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## Long-duration hectometric type III radio bursts and their association with solar energetic particle (SEP) events

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[1] It has recently been suggested by *Cane et al.* [2002] that a class of type III solar radio bursts, called type III-*l*, is reliably associated with intense solar energetic particle (SEP) events. They proposed that the causative electrons for these bursts are accelerated in regions of reconnecting magnetic field in the wakes of coronal mass ejections (CMEs). In this paper, we examine the durations, intensities, and other characteristics of such radio bursts in the hectometric frequency range and compare them to several groups of control events. We conclude that simple criteria, based on hectometric data alone, can identify the majority (~80%) of type III-*l* radio bursts, which are associated with >20 MeV SEP proton events, while *excluding* almost 100% of the control events. Detailed study of these type III-*l* bursts may play a significant role in a better understanding of the acceleration of SEPs and of the magnetic field evolution in the vicinity of CMEs. **INDEX TERMS:** 7534 Solar Physics, Astrophysics, and Astronomy: Radio emissions; 7514 Solar Physics, Astrophysics, and Astronomy: Energetic particles (2114); 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections. **Citation:** MacDowall, R. J., A. Lara, P. K. Manoharan, N. V. Nitta, A. M. Rosas, and J. L. Bougeret, Long-duration hectometric type III radio bursts and their association with solar energetic particle (SEP) events, *Geophys. Res. Lett.*, 30(12), 8018, doi:10.1029/2002GL016624, 2003.

### 1. Introduction

[2] In the outer corona and interplanetary medium, the most common solar radio bursts are type III bursts, which are usually produced by electrons accelerated at solar flare sites. Particularly intense and long duration type III bursts were first studied using ISEE-3 spacecraft data [*Cane et al.*, 1981]. Because these bursts were associated statistically with metric type II bursts [*MacDowall et al.*, 1987], they were called shock associated (SA) events. *Cane et al.* [1981] had argued, based on the temporal association with metric type II bursts, as well as the lack of metric type III bursts, that these SA events were produced by shock accelerated electrons; however, others disagreed (see *Cane et al.* [2002] for a detailed discussion). Recently, *Dulk et al.*

[2000] examined 8 potential shock-associated radio events using Wind Waves and ground-based radio data and concluded that the type III electrons were indeed shock accelerated. Using Wind Waves and ground-based data, *Reiner et al.* [2000] studied similar events and concluded that, for many events, the electrons were not shock accelerated, but rather, were flare accelerated, because of similar intensity profiles at GHz frequencies.

[3] *Cane et al.* [2002] reanalyzed long duration type III bursts using Wind Waves and ground-based data and proposed a new source for the electron acceleration. Specifically, these type III events were always associated with fast coronal mass ejections (CMEs), so the electrons could originate in reconnection regions in the wake of the CMEs. Because this hypothesis was unrelated to shocks, *Cane et al.* [2002] proposed calling the bursts type III-*l*, where the *l* stands for long duration, extending to low frequencies, and including components occurring late relative to the start of the flare. Contrary to some previous reports, the type III-*l* emission was often observed to start at frequencies higher than the type II burst; therefore, the causative electrons were unlikely to be shock accelerated.

[4] Our primary goal for this paper is to reevaluate the existence of a subclass of type III radio bursts, the type III-*l* burst, which, as described by *Cane et al.* [2002]:

- commences or extends beyond 5–10 min (at or above 10 MHz) after the start of a flare
- usually commences at frequencies higher than the associated (metric) type II burst, when present
- is a dominant feature in the dynamic spectra of (Wind Waves) radio events associated with SEP events, i.e., is intense in the Waves RAD1 receiver range
- only occurs when proton acceleration occurs at Sun
- always occurs in association with a CME, but
- does not occur in association with every large (>140°) CME. Conversely, CMEs without type III-*l* bursts do not produce >20 MeV protons.

### 2. Observations

[5] This analysis was carried out as part of a Living with a Star (LWS) Coordinated Data Analysis Workshop (CDAW) on solar energetic particle (SEP) events in July 2002, which provided a list of 47 SEP events and a wealth of correlated data. Due to limited space, we do not replicate the event list here: the first 43 events are those described by *Gopalswamy et al.* [2002]; additional SEP events on 2001/11/17, 2001/11/22, 2001/12/26, and 2001/12/28, were added. All of these events were intense SEPs with >10 pfu at 10 MeV (1 pfu = 1 particle cm<sup>-2</sup> sr<sup>-1</sup> s<sup>-1</sup>); almost all had temporally associated type III radio bursts, such as those shown in Figures 1a and 1b.

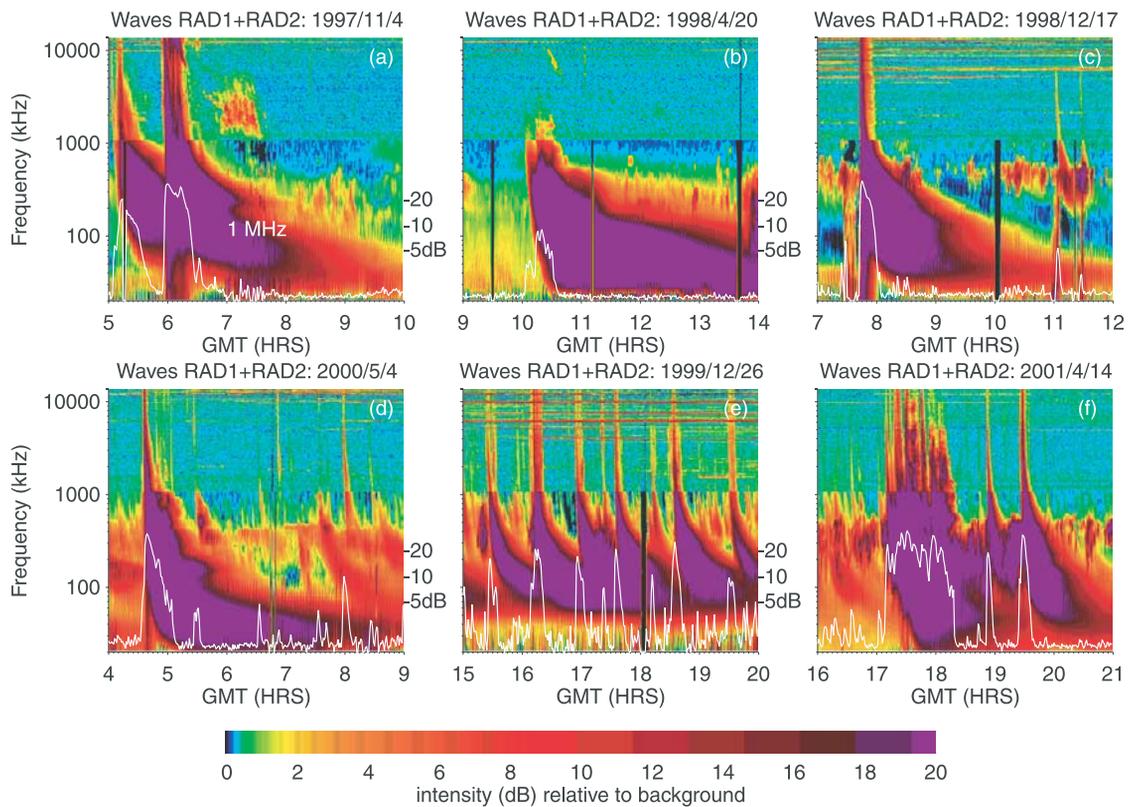
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**Figure 1.** Six dynamic spectra of Wind Waves radio data. The intensity of the radio emission relative to background as a function of time and frequency is displayed using a color (or gray) scale. The 1 MHz intensity profile is overlotted (white) on each panel. Panels (a) and (b) are two of the complex CDAW SEP events. Panels (c) and (d) are typical examples of the control groups 1 and 2, respectively. Panels (e) and (f) are two examples of the  $^3\text{He}$ -rich group. Panel (e) shows the relatively long duration of several similar type III burst events which are apparently groups of a number of closely-spaced components; the event associated with the  $^3\text{He}$  event starts at  $\sim 16:10$ . Panel (f) shows one example of a more complex radio burst associated with a  $^3\text{He}$ -rich SEP event; such complex events are not common in this group.

[6] SEP detections by near-Earth spacecraft indicate magnetic connection between the acceleration region and the spacecraft for these events. Three groups of events serve as “control” populations. Control group 1 (flares with no SEPs) consists of 25 solar events with soft x-ray (SXR) flares of class  $\geq M3.0$ , location  $\geq W30$  solar longitude, and no SEP flux  $>10^{-3}$  pfu at 20 MeV (Wind EPACT data) (E. Cliver, personal communication). Control group 2 (fast CMEs with no SEPs) consists of 19 solar events based on fast CMEs with speeds  $\geq 700$  km/s; location  $\geq W30$  solar longitude, and no SEP flux  $>10^{-3}$  pfu at 20 MeV (E. Cliver, personal communication). In each group, one event was excluded from the original list because of a Wind Waves data gap. Control group 3 is a list of 38  $^3\text{He}$ -rich SEP events prepared for the workshop by S. Yashiro. Because this list consists of events observed near-Earth, it indicates magnetic connection to the source comparable to the CDAW study events. Since the  $^3\text{He}$ -rich events are impulsive SEP events generally believed to be associated with solar flares, as distinct from CME/shock-produced gradual SEP events, this list is also a useful control group.

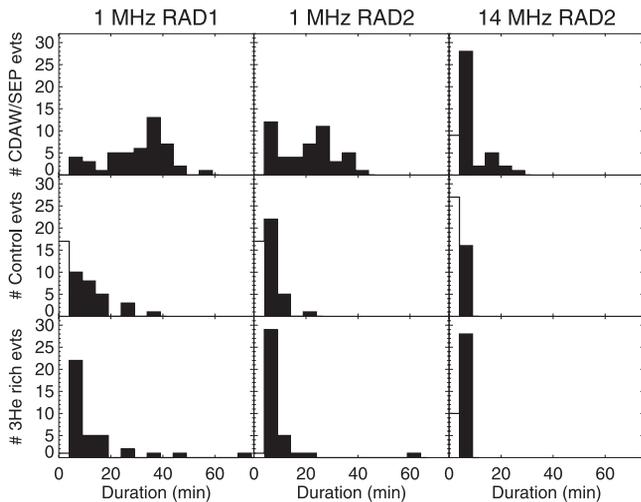
[7] To measure the type III event durations in a consistent manner, the start and end times of each radio event were determined by computer algorithm using 1-min average Wind Waves data. The “definition” for a long duration

event is at least 10 min with flux density exceeding 4 times (6 dB) the daily background at that frequency. The algorithm produces unbiased measurements similar to what a human observer would determine to be the start and end of the intense event, as confirmed by examination of start and end times overlotted on Wind Waves dynamic spectra.

[8] In Table 1, a summary of the event durations derived for the Wind Waves RAD1 1 MHz dataset is presented for the four groups. The CDAW events have a significantly higher likelihood of long duration than any of the three control groups. It is particularly striking that for control groups 1 and 2, there are often no clearly associated type III bursts, i.e., no radio event. (When the only type IIIs are weak “storm” bursts, then we assume no association, i.e., there is “no radio event”.) For all three control groups, the

**Table 1.** Event Duration Statistics - Wind Waves RAD1 1 MHz Data

Group	Events $\geq 10$ min	Events $< 10$ min	No radio event	Total
CDAW SEP	43 (91%)	4 (9%)	0 (0%)	47
Control 1	8 (32%)	4 (16%)	13 (52%)	25
Control 2	9 (47%)	6 (32%)	4 (21%)	19
$^3\text{He}$ -rich	15 (39%)	22 (58%)	1 (3%)	38



**Figure 2.** Histograms of the durations of 3 groups of events studied in this paper at 3 “frequencies”. The groups are the CDAW SEP event list, control groups 1 and 2 combined, and the  $^3\text{He}$ -rich event list. The frequencies are 1 MHz (Wind Waves RAD1 receiver), 1 MHz (Wind Waves RAD2 receiver), and 14 MHz (Wind Waves RAD2 receiver). Events with no type III radio event are put in the first bin (not shaded, starts at 0 min); events with radio duration  $<10$  min (not determined by algorithm) in the second bin (shaded).

percentage of events where there is either a short duration type III burst or no burst at all exceeds 50%, whereas less than 10% of the CDAW SEP events do not have a type III burst with duration longer than 10 min at 1 MHz.

[9] Histograms of event durations derived from the measured start and end times are shown in Figure 2. Data are presented for three “frequencies”, specifically, durations measured at 1 MHz in Waves RAD1 data, 1 MHz in Waves RAD2 data, and 14 MHz in RAD2 data. The first two determinations differ because RAD1 uses the longer Wind spin-plane antenna (100 m tip-to-tip providing greater sensitivity), whereas RAD2 uses the shorter spin-plane dipole antenna (15 m tip-to-tip) [Bougeret *et al.*, 1995]. The three groupings of events shown are the CDAW list, a combination of control groups 1 and 2, and the  $^3\text{He}$ -rich event list. The following points are noteworthy:

- the CDAW events are on average longer duration than the control events, due only partially to their intensities. As seen in Figure 1a, the typical CDAW event is composed of a number of components occurring over 10–60 min. At 14 MHz, there may be confusion with type II radio emission occurring at the same time as the type III burst, but this is not the case at 1 MHz.

- the distribution of the duration at 14 MHz (last column) is significantly different from a similar plot by Cane *et al.* [2002] (Figure 1) because only intense events (CDAW list) are included here, not a complete set as in Cane *et al.*

- for each category of event, there are fewer events detected at 14 MHz. This is due in part to lower intensity and duration at 14 MHz and in part due to effects such as observed in Figure 1b. There, the type III burst appears at  $\sim 1$  MHz and increases in intensity below that frequency. Because all CDAW events showing this behavior are

associated with flares at solar longitude  $\geq 90^\circ\text{E}$ , this effect probably results from occultation of the source by high-density regions of the corona as seen from Wind.

- the 4 CDAW SEP events with durations less than 10 minutes only miss the cutoff by a few minutes each. They are all events similar to Figure 1b, although somewhat weaker in intensity.

- for all three “frequencies,” the control groups have proportionally more events with duration  $<10$  minutes (including “no event detected”) than the CDAW SEP group. Reasons for this are clear in Figure 1c (an event from control group 1) and Figure 1d (from control group 2). Although these are very intense radio bursts, they are each single, short duration ( $<10$  min) bursts at frequencies as high as 14 MHz. (Note: events with no associated type III radio event are put in the first bin (starts at 0 min) and events with durations  $<10$  min (not assigned durations by the algorithm) in the second bin.)

- the  $^3\text{He}$ -rich events have more varied radio behavior. A number of them are only associated with weak type III bursts as observed by Wind. Only the most intense  $^3\text{He}$ -rich events, like those shown in Figure 1e (starting at  $\sim 16:10$ ) and, especially, Figure 1f, have complex radio events with multiple components, etc.

[10] Other features of the CDAW SEP type III events, as observed by Wind Waves, may make them unique. After some experimentation, we selected the following provisional type III-*l* criteria, based on Wind Waves data only:

- duration at 1 MHz (Wind Waves RAD1 data) greater than or equal to 10 min

- peak intensity in the RAD1 data (frequency range 100–200 kHz) greater than 20 dB above background

- type III event appearance in RAD2 data (1–14 MHz) more complex than multiple type III bursts or a group of type III bursts (as described below).

[11] The first criterion is simply the time duration as reviewed above. The second criterion serves to ensure that the event is at least a moderately intense interplanetary type III burst, as noted by Cane *et al.* [2002]. The third criterion is a semi-quantitative method of including the complexity typical for the CDAW events, which is consistent with previous discussions regarding multiple components [MacDowall *et al.*, 1987] and complex type III-like radio bursts [Reiner *et al.*, 2000]. Reiner and Kaiser [1999] note that the unusual features of the “complex type III-like bursts” may include bursty emissions above  $\sim 7$  MHz, typically without measurable frequency drift, distinct diminution of the radio emission near 7 MHz, coalescence in fast frequency drifting features below  $\sim 7$  MHz, short duration, and narrow-band features with slow or no frequency drift. We identify a simple type III profile as one like that shown in Figure 1c, a multiple burst profile as the combination of several simple profiles that can be separated visually (Figure 1d), a group as multiple bursts that occur sufficiently close in time that they appear to be merged together into one longer duration event (Figure 1e,  $\sim 16:10$ – $16:20$ ), and a complex event (Figures 1a and 1f) as one where the appearance cannot be explained as a simple combination of several simple fast-drift profiles. In Figure 1f, for example, the major (complex) event is characterized by enhancements and several narrow-band features, in addition to the fast-drift components. These features may be compared to the

**Table 2.** Event Statistics for Groups in Table 1 Using the 3 Type III-*l* Criteria of This Paper

Group	# events meeting 3 criteria	# events meeting #2 criteria	No radio event	total
CDAW SEP	37 (79%)	10 (21%)	0 (0%)	47
Control 1	0 (0%)	12 (48%)	13 (52%)	25
Control 2	0 (0%)	15 (79%)	4 (21%)	19
<sup>3</sup> He rich	2 (5%)	35 (92%)	1 (3%)	38

two weaker type III events later in Figure 1f, both of which are simple in appearance. It is noteworthy that the major event of Figure 1f has protons >20 MeV, but the SEP event is obscured by a data gap.

[12] Applying these criteria to each of the event groups, we obtain Table 2. The criteria, in particular, the requirement that the profile be complex, discriminate strongly against the control events. They also exclude a small fraction of the CDAW events, which are not sufficiently complex or only appear below 1 MHz. However, nearly 80% of the CDAW SEP events meet the three criteria, compared to only two of the combined 82 control events.

### 3. Discussion and Conclusions

[13] Long duration, complex type III bursts have been recognized by a number of authors as being “different” from the simple type III burst; however, disagreement about the electron acceleration exists. With the proposal by *Cane et al.* [2002] that these events are closely associated with SEP proton events and accelerated by post-CME reconnection, there is a new opportunity to better understand these radio bursts. Using the groups of events described above, we address several points raised by *Cane et al.* [2002].

[14] Do LWS CDAW SEP events have associated type III-*l* bursts? In terms of Wind Waves observations of duration, essentially “yes”. Of the 47 CDAW events, all but four have durations (as defined above) at 1 MHz (RAD1) greater than or equal to 10 min. These four “missing” events appear at ~1 MHz and have durations >10 min below 1 MHz. Inspection of Wind Waves dynamic spectra for the events indicates that all but a few are intense at lower frequencies (100–200 kHz in RAD1). With the additional consideration of the “complexity” of the type III events, a set of criteria can be developed that discriminates against 98% (80/82) of the control events, using Wind Waves data alone. The same criteria reject only 21% (10/47) of the CDAW SEP events. It is possible that even better criteria exist.

[15] Do control groups w/o SEPs have associated type III-*ls*? The majority of time, they do not, based on Wind Waves data, due to short duration times and/or weak intensity. Of those that satisfy the 1 MHz duration and ~100 kHz intensity criteria, almost all are visibly not complex (as defined above) type III bursts (see Figures 1c, 1d, and 1e).

[16] What is the significance of type III-*l* bursts? Clearly, they usually represent an extreme in duration and intensity for type III bursts. This was evident for their SA prede-

cessors from statistical studies of the ISEE-3 radio data [e.g., *MacDowall et al.*, 1987]. There appear to be one or more situations that result in the acceleration of type III electrons over intervals of up to ~1 hour, producing multiple radio components that are readily observed on the dynamic spectrum at frequencies above 1 MHz. In addition, other features may be observed that do not correspond to the simple evolution of a propagating electron beam, e.g., narrow-band non-drifting features. The acceleration mechanism proposed by *Cane et al.* [2002] would likely produce such multiple components and long durations, but this is difficult to confirm with existing data. Ultimately, two-dimensional imaging of the radio sources may permit determination of the electron acceleration site(s).

[17] In conclusion, the statistical analysis presented here is *consistent* with the conclusions of *Cane et al.* [2002] that long duration type III-*l* radio bursts are usually associated with the occurrence of intense SEP proton events. Further investigation is warranted to understand the source of the electron acceleration that causes these atypical type III bursts, as well as to establish the physical connections to CMEs and SEPs.

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