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LONG-DURATION LOW-FREQUENCY TYPE III BURSTS AND SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

We analyzed the coronal mass ejections (CMEs), flares, and type II radio bursts associated with a set of three complex, long-duration, low-frequency (<14 MHz) type III bursts from active region 10588 in 2004 April. The durations were measured at 1 and 14 MHz using data from *Wind*/WAVES and were well above the threshold value (>15 minutes) normally used to define these bursts. One of the three type III bursts was not associated with a type II burst, which also lacked a solar energetic particle (SEP) event at energies >25 MeV. The 1 MHz duration of the type III burst (28 minutes) for this event was near the median value of type III durations found for gradual SEP events and ground level enhancement events. Yet, there was no sign of an SEP event. On the other hand, the other two type III bursts from the same active region had similar duration but were accompanied by WAVES type II bursts; these bursts were also accompanied by SEP events detected by *SOHO*/ERNE. The CMEs for the three events had similar speeds, and the flares also had similar size and duration. This study suggests that the occurrence of a complex, long-duration, low-frequency type III burst is not a good indicator of an SEP event.

Key words: Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: particle emission – Sun: radio radiation

1. INTRODUCTION

Understanding the mechanism by which solar energetic particles (SEPs) are accelerated has been a long-standing problem in solar physics (see, e.g., Cliver 2009a). There is concrete evidence for particle acceleration by two different processes: a flare reconnection process (as evidenced by impulsive SEP events not accompanied by a coronal mass ejection (CME)) and energetic storm particle events found in CME-shock fronts propagating past an observing spacecraft long after the associated flare has decayed. Large SEP events (particle intensity in the >10 MeV energy channel exceeds 10 particles cm^{-2} s^{-1} sr^{-1}) are always accompanied by large flares and CME-driven shocks (indicated by type II bursts; Gopalswamy 2006), so one expects that both the flare and shock processes contribute to the observed particle flux. However, the relative contribution from the two processes remains a matter of debate (Cliver 2009b; Klecker et al. 2007). Radio signatures in the form of type III and type II radio bursts are important indicators of the flare and shock processes, respectively (Wild et al. 1963). These bursts are produced by low-energy electrons (up to ∼10 keV) energized at and escaping from the flare site (type III burst) and shock front (type II burst).

Pursuing the flare process, Cane et al. (2002) linked ∼20 MeV SEP events to extended (duration ∼20 minutes on the average) complex type III bursts observed at frequencies below 14 MHz. MacDowall et al. (2003) confirmed this suggestion that the long-duration, low-frequency type III bursts are statistically associated with intense SEP (proton) events. Recently, these authors revisited this issue and found that the type III burst duration and complexity were almost always greater for SEP events with intensity >1 proton cm^{-2} s^{-1} sr^{-1} MeV^{-1} than those for a control sample (MacDowall et al. 2009). However, Cliver & Ling (2009) compared type III bursts associated with impulsive and gradual SEP events and found that the type III intensity did not distinguish between impulsive and gradual SEP events, but the presence of a type II burst did. The presence of a type II burst favors the shock mechanism for large SEP events as opposed to the impulsive SEP events thought to be due to flare acceleration. Motivated by these conflicting results, we consider a set of complex long-duration type III bursts from NOAA active region (AR) 10588 in 2004 April, and examine their CME, shock, and SEP associations to gain insight into the relative importance of flares and shocks for SEP events.

2. DATA

This investigation makes use of data on radio bursts, flares, CMEs, and SEPs from various sources. The radio data are from the Radio and Plasma Wave experiment (WAVES; Bougeret et al. 1995) on board the *Wind* satellite. The WAVES data we use are from the two WAVES receivers known as RAD1 (20 kHz–1.04 MHz) and RAD2 (1.075–13.825 MHz) that cover radio emission taking place from the entire Sun–Earth space. The Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*) mission images the corona up to a radial distance of ∼32 solar radii ($R_\odot$). The LASCO field of view significantly overlaps with the near-Sun interplanetary (IP) medium probed by the WAVES experiment. Information on flares and high-frequency (>20 MHz) radio emission is available from ground-based observations in the Solar Geophysical Data (SGD) archive. The SGD has information on various types of radio bursts and the associated solar flares in soft X-rays and H-alpha. Information on SEPs comes from two sources: the *Geostationary Operational Environment Satellite* (*GOES*) and the Energetic and Relativistic Nuclei and Electron (ERNE) experiment (Torsti et al. 1995) on board *SOHO*. ERNE's low-energy detector measures particle energies in the range 1.3–13 MeV, while the high-energy detector measures protons in the energy range 11–120 MeV. We make use of data in selected energy channels (1.8–3.3 MeV, 3.3–6.4 MeV, 6.4–13 MeV, 13–28, and 26–54 MeV) for the present study.

3. ANALYSIS AND RESULTS

We consider the long-duration, low-frequency type III bursts from AR 10588 in 2004 April that had a duration >25 minutes at 1 MHz. The search criterion is well above the one (>15 minutes) used by Cliver & Ling (2009). We used the high-resolution (16 s)

Table 1
Type III Bursts from AR 10588 and the Associated Flares, CMEs, and Type II Bursts

Property	4/8 E1	4/9 E2	4/11 E3
Type III onset at 1 MHz	09:51	20:12	03:57
Type III dur. (14, 1 MHz) (minutes)	31, 29	25[a], 28	18, 31
Type III intensity (peak)[b]	1.1, 0.1	0.33, 0.09	1.0, 1.0
Type III intensity (integrated)[b]	2.3, 0.28	0.88, 0.32	1.0, 1.0
Soft X-ray flare size	C7.4	C2.8	C9.6
Soft X-ray flare onset	09:53	20:13	03:54
Soft X-ray flare dur. (minutes)	54	49	41
Soft X-ray flare rise time	26	27	25
H-alpha flare size	SF	SF	1F
H-alpha flare location	S15W11	S17W29	S14W47
CME first appearance	10:30:19	20:30:05	04:30:06
CME speed (km s^{-1})	1068	977	1645
CME width	H[c]	273°	314°
CME acceleration (m s^{-2})	−36.5	−3.3	−77.6
Type II (freq. range MHz)	3–0.5	None	14–0.5
IP shock (m/d hh:mm)	4/10 19:25	None	4/12 17:35
SEP (1.8–3.3 MeV)	Yes	None	Yes
SEP (26–54 MeV)	None	None	Yes

Notes.
[a] The duration was measured at 9 MHz because of the interference at higher frequencies.
[b] The first numbers are at 14 MHz and the second numbers are at 1 MHz. The intensities of the bursts B1 and B2 are normalized with respect to the values of B3.
[c] Halo CME.

data from *Wind*/WAVES to measure the duration of the type III bursts. Table 1 provides information on the three type III bursts that had duration >25 minutes, and the associated type II bursts, CMEs, flares, and IP shocks. We refer to the eruptions as E1 (April 8), E2 (April 9), and E3 (April 11) and the corresponding type III bursts as B1–B3. All the eruptions were accompanied by major CMEs that were fast (speed $\geqslant$977 km s^{-1}) and wide (angular width $\geqslant$273°). The speeds, widths, and accelerations of CMEs listed in Table 1 are with respect to the sky plane and no attempt has been made to correct for the projection effects. H-alpha flare observations reported in SGD indicate that the eruptions occurred from W11 to W47, in the southwest quadrant of the disk (see Table 1). The last two eruptions are from the well-connected zone (W20–W89) considered by Cliver & Ling (2009), while the first one is only 9° away from this zone.

All the eruptions were associated with C-class flares. The soft X-ray flare durations (reported by SGD) were similar: 54, 49, and 41 minutes for E1, E2, and E3, respectively. The flare rise times (onset to peak) were also nearly identical (26, 27, and 25 minutes). The onsets of type III bursts and soft X-ray flares were within 3 minutes. In H-alpha, the flares were generally weak: the first two were subflares (SF), while the last one was a 1F flare. Thus the flare, CME, and type III burst characteristics were similar for the three eruptions.

One of the major differences between the three eruptions was the type II burst association: E1 and E3 were accompanied by type II bursts that started in the decameter–hectometric (DH) wavelength domain (WAVES/RAD2) and continued into the RAD1 spectral domain (no metric counterparts). The starting and ending frequencies of the type II bursts are listed in Table 1. IP shocks were also detected by *SOHO* and *ACE* spacecraft at L1 in association with CMEs from E1 and E3, but not E2. Figure 1 compares WAVES/RAD2 dynamic spectra of a few hours duration centered on the three type III bursts B1–B3. The 1 MHz type III durations are very similar (29, 28, and 31 minutes, respectively, for bursts B1, B2, and B3) and are close to the median value (29 minutes) reported by Cliver & Ling (2009) for a set of 25 type III bursts associated with gradual SEP events. The three type III bursts are similar in appearance and complexity along the frequency and time axes. The peak and integral intensities of B1 and B2 are also comparable (see Table 1). The ending frequency of type III bursts inferred from WAVES low-frequency data (not shown) is very close to the local plasma frequency, indicating similar magnetic connectivity to Earth in all the three cases. The only difference seems to be that B1 and B3 are accompanied by a DH type II burst, while B2 is not (see Figure 1). Thus, the lack of a type II burst seems to be a major characteristic that distinguishes B2 from the other two. Note, however, that the type II bursts themselves are not prominent and their intensity is much smaller than that of the type III bursts.

Now let us look at the association of energetic particle events with the three type III bursts. Figure 2 shows the time variation of the energetic proton flux from *SOHO*/ERNE in four energy channels for the period 2004 April 5–14. The plots are made with a 5 minute time resolution. The first appearance times of the three CMEs are indicated by the solid vertical lines (C1–C3). In the highest energy channel (26–54 MeV), there is clearly only one event, which is a gradual SEP event starting at 05:10 UT on April 11 associated with the CME C3. This is also a large *GOES* SEP event with a >10 MeV intensity of 35 pfu. The event shows clear velocity dispersion in that the event peaks first at higher energy channels. The second largest SEP event starts at 15:45 UT on April 6, in association with the CME C1. The event can be seen in all the lower energy channels, but not in the 26–54 MeV channel. Note that the April 6 event is not a large SEP event because the >10 MeV flux was $\ll$1 pfu. The peak of this event at 17:45 UT on April 9 seems to be an IP modulation (no velocity dispersion) and occurs ∼2.4 hr before the first appearance of C2. This is well before the onset of the CME, which is estimated to be around 20:10 UT on April 9. Thus, there is no SEP event in association with the type III burst B2 in the highest energy channel. Even though there is no evidence for a fresh injection at lower energies, one cannot rule out a small event masked by the preceding event associated with C1.

Each of the two eruptions associated with type II bursts (E1, E3) also resulted in a shock at 1 AU, consistent with the fact that fast mode shocks driven by CMEs produce type II bursts. The shock arrival times are marked as S1 and S3 in Figure 2. Properties of these shocks can be found in Gopalswamy et al. (2010). There was another shock S0 (April 9, 1:27 UT), which was due to a previous CME that left the Sun on April 6 around 13:31 UT. The SEP flux showed some variation at the time of the arrival of the shocks at 1 AU: S0 and S1 showed a slight increase following the shock, while S3 showed a Forbush-like decrease.

It should be mentioned that the SEP flux in the lowest energy channel (1.8–3.3 MeV) shows two small additional enhancements (pointed by arrows in Figure 2). The first one at 9:20 UT on April 5, but the intensity was below 2σ, so we are not confident of its reality. There was a CME from the same active region at 6:06 UT, some 3 hr earlier and a metric type II burst reported by the SGD. The eruption region was poorly connected (S18E35), which might explain the delayed onset. The second small event at 15:45 UT on April 6 was also associated with a fast CME (1368 km s^{-1}) from the same active

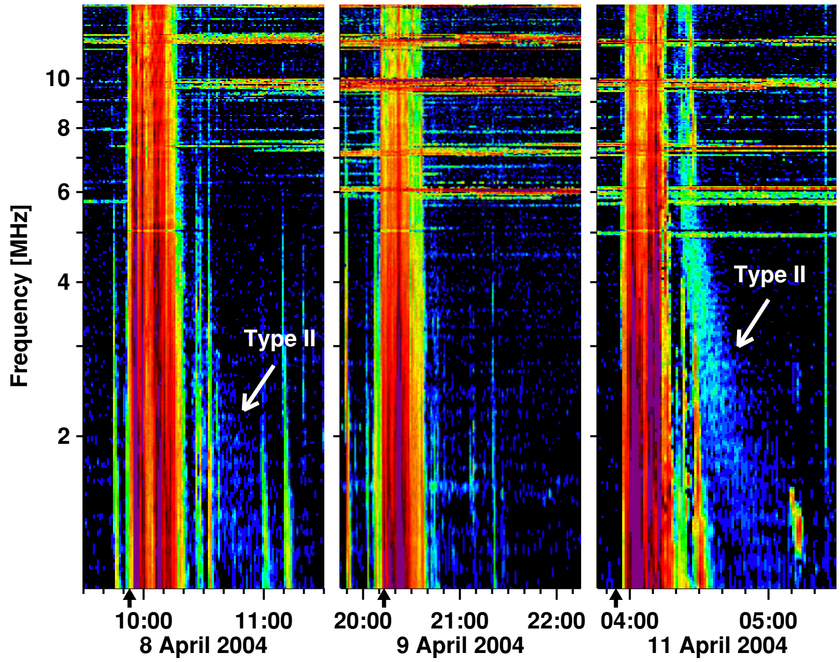

Figure 1. Dynamic spectra of B1 (left), B2 (middle), and B3 (right) of similar duration from AR 10588. B2 was not associated with a type II burst. The soft X-ray flare onsets are marked by the dark arrows. Type II bursts are marked by white arrows.

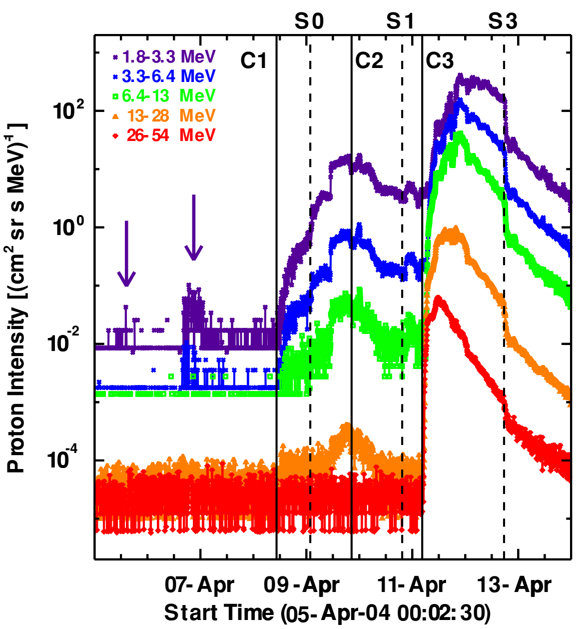

Figure 2. SEP intensity as a function of time in several energy channels around the time of the three type III bursts. The solid vertical lines mark the first appearance times of the three CMEs (C1–C3). The dashed vertical lines mark the IP shocks S0, S1, and S3. C2 was not associated with an IP shock; S0 was due to a CME on April 6. The arrows indicate two minor SEP events.

region (S18E15) and associated with a DH type II burst. Recall that the IP shock S0 was associated with this CME. The 1 MHz durations of the type III bursts associated with these two CMEs were 20 and 16 minutes, respectively. Even though of very low SEP intensity, these two events are consistent with the presence of some SEP enhancement when there was a type II burst.

In summary, the lack of SEP event in association with the long-duration, low-frequency type III burst B2 on April 9 type III burst is remarkable: this type III burst has all the properties to indicate an SEP event, yet it was not associated with an SEP event. On the other hand, similar bursts from the same active region were associated with SEP events when they were accompanied by type II radio bursts. The type III burst B2 is clearly a prominent counterexample in the SEP association.

The physical argument behind the low-frequency type III bursts has been that the underlying low-energy electrons and SEP ions are accelerated in the extended flare that occurs behind an erupting CME (Cane et al. 2002). In the case of B2, there is extended electron acceleration and an energetic CME, but no SEP event. The explanation we suggest is that either the CME did not drive a shock or the shock was so weak that it did not accelerate electrons (no type II bursts) or protons (no SEP event). This result is consistent with the past studies showing that a type II burst is always present in an eruption that produced a large SEP event (Gopalswamy et al. 2002; Gopalswamy 2003; Cliver et al. 2004).

4. DISCUSSION AND CONCLUSIONS

By comparing three solar eruptions that occurred from the same active region over a period of four days, we examined whether an extended type III burst at low frequencies (below 14 MHz) is a reliable indicator of large SEP events. We did not find support for this idea because when an extended type III burst lacked a type II burst association, it also lacked an SEP event. It appears that the extended low-frequency type III bursts are a byproduct of the eruption similar to an extended soft X-ray flare. It is true that these type III bursts are indicative of <10 keV electrons produced in the reconnection region under the CME, but not of SEP events. The magnetic connectivity is also not an issue: E2 was from S17W29, which has a better connectivity than that of E1 (S15W11).

Since the duration of the low-frequency type III burst is considered to be a primary parameter (Cane et al. 2002; MacDowall et al. 2003, 2009; Cliver & Ling 2009), we compare B2 durations (25 minutes at 14 MHz and 28 minutes at 1 MHz)

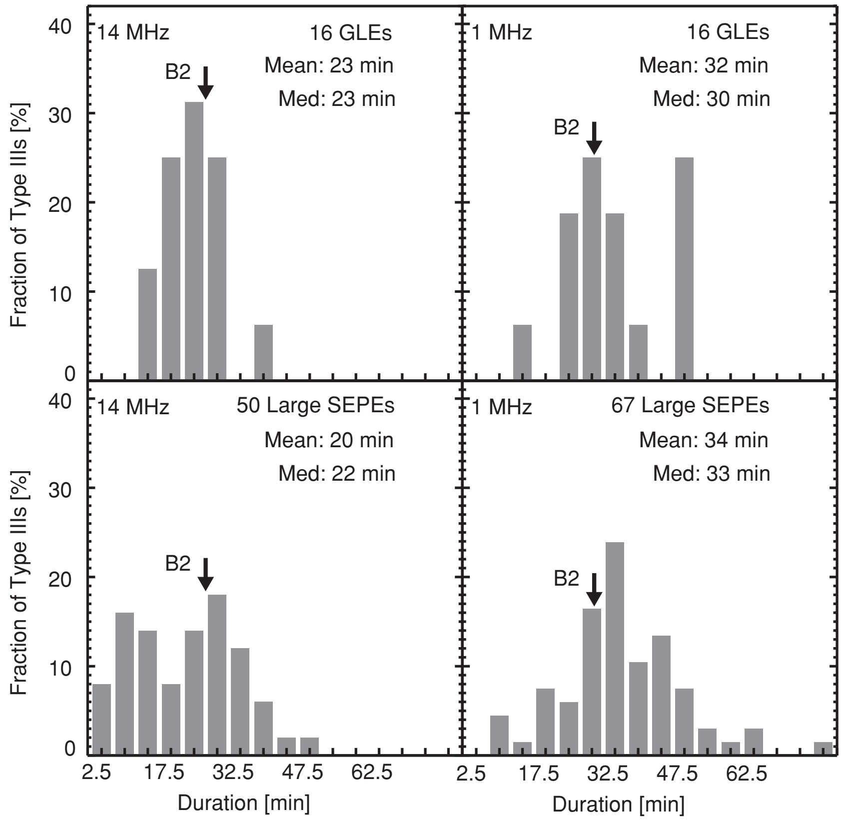

Figure 3. Distributions of the durations of low-frequency type III bursts associated with solar energetic particle events: (top) ground level enhancement (GLE) events and (bottom) other large SEP events. The B2 duration is indicated by arrows.

with the durations of all type III bursts associated with the large SEP events of solar cycle 23. There were 83 of them with *GOES* >10 MeV intensities $\geqslant 10$ pfu. We also divided the SEP events into two groups, one with ground level enhancement (GLE) events and the other without. The duration distributions are shown in Figure 3 at 14 and 1 MHz. Clearly, the duration of B2 is not marginal, but is very close to the mean and median values of the distributions at the two frequencies. We see that nearly half of the SEP events have their type III durations less than that of B2. This is also true for the type III bursts associated with GLE events, which are known to be the highest-energy SEP events (there is essentially no difference between the type III duration distributions of SEP and GLE events).

The question, therefore, is why the type III burst B2 was not associated with an SEP event. We can look at the three associated phenomena listed in Table 1 (CMEs, flares, and type II bursts). About 10% of CMEs associated with large SEP events have speeds less than that of C2. Under the shock paradigm, one can understand this as due to the variability in the Alfvén speed of the ambient medium, which can vary by a factor $\sim$4 (Gopalswamy et al. 2008). Thus, a slower CME propagating through an ambient medium of low Alfvén speed can drive a shock and accelerate particles. On the other hand, a faster CME propagating through a region of high Alfvén speed may not be able to drive a shock. Among the 83 large SEP events of solar cycle 23, the event with the lowest CME speed (478 km s^{-1} for the 2001 September 15) occurred at W49 and was barely a large SEP event. Correcting for projection effects, one can see that the CME speed could be as high as 633 km s^{-1}. This seems to be a cutoff speed below which there is no SEP event. The CME speed in the case of B2 was well above this cutoff.

As for soft X-ray flares, the three type III bursts in Figure 3 were all associated with C-class flares, but the ones that had SEP events had a slightly larger size within the C class (C7.4 for B1 and C9.6 for B3 compared to C2.8 for B2). It is not clear how the flare size selectively suppresses the proton production (because there is copious $<$10 keV electron production inferred from the low-frequency type III burst). It is known that soft X-ray flares associated with large SEP events are generally larger ($\geqslant$ C4.0 excluding two events with smaller flares that were partly occulted by the solar limb—see Gopalswamy et al. 2004). Among the 83 large SEP events of solar cycle 23, there were only 5 C-class flares (6%). There seems to be a cutoff in the peak flare flux (C4.0) for large SEP events. However, minor SEP events are associated with even weaker flares (see, e.g., Cane et al. 1986). The well-studied eruption of 1997 May 12 at 04:42 UT had a 1 pfu SEP event that lasted for at least two days (Gopalswamy et al. 2002; see also http://cdaw.gsfc.nasa.gov/CME_list/daily_plots/sephtx/1997_05/sephtx_19970513.png), even though it was associated with only a C1.3 flare, but it was accompanied by a type II burst at metric and longer wavelengths. In the shock paradigm, the flare flux cutoff simply reflects the CME speed cutoff because of the correlation between flare flux and CME kinetic energy (Yashiro & Gopalswamy, 2009). Finally, the lack of type II burst during B2 is consistent with the shock paradigm because when there is no shock, one does not expect a gradual SEP event.

This study is complementary to the statistical investigation performed by Cliver & Ling (2009). They began with a sample of large impulsive and gradual SEP events and examined the associated type III emission. They found that the peak and integrated intensity of type III bursts were the same for the impulsive and gradual SEP events. They found that large favorably located 1 MHz type III bursts with associated DH type II bursts were ∼10 times more likely to have large associated >30 MeV SEP events than those that lacked such type II bursts. The type III burst considered in this Letter has duration two times the lower limit considered by Cliver & Ling (2009) in their search for large type III bursts. Furthermore, we considered bursts from the same active region, so the magnetic and coronal environment remains roughly the same for all the eruptions so the type III bursts can be effectively compared.

In conclusion, we considered an extreme example of a complex, long-duration, low-frequency type III burst associated with a fast and wide CME but not associated with a type II burst; the type III burst was also not accompanied by an SEP event (neither gradual nor impulsive), indicating that the presence of a long-duration, low-frequency type III burst is not sufficient for the occurrence of a gradual SEP event. On the other hand, similar type III bursts from other eruptions from the same active region that were associated with type II bursts were also accompanied by SEP events. As noted before, the long-duration, low-frequency type III burst requires the liftoff of a CME, but whether the CME drives a shock that accelerates protons depends on coronal conditions well above the flare site where the type III electrons are accelerated.

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