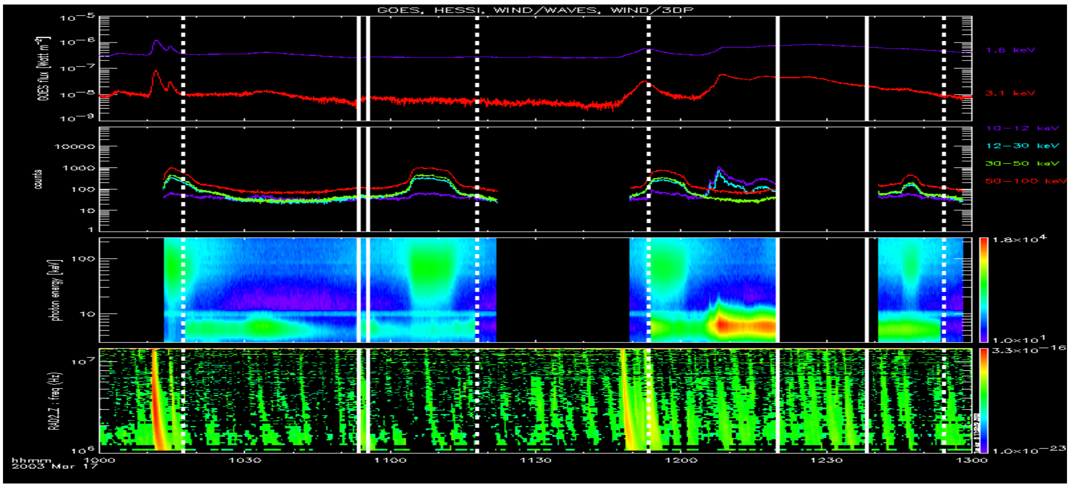

Figure 1: Summary plot of (GOES/RHESSI/WIND) data for 17 Mar 2003, within the time interval from 10:00 UT to 13:00 UT. Top panel: Soft X-rays observed by GOES with energies 1.6 and 3.1 keV. Second panel: Hard X-rays at energies >10 keV detected by RHESSI. Bottom panel: WIND/WAVES radio spectrum showing only type IIIs in this interval without type II bursts.

was the radio quiet [14].The weak intensity, short duration ($\sim$ 8hr), and He^3/He^4 ratio within the range 0.04-0.06, being two orders of magnitude higher than in normal gradual events (0.0005), suggest that this event was an impulsive event caused by the X1.5 flare rather than the associated CME bow shock [14]. The CME (hereafter CME1) from the same active region was observed by the SOHO/LASCO with the time of first appearance in C2 coronagraph field of view at 19:54 UT at heliocentric distance of4.43R. The linear plane-of-sky velocity was 1020 km/s and the width 96^o. The extrapolated CME liftoff time was 19:17 UT $\pm$1 minute. The CMEs has quite small angular width, which could be the reason for not detecting any radio type II bursts. The X-class flare seems to be long-lasting with thermal emission and superposed peaks listed as separate flares (Figure 2).

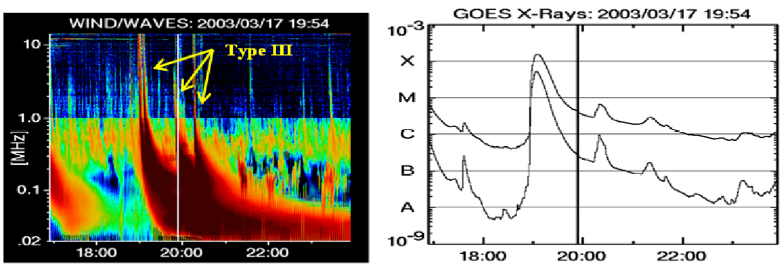

Figure 2: The spectrum from Wind/WAVES experiment for 17 March 2003. No type II emission is associated with the flare showing thermal emission and superposed peaks (left panel). The right panel presents GOES soft X-rays in two energy channels showing the X1.5 flare associated with a CME.

2.3 Third solar event on 18 Mar 2003

On 18 March 2003, LASCO detected a partial halo CME (hereafter CME2) followed by radio type II burst, which indicates emergence of a coronal shock wave (Figure 3). The times of first appearance of the CME in the LASCO/C2 field of view was at 12:30 UT with the linear speed 1601 km/s at heliocentric distance 3.32$R_\odot$. The extrapolated CME-liftoff time was 12:11 UT ± 1 minute. This CME was associated with an Hα flare and an X-ray flare with magnitude X1.5 from the same active region. The Hα flare started at 11:51 UT, peaked at 12:08 UT and ended at 12:20 UT in AR10314, which was located near the western limb at S15W46. Soft X-rays started to rise five minutes later at 11:56 UT, peaked at 12:07 UT and ended at 13:11 UT. Almost all large SEP events are associated with decametric-hectometric (DH) type II radio bursts [15] and this association rate rises when the radio bursts occur at metric and DH wavelengths [16]. A DH type II burst started at 12:25 UT and ended at 13:45 UT. Observation of type II burst in the DH means that the shock is near the Sun in interplanetary medium (heliocentric distance in the range 3-10$R_\odot$) [17]. On 18 March 2003 LASCO observed a halo CME in the south and south west at 13:54 UT with the speed 1042 km/s developing to a full halo CME by 14:30 UT. Studying the EIT images at this time suggests that this CME was backside in the origin or perhaps related to a disappearing filament without a given position. Therefore no peak in the X-rays was observed from the visible disk. Type III and type II radio bursts are observed, so there probably was a shock wave that could have accelerated particles, but we do not observe any enhancement in proton intensity at this time by ERNE.

Shock wave driven by the fast and wide CME associated with the X1.5 flare on 18 March 2003 arrived to ACE spacecraft late on March 19 and peak solar wind velocities reached 850 km/s early on the next day(blue vertical dash-dot line in Figure 4). The shock arrival resulted in a rotation of structured Bz, first oriented northward, then for a 3-4 hour period southward Bz occurred by midday on 20 March.

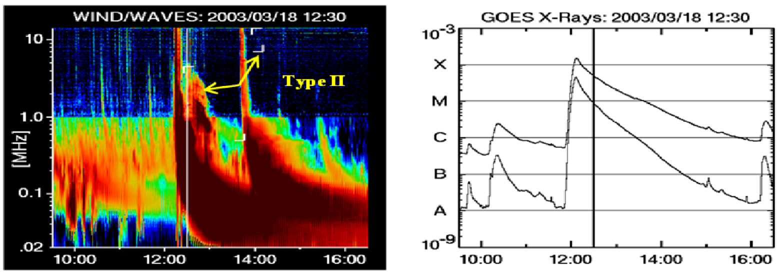

Figure 3: The left panel is the spectrum from Wind/WAVES experiment for 18 March 2003 showing type II burst emission associated with the CME. The right panel shows GOES soft X-rays in two energy channes with a X1.5 flare associated with the CME.

Figure 4 recaps the IP parameters from 17-22 March 2003, observed by ACE spacecraft. Figure 4 a-d represent the IP magnetic field strength and the components in GSE Cartesian coordinates (with time resolution 5 min). Figure 4 e shows the solar wind speed varying between ∼600 to 800 km s^{-1}, Figure 4 f indicates to the proton density. The temperature of the proton is showing in the Figure4 g, while Figure 4 h is the ram pressure of the solar wind. All these features have clear changes in their structure while moving toward the Earth due to the forward shock that appears to be caused by 12:30 UT CME associated with the X1.5 solar flare. On March 17 ∼ 19:20 UT ACE observed only a current sheet, while the shock wave was observed on 20 March 2003 by SOHO at 04:21 UT and by ACE at ∼04:20 UT at (GSE= 219.57, -0.08, -11.72) R_E.To determine the parameters of the March 20 shock, the Rankine-Hugoniot relations were applied by [18]to solar wind data. They obtained the results $\Theta_{Bn}= 50\pm3\ ^{0}$, indicating an oblique shock, with magnetosonic Mach number of 1.55 $\pm$0.03 and the shock velocity (-860,66,69) km s^{-1} in GSE with a compression ratio of 1.5 [18]. The transit time from the liftoff on the Sun to arrival at the spacecraft ACE and SOHO were 40.9 and 40.10 hours, respectively, implying an average transit speed of ($\sim$1035, 1034,5) kms^{-1}. The forward shock was followed 8 hours later by an IP magnetic cloud. Figure 4 a to d) shows the passing IMC characteristics between the two vertical red lines.

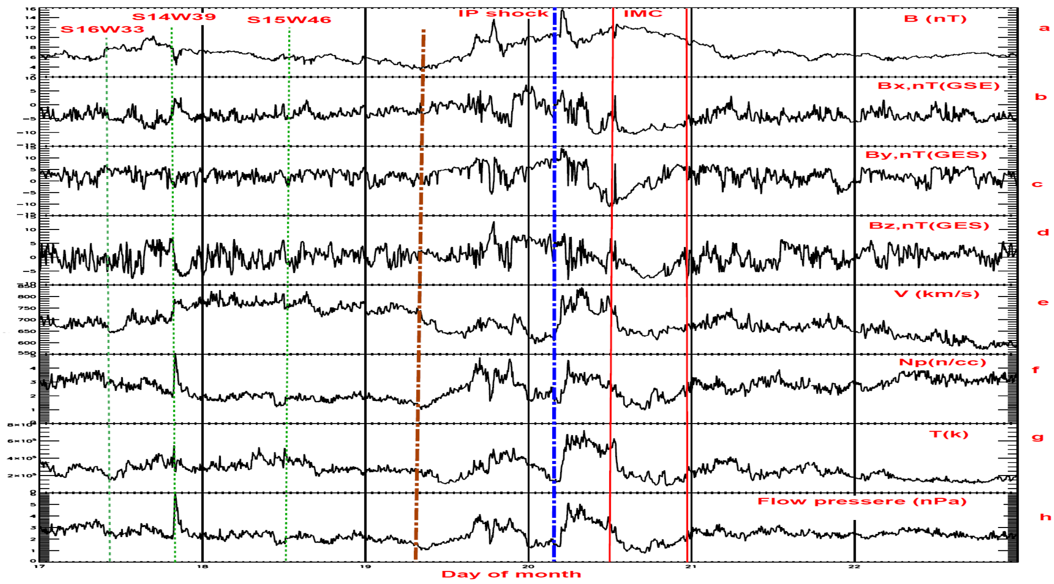

Figure 4: Overview of IP parameters during 17-22 March 2003 observed by Wind and ACE spacecraft.

3. Data analysis

We have calculated the injection time of particles by assuming that the particles travel without scattering along the Archimedean spiral with a fixed length of 1.2 AU [19] or by using velocity disperison analysis (VDA) [20]. For the first event (P1 in Figure 5), the injection time of the protons with the 1.2 AU path length was found to be 10:22 UT $\pm$8 minutes at the energy 15.4 MeV. VDA gave the result 10:06 UT $\pm$ 6 minutes, close to the solar flare start, with the apparent path length of 1.627$\pm$0.03 AU. It is difficult to use VDA for the second event (P2 in Figure 5), because of the first enhancement of SEPs is masking the rising phase of the second peak. For this reason, we determine the velocity dispersion of particles in peak 2 from the differences between the maximum-intensities times of lower energy channels compared to higher energy ones or from the start of the increasing intensity. For $\approx$29 Mev the injection time assuming 1.2 AU path length was 19:05 UT $\pm$8 minutes, which is the time of the flare peak time. From the VDA we get 19:00 UT $\pm$ 3 minutes, which is in agreement with the time obtained for the CME liftoff from the linear fit to LASCO observations (19:04 UT). The apparent path length was 1.238 $\pm$0.03 AU. For the third event (P3 in Figure 5), with the onset 13:03 UT at the energy channel $\approx$29 Mev, we get the injection time

12:29 UT ± 8 minute with the fixed-path length method and 12:37 UT ± 17 minute and path length 2.16 ± 0.22 AU based on VDA.

The variation of the ratio ^{4}He/P during the SEP events suggests that for each peak we had new injections of particles from different seed populations. Combining the measurements of ^{4}He/P ratios with velocity dispersion analysis and anisotropy observations strengthens our assumption of multi eruption sources. Different ^{4}He/P ratios indicate different seed particle populations. Left panel in Figure 5 illustrate three different ratios of ^{4}He/P denoted for the peaks P1, P2, and P3, while the right panel illustrates the rising of the anisotropy index (ratio between the maximum and minimum intensities in the 241 directional bins in the view cone of ERNE/HED) to its maximum for the third peak (P3) and decay associated with the second CME.

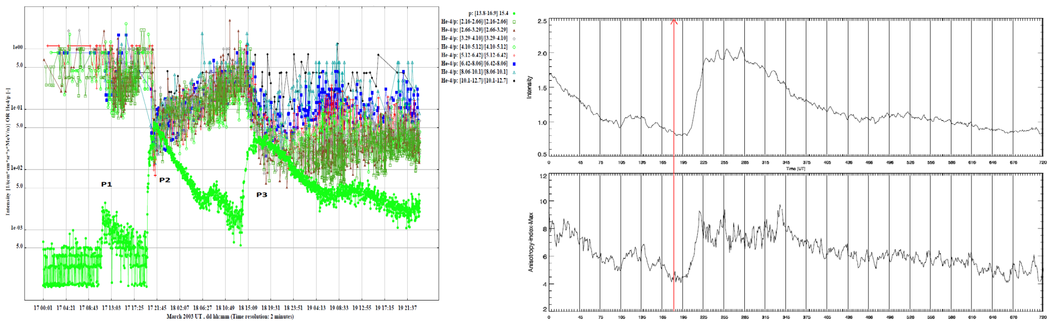

Figure 5: Left panel illustrate intensity-time profile for P and ^{4}He/P of 17-19.Mar.2003 with resolution time 2 minute.The CMEs and flares are marketing in (P1,P2,P3).Right panel illustrate high energy detector (HED)/ERNE anisotropy proton of 18.03.2003.

4. Discussion and conclusion

Particles in gradual events are accelerated by the CME bow shocks during their passage from the Sun to the Earth [4]. In multi eruption solar energetic particle events, coronal and interplanetary shock accelerations take place at the same time with continuous intensity-time profiles in agreement with gradual SEP events characteristics. The SEP enhancement in the IP space can be affected by different factors such IP magnetic clouds (IMCs) and stream interaction regions (SIRs). No IMCs or SIRs were observed on 17-18 March 2003, so these are not feasible explanations for the observed particle enhancements on 17-18 March 2003.

The events on 17-18 March 2003 have significant active region associations. The AR 10314 showed precipitating growth phase on 17-18 March. It was the source of most of the activity during this period. This region produced two X1.5/1b flares, and also two M-class events and numerous C-class events on March 18. Table1 indicates to the energetic events during this period, bold events are the most energetic and homologous flares associated with the EIT waves and CMEs in the same AR. The first particle event was weak and proton intensity enhancement was observed only below ∼25 MeV. The event was associated only with an impulsive Hα flare (no CME synchronized with this flare). Both type III radio bursts (10:10 and 11:45 UT) can be related with the possible accelerators for the first peak (section 2.1). The second peak in our series of events was small (proton intensity $<$ 1 pfu) probably associated with a flare reconnection during the radio-quite

Date	Flare Max Time	CME Time	comments
17 Mar	**1014**	-	
17 Mar	**1902**	1954	**Flare X1.5/1B**
18 Mar	0035	0254	flare M1.6/1N,sandwiched CME [18]
18 Mar	0600	0731	flare M2.5/1B
18 Mar	**1207**	**1230**	**Flare X1.5/1B, partial halo CME**
18 Mar	-	1354	backsided halo CME
19 Mar	-	0230	backsided halo CME

Table 1: Characteristics of energetic events in AR 10314 during 17-18 March 2003.

CME1, and accelerated by the CME driven shock [14]. Another study [21] considered this event gradual based on their investigation of the source region of the IP magnetic field and variability in heavy ion elements composition in gradual SEP events . The CME2 associated with the X1.5 flare, on 18 March appears to be the solar source of shock wave observed on 20 March. We summarize our events in three eruptions as follows. The first small SEP enhancement is due to flare acceleration. The following two peaks are produced by shock waves driven by fast CMEs. The slow shock of the second event is unable to accelerate particles of the third event in IP medium. The shock wave driven by CME1 in the IP space does not become an obstacle for CME2. The arrival of the shock in the IP medium produced by CME1 can be seen in Figure 5 as the area between the brown and blue dash-dots lines. Shock wave driven by CME1 is pellucid for protons with energies $>$ 1 MeV (this result is different from the results of [12, 13], where the decelerating shock was unable to accelerate particles with energies $>$ 10 MeV), and the particles accelerated in the third event reached to the detector without any distinctive interruption by the IP shock of the second event.

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