Solar flares, type III radio bursts, coronal mass ejections, and energetic particles

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[1] In this correlative study between >20 MeV solar proton events, coronal mass ejections (CMEs), flares, and radio bursts it is found that essentially all of the proton events are preceded by groups of type III bursts and all are preceded by CMEs. These type III bursts (that are a flare phenomenon) usually are long-lasting, intense bursts seen in the low-frequency observations made from space. They are caused by streams of electrons traveling from close to the solar surface out to 1 AU. In most events the type III emissions extend into, or originate at, the time when type II and type IV bursts are reported (some 5 to 10 minutes after the start of the associated soft X-ray flare) and have starting frequencies in the 500 to ~100 MHz range that often get lower as a function of time. These later type III emissions are often not reported by ground-based observers, probably because of undue attention to type II bursts. It is suggested to call them type III-*l*. Type III-*l* bursts have previously been called shock accelerated (SA) events, but an examination of radio dynamic spectra over an extended frequency range shows that the type III-*l* bursts usually start at frequencies above any type II burst that may be present. The bursts sometimes continue beyond the time when type II emission is seen and, furthermore, sometimes occur in the absence of any type II emission. Thus the causative electrons are unlikely to be shock accelerated and probably originate in the reconnection regions below fast CMEs. A search did not find any type III-*l* bursts that were not associated with CMEs. The existence of low-frequency type III bursts proves that open field lines extend from within 0.5 radius of the Sun into the interplanetary medium (the bursts start above 100 MHz, and such emission originates within 0.5 solar radius of the solar surface). Thus it is not valid to assume that only closed field lines exist in the flaring regions associated with CMEs and some interplanetary particles originating in such flare regions might be expected in all solar particle events. *INDEX TERMS:* 7519 Solar Physics, Astrophysics, and Astronomy: Flares; 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections; 7534 Solar Physics, Astrophysics, and Astronomy: Radio emissions; 7514 Solar Physics, Astrophysics, and Astronomy: Energetic particles (2114); 2118 Interplanetary Physics: Energetic particles, solar; *KEYWORDS:* Particles, flares, radio bursts, CMEs

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1. Introduction

[2] Electromagnetic emissions are an important diagnostic for particle acceleration processes. Radio waves from the Sun indicate electron acceleration, primarily to energies of tens of keV, and such electrons are likely to be accelerated at any time that high energy ions are accelerated. At frequencies below a few hundred MHz the characteristics of solar radio emissions as a function of frequency and time have been described in terms of five main types of bursts named type I through V [*Wild et al.*, 1963]. All are likely to be plasma radiation in which the emission frequency is directly related to the plasma frequency (frequency in kHz equals 9 times the square root of the electron density (cm^{-3})). Thus emission above 100 MHz originates within 0.5 solar radii of the photosphere whereas emission at 10 MHz, approximately the lowest frequency observable below the Earth's atmosphere, originates at about 2 solar radii. Space-based

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observations are possible down to the local plasma frequency, which near Earth is typically 30 kHz; electromagnetic radiation cannot propagate below the plasma frequency. Descriptions of solar radio bursts may be found in the books by *Kundu* [1965] and *Krüger* [1979]. Unfortunately, the compendium produced by the Australian researchers ("Solar Radiophysics" edited by D. J. McLean and N. R. Labrum) and published in 1985 is no longer in print. The following description pertains to bursts below 500 MHz and the supporting observations, when not quoted, may be found in the aforementioned books.

[3] Type III bursts, the most common type, last a few seconds, drift rapidly to very low frequencies, and often occur in groups lasting about 5 minutes. They are a classic signature of the so-called "impulsive phase" of flares in which the radiation is primarily non-thermal. The exciting agent is a stream of electrons. The production mechanism is believed to be a two step one in which the electrons create Langmuir waves that then interact with the ambient plasma to produce radio waves [see, e.g., *Bastion et al.*, 1998]. The energy release is most likely the result of magnetic reconnection with the type III burst resulting from an upward directed electron beam. A downward directed electron beam interacts with the higher density solar atmosphere to produce hard X-ray emission via bremsstrahlung and, in energetic events, gamma-ray emission. Subsequent heating leads to enhanced emission in soft X rays and an Hα brightening. This whole sequence we call a "flare". Some researchers use a more restrictive definition and by flare mean a chromospheric brightening. We adhere to the *Hudson et al.* [1995] definition: "a flare is a sudden energy release in the solar atmosphere". Thus the events leading to weaker soft X-ray intensities and fainter Hα parallel ribbon brightenings seen with CMEs arising outside active regions would also be described as flares [cf. *Cliver*, 1995; *Hudson et al.*, 1995; *Švestka*, 2001].

[4] Most type III bursts occur at the beginning of flare events, in the impulsive phase. Thus type III bursts trace electron streams as they propagate along open field lines from flaring regions near the Sun into the interplanetary medium. Sometimes type III bursts have an associated continuum that is called type V. This emission is probably from a part of the electron population that remains trapped in closed magnetic loops. *Cane and Reames* [1990] found that type III/V bursts are associated with short-duration flares and that in intense flare events with type III/V emission electrons above 200 keV, and often protons above 10 MeV as well, are released into the interplanetary medium.

[5] Type II bursts last from a few minutes to about 30 minutes and are distinguished by their slow drift rates relative to type III bursts. They usually appear as two main narrow bands occurring simultaneously at frequencies differing by approximately a factor of two. The bands correspond to the fundamental plasma frequency and its first harmonic. The main bands may be further broken into multiple bands. Type II bursts typically start below 100 MHz (the lower band) and cease at about 20 MHz. They occasionally start at several hundred MHz and may extend to about 1 MHz, although not in the same event. An extension of the slope of the burst to higher frequencies intercepts the start of the associated type III bursts, when present, at the start of the flare. Type II bursts start within a few minutes of the maximum brightness in Hα. When flares are more gradual and last longer, then type II bursts tend to start at lower frequencies and preceding type III bursts are less common [*Cane and Reames*, 1988]. The frequency drift rates of type II bursts imply speeds appropriate for coronal shock waves, typically around 1000 km/s. Thus the causative electrons are assumed to be shock accelerated. Evidence in support of the shock acceleration of the electrons was the observation in some type II events of the occurrence of a succession of short duration, fast-drift elements emerging from both sides of the "backbone" of the type II burst. This was called "herringbone structure" [*Roberts*, 1959]. In the early 1980's, *Cane et al.* [1981] suggested that the electrons producing herringbone structure could occasionally, in energetic events, escape to the interplanetary medium. They concluded this because they observed fast-drifting, relatively intense and long lasting bursts at low frequencies ($\lesssim$2 MHz) that occurred at the time when ground-based observers recorded type II bursts with herringbone structure. These low-frequency fast-drift bursts were named SA (shock accelerated) events. The importance of these bursts is that they are well associated with high energy (>50 MeV) solar particle events as was noted in the 1981 "discovery" paper.

[6] Radio emission associated with interplanetary (IP) shocks is also seen, but much less frequently. *Cane* [1985] called these IP type II events to distinguish them from flare-associated type II bursts. IP shocks, and associated radio emission, are caused by coronal mass ejections (CMEs) [*Cane et al.*, 1987]. From the ISEE-3 observations it seemed that IP type II events started below 1 MHz. However there were no observations above 2 MHz and no frequency coverage between 1 and 2 MHz. Observations from the Wind spacecraft suggest that they are occasionally seen as high as 6 MHz.

[7] Type IV emission is broadband and results from trapped electron populations. There are several subclasses of type IV bursts, the type most tightly coupled to flares is called type IV flare continuum. This emission lasts from about 3 to 45 minutes and starts shortly after type III bursts, when present, and before the type II burst, when it is present. Type IV flare continuum has been found to precede many large solar proton events as first noted by *Boischot and Denisse* [1957]. In their 1963 review paper Wild et al. reported "the fact has clearly emerged that nearly all proton events are associated with type IV bursts and that the type IV burst is the most reliable known indicator that a flare should produce accelerated protons that bombard the Earth". Similarly, about 20 years later *Kahler* [1982] found that "the metric type IV bursts serve as the key signature in deciding whether proton acceleration occurs in a candidate flare".

[8] Surprisingly, both *Wild et al.* [1963] and *Kahler* [1982] discussed proton acceleration in terms of shock acceleration as evidenced by type II bursts despite the fact that *Kahler* [1982] found that a type II burst "is not a sufficient condition for the occurrence of an interplanetary proton event" and that "*most* type II bursts are *not* associated with interplanetary energetic protons". There are many more type II bursts than proton events. Previously *Švestka and Fritzova-Švestková* [1974] had determined that the fraction of proton events associated with type II bursts was about 75%. A careful reading of the *Wild et al.* [1963] paper also reveals that even at that time it was recognized that in some major solar events type II bursts are missing

and replaced by activity having ''the appearance of a group of type III bursts'' with ''suggestions of frequency drift, at rates typical of type II bursts, in the high and low-frequency edges of successive features''.

[9] It is not clear why *Wild et al.* [1963] focused their attention on type II bursts rather than type IV bursts. The most likely reason is that type II bursts are thought to originate in shocks, and that shocks are known to be efficient particle accelerators. Thus type II bursts have assumed great importance and are regularly reported by patrol spectrograph observers, even when they are only a few minutes long, while other emissions, particularly type III bursts, that occur at the same time are not reported at all. In this paper it will be shown that type II bursts do not appear to be the dominant feature in the dynamic spectra of radio events associated with solar energetic particle (SEP) events.

[10] A small group of solar particle physicists has gone a step further away from the observations and considered major proton events to be completely independent of flares. A relationship between major SEP events and flares was deemed a '*myth*' [e.g., *Reames*, 1999, and references therein]. However the association was established with the first observations of solar particle increases in neutron monitor data in the 1940's and 1950's wherein the onset times of the particles indicated that in many cases the particles left the Sun within a few minutes of the maximum of the flare emissions [e.g., *Webber*, 1964; *Křivský*, 1977, and references therein; *Cliver et al.*, 1982]. One assumes that in the Reames paradigm the associations between e.g. gradual soft X-ray events and other flare phenomena and so-called ''gradual'' SEP events are considered an indication of the presence of a CME; the sites of particle acceleration are taken as the putative shocks driven by CMEs in the low corona. These shocks are supposedly evidenced by type II radio bursts at frequencies above 10 MHz. The fact that such bursts are also a flare phenomenon is ignored. Also ignored are the Culgoora radioheliograph observations [*Gary et al.*, 1984] that showed that type II sources occur behind the leading edges of CMEs, not in front where any shocks would form. Images from the Nançay radioheliograph have now revealed the weak sources that do originate at the CME leading edge [e.g., *Pick*, 1999]. *Pick* [1999] presents data consistent with the idea that ''coronal and interplanetary shocks have independent origins''.

[11] Major SEP events and CMEs are well correlated [*Kahler et al.*, 1978, 1984]. These studies also found that there were correlations between peak proton intensity (at energies >4 MeV) with CME speed and size. These correlations provided support for the shock acceleration scenario since only fast CMEs drive shocks and the size of the CME is a measure of the size of the shock. Furthermore, the angular sizes of CMEs were found to be comparable to the size of the longitude region on the Sun from which prompt SEP events can occur [*Reinhard and Wibberenz*, 1974]. However the particle intensity vs. CME speed correlation is not particularly strong; *Kahler* [2001] found that the range of particle intensities spreads over 3–4 orders of magnitude for any particular CME speed. Of course CMEs do drive interplanetary shocks and are important particle accelerators [e.g., *Cane et al.*, 1988] but unanswered questions remain: a) at what height in the corona do the shocks actually form b) what delay occurs before particles are accelerated to high energies and c) can an additional source be ruled out i.e. are there flare particles in addition to particles accelerated at a CME-driven shock? These questions will not be addressed in this paper. Rather, this paper looks more closely at *the flare phenomena that are clearly present in all solar particle events*.

[12] The exact relationship between flares and CMEs is a topic of heated debate but it is likely that all long-lasting (gradual) flares and some impulsive flares result from the reconnection of field lines pulled out by CMEs. A number of workers have suggested that this reconnection region could be a source of interplanetary energetic particles [e.g., *Švestka et al.*, 1980; *Litvinenko and Somov*, 1995]. An argument that has been used against such a scenario is the assumption that field lines threading this reconnection region are closed. Thus, any accelerated particles are assumed to have no access to the interplanetary medium [see, e.g., *Kahler et al.*, 2000, Figure 1]. However, *Klimchuk* [1996] suggests that there may be many open field lines threading through the closed structures of post-CME arcades. He arrived at this suggestion by comparing the observed rate of plasma heating in a particular event with that expected from a standard model of post-CME reconnection. To account for the low amount of heating he suggested that only a small fraction of the field can reconnect, the rest being open. Evidence for such patchy reconnection are the supra-arcade downflows seen in soft X rays from Yohkoh [*McKenzie*, 2000]. Strong evidence for the escape of energetic electrons would be the presence of type III bursts. If the bursts extend to the lowest frequencies seen near Earth then there must be direct field line connection from the reconnection region to Earth. With this in mind, this paper reinvestigates the radio bursts associated with SEP events. Of particular interest are the low-frequency observations from the WAVES experiment on Wind [*Bougeret et al.*, 1995], that bridge the gap between ground-based and space-based observations. Solar associations have been made for 123 SEP events that had measurable intensities above 20 MeV in the GSFC IMP 8 experiment [*McGuire et al.*, 1986] during the period January 1997 through May 2001. It is found that all of the particle events are indeed preceded by type III bursts extending to low frequencies and they are the dominant feature in the WAVES daily plots in about 80% of the events. In most events the type III bursts last longer than the 5 minutes of typical ''impulsive phase'' type III bursts (on average they last 20 minutes) and extend into the time when type II bursts are reported. In other words they have the characteristics of SA events [*Cane et al.*, 1981]. (In this paper we call them type III-*l*.) The question then is whether the causative electrons are shock-accelerated. If the electrons are shock-accelerated and *if* >10 MHz type II bursts did in fact result from shocks in front of CMEs then there is no inconsistency with the current paradigm. However various researchers, in particular Kundu [e.g., *Kundu and Stone*, 1984] and Klein [e.g., *Klein and Trottet*, 1994] have long argued that the electrons responsible for SA events are not shock accelerated. More recently, with the advent of the WAVES experiment, there have been opposing opinions. *Reiner et al.* [2000] have concluded that the bursts are not shock accelerated while *Dulk et al.* [2000] have concluded that they are.

[13] Using interference reduction techniques the Bruny Island Radio Spectrometer (BIRS) [*Erickson*, 1997] is able

to observe at frequencies below those of any other ground-based instrument. In this paper we shed light on the question by combining data from Culgoora, BIRS and WAVES experiments to provide complete coverage from 1.8 GHz to the lowest frequencies with no frequency gaps.

[14] This paper begins by listing and describing the solar associations for 123 particle events (plus two probable events) and, in particular, the times of the associated activity first seen in the WAVES data, i.e. near 10 MHz. Also included are the Hα flare coordinates, and the start time, rise time and peak intensity in soft X rays. Many of the behind-the-limb events had associated soft X-ray flares. For the events farthest behind the limb the low coronal emissions were occulted and the time of the 1 MHz emission is listed. All events were preceded by a CME and the time of the first CME observation is also listed.

[15] Next radio spectra are presented for 8 of the particle events showing that in these typical events the type III bursts do *not* originate in type II bursts. Having found the excellent correlation between SEP events and long-lasting type III emissions and CMEs, searches were made to see if such radio bursts and CMEs occurred in the absence of an SEP event. None were found apart from cases where an SEP event would not be listed because of high background from a previous event or the radio burst indicated poor magnetic connection. Finally, the results are discussed, including the possible reasons why some researchers have concluded that some type III burst electrons are shock accelerated.

2. Data Analysis

2.1. Data Sets and Their Statistics

[16] The starting point was a list of >20 MeV solar particle events with a measurable 24–29 MeV proton intensity above background (at least three 30 min averages exceeding the preceding background level by at least one sigma) as measured by the MED telescope of the Goddard experiment on IMP 8. The background level of this telescope in this energy range is $\sim 10^{-4}$ particles/(cm^2-sec-ster-MeV). Interplanetary events (shock accelerated and modulations of the intensity of an event) were excluded by examining the full 1–$\sim$200 MeV range of the experiment and requiring velocity dispersion (i.e. increases that occurred at later times as a function of decreasing energy) indicative of a solar origin for the particles. One hundred and twenty-three such events were tabulated for the period January 1997 through May 2001 and are listed in Table 1. Some small events are missing because of data gaps and some events within data gaps have been verified by examining the data from the COSTEP experiment on SOHO (PI H. Kunow) available from the NASA CDA Web site. Other solar events may have produced particles that reached Earth but are indistinguishable as a new injection because of high intensities from previous events. Two solar events in this category (i.e. high background) are included in the list because there is evidence of an additional particle population above 100 MeV. The first columns of Table 1 give information about the SEP event. The timing information is of two types. For events that show a rapid increase in intensity and a clear maximum intensity, at any energy, within a few hours of the first increase above background, the onset time is given to the closest hour. For the remaining events, the start and end dates are given, to the closest day, with an indication of the probable start time. Sometimes this start time is greater than 24 hours; this is to make the date agree with the date of the solar event. The next column gives an estimate of the highest energy to which a particle increase was observed. The highest energy range available was 121–230 MeV so energy estimates above this range are not possible except for events that were observed from the ground by neutron monitors, implying energies >500 MeV. Also listed is the peak intensity in the 24–29 MeV energy range that occurred within about 12 hours of the associated solar event. Two events (July 14 and November 8, 2000) saturated the IMP 8 MED telescope above 24 MeV so the intensity in the 16–23 MeV channel of the LED telescope was used after division by a factor determined from other large events in which saturation did not occur.

[17] The list provides a set of consistent associations between the SEP events, radio bursts, flares and CMEs. In the most energetic events these associations are straightforward and follow patterns established decades ago. In particular there were radio bursts of type II and/or IV, long duration soft X-ray events, large and bright Hα flares and fast CMEs. These phenomena occurred about an hour or so before the particle event. Also important are the intensity-time profiles of the particles that follow an organization with respect to the longitude of the associated flare [*Cane et al.*, 1988]. Eastern events typically have slowly rising intensities whereas western events increase rapidly and peak at high energies within a few hours of the flare starting time. For some SEP events, especially the smaller increases or ones that commenced gradually, an iterative process was necessary to make a complete and reliable set of consistent associations.

[18] The next data set to be considered is the low-frequency radio data from the WAVES experiment (PIs, M. L. Kaiser/J.-L. Bougeret) on the Wind spacecraft [*Bougeret et al.*, 1995]. Daily spectral plots were obtained from the WAVES internet site maintained by M. L. Kaiser (http://lep694.gsfc.nasa.gov/waves/waves.html). *All but two* of the 123 events were clearly preceded by a fast-drift burst. These bursts started a few hours before the particle event and in most cases were the dominant feature of that day's plot. The bursts usually reached the lowest frequencies (tens of kHz) within about 30 minutes of when the particle event commenced.

[19] One of the SEP events without an obvious radio burst below 14 MHz was a slow rising event from a far eastern longitude. The other originated near central meridian and was also slow rising with large intensity fluctuations. Both were preceded by type III emission above 25 MHz. In both cases there were weak radio emissions below 14 MHz at the appropriate times but the situations were ambiguous because of other ongoing radio activity.

[20] Using the daily spectral plots the start and end times of the bursts associated with the other 121 SEP events were estimated to the nearest 5 minutes at 14 MHz. These times are given in Table 1. In many cases a more accurate time might be obtained by examining individual frequency profiles, but this is a difficult and time consuming process that was not deemed to be worthwhile, although some events were examined this way in order to test the accuracy of the estimates found from the daily spectra. When only one type III time is given it means that no radio burst was observed at 14 MHz and that the time given is the approximate start time

Table 1. Solar Energetic Particle Events, 1997–2001

Year	Particle Event				Type III Time,[d] UT	Flare Event				CME First Ob., UT
	Time[a]		E,[b] MeV	Intens.[c]		Start, UT	Rise, min	Hα Pos.	X-Ray[e] Peak	
	Date(s)	Hours								
1997	April 01	16	50	dg	1345–1355	1325	23	25S 16E	M2	1518
	April 07	15	70	0.005	1355–1440	1350	17	28S 19E	C7	1427
	May 12	06	80	0.009	0455–0510	0442	13	21N 07W	C1	0630
	May 21	21	70	0.001	2010–2015	2003	12	05N 12W	M1	2100
	July 25	21	40	dg	2015–2025*	2017	17	16N 54W	C5	2101
	Sept. 24	04	>120	0.003	0250–0300	0243	9	31S 19E	M6	~0300
	Oct. 07	14	50	dg	~1320	...	...	S 120W	...	1330
	Oct. 21	20	45	dg	1740–1750	1700	54	16N 07E	C3	1803
	Nov. 03	<12	40	0.002	1025–1030*	1018	11	17S 22W	M4	1111
	Nov. 04	07	>120	0.4	0555–0615	0552	6	14S 33W	X2	0610
	Nov. 06	12	>500	4.3	1150–1215	1149	6	18S 63W	X9	1210
	Nov. 13	23	70	0.02	2115–2120	...	...	N 110W	...	2225
	Nov. 14	15	60	0.008	~1300	...	...	N 120W	...	1336
	Dec. 06	17	30	0.0007	~1240	1059	270	47N 13W	B7	1027
1998	Jan. 26	23	50	dg	2235–2240	2219	16	17S 55W	C5	2327
	March 31–April 13	<31	40	B0.0002	~0500?	...	...	S 120E	...	0612
	April 20	12	>120	8	~1000	0938	43	S 90W	M1	1007
	April 23	**	**	**	0540–0610	0535	20	S 95E	X1	0527
	April 29–May 02	<24	70	0.009	1615–1650	1606	31	18S 20E	M7	1658
	May 02	14	500	1.1	1335–1400	1331	11	15S 15W	X1	1406
	May 06	08	500	1.4	0800–0830	0758	11	11S 65W	X3	0829
	May 09	05	>120	0.08	0325–0350	0304	37	S 100W	M8	0335
	May 27	15	50	0.001	1315–1330	1313	67	21S 83W	C8	1345
	May 30	<25	70	0.002	2250–2255	...	...	S 120W	...	2328
	June 04–Jun 06	14	40	0.0002	~0200	...	...	S 120W	...	0204
	June 16	21	70	0.01	~1810	1803	39	S 115W	M1	1827
	Aug. 18	24	70	0.002	2215–2220*	2210	9	33N 87E	X5	dg
	Aug. 19	23	>120	0.008	2145–2155	2135	10	32N 75E	X4	dg
	Aug. 24	23	>500	dg	2205–2230	2150	22	35N 09E	X1	dg
	Sept. 06	07	70	0.008	~0600	0556	28	N 100W	C3	dg
	Sept. 09	06	50	0.003	0455–0500*	0452	6	N 140W	M2	dg
	Sept. 20–Sept. 23	<27	70	B0.0003	0235–0250	0233	18	22N 62E	M2	dg
	Sept. 23	10	>120	0.009	0700–0715	0640	33	19N 09E	C7	dg
	Sept. 30	14	>120	6.7	1320–1350	1304	44	19N 85W	M3	dg
	Oct. 18	22	>120	0.022	2105–2110	...	...	N 130W	...	dg
	Nov. 05–Nov. 10	<22	60	0.0008	???	1900	55	26N 18W	M9	2044
	Nov. 14	06	>120	2.3	0500–0535	...	...	N 120W	...	dg
	Nov. 22	08	>120	0.04	0640–0645	0630	12	27S 82W	X4	dg
	Nov. 24	03	>120	0.01	0215–0220	0207	13	S 108W	X1	0230
	Dec. 17	11	30	0.0003	0745–0750*	0740	5	27S 46W	M3	0830
1999	Jan. 03	16	30	0.0005	1450–1520?	1449	25	23S 49W	C6	dg
	Jan. 06	25	30	0.0006	2400–2410	2354	12	S 95W	C8	dg
	Jan. 20	21	>120	0.02	1905–1955	1906	58	S 95E	M5	dg
	Feb. 16	06	70	0.001	0300–0320	0249	23	23S 14W	M2	dg
	April 24	15	70	dg	1300–1340	...	...	S 150W	...	1331
	May 03–May 09	<20	50	0.0002	0540–0615	0536	26	15N 32E	M4	0606
	May 09	19	70	0.02	1800–1805	1753	14	N 95W	M8	1827
	May 27	11	>120	0.06	1045–1110	...	...	S 120W	...	1106
	June 01	20	>120	0.29	1845–1910	...	...	N 120W	...	1937
	June 04	08	>120	0.29	0655–0730	0652	11	17N 69W	M4	0726
	June 11	01	>120	0.042	~0040	...	...	N 120W	...	0126
	June 18	18	30	0.001	1635–1640*	1638	19	N 120W	C6	dg
	June 27	<11	70	0.002	0835–0840*	0834	10	22N 26W	X1	0906
	June 29–July 04	<12	70	B0.0004	0455–0515	0501	9	18N 07E	M1	0554
	July 25	<20	70	0.0008	~1325	1308	30	N 95W	M2	1331
	Aug. 28	20	70	0.0005	1755–1810	1752	13	26S 14W	X1	1826
	Sept. 13–Sept.16	<13	40	0.0003	1620–1640	1630	15	15N 06E	C3	1731
	Oct. 14–Oct. 19	<18	30	B0.0001	0855–0910	0854	6	11N 37E	X1	0926
	Nov. 17	~12	60	dg	0950–1015?	0947	10	17N 21E	M7	dg
	Dec. 28	02	>50	dg	0040–0050*	0039	9	20N 56W	M5	dg
2000	Jan. 09	14	70	0.006	1415–1420	...	...	N 120W	...	dg
	Jan. 18	18	>120	0.009	1710–1735	1707	20	19S 11E	M4	1754
	Feb. 12	05	>120	0.009	0405–0420	0351	19	26N 24W	M1	0431
	Feb. 17	21	>120	0.009	2025–2040	2017	18	29S 07E	M1	2130
	Feb. 18	10	>120	0.075	0925–0930	...	...	N 120W	...	0954
	March 02	09	>120	0.006	0825–0835	0820	8	14S 52W	X1	<1154
	March 22	20	70	0.004	1845–2015?	1834	14	14N 57W	X1	1931

Table 1. (continued)

Year	Particle Event				Type III Time,[d] UT	Flare Event				CME First Ob., UT
	Time[a]		E,[b] MeV	Intens.[c]		Start, UT	Rise, min	Hα Pos.	X-Ray[e] Peak	
	Date(s)	Hours								
	March 24	10	70	0.002	0750–0755	0741	11	15N 82W	X2	dg
	April 04	16	70	0.117	1515–1535	1512	29	16N 66W	C9	<1632
	April 23	14	>120	0.007	~1225	...	...	N 110W	...	1230
	April 27	15	dg	dg	~1420	...	...	N 120W	...	1430
	May 01	11	50	0.0009	1020–1025*	1016	11	20N 54W	M1	1054
	May 04	12	60	dg	1100–1105*	1057	11	20S 90W	M8	1126
	May 05–May 10	<20	50	0.001	1525–1530	...	...	N 120W	...	1550
	May 10–May 15	<27	70	0.0006	1930–1945	1926	11	14N 20E	C9	2006
	May 15	18	70	0.005	1600–1605	1546	15	22S 68W	C8	1626
	June 02–June 06	<36	30	B0.0001	???	1848	50	16N 60E	M8	2030
	June 06–June 10	19	>120	0.02	1510–1545	1458	27	20N 14E	X2	1554
	June 10	18	>120	0.4	1700–1715	1640	22	22N 40W	M5	1708
	June 15	21	30	0.001	1945–1950*	1938	19	20N 62W	M2	1950
	June 17	05	70	0.004	~0230	0225	12	22N 72W	M4	0328
	June 17	26	70	0.014	~2255	2227	49	N 95W?	C5	2310
	June 23	16	70	0.008	1420–1425*	1418	13	23N 72W	M3	1454
	June 25	12	70	0.007	0740–0745	0717	35	16N 55W	M2	0754
	June 28	20	70	0.0006	1845–1905	1848	22	N 95W?	C4	1931
	July 10	24	70	0.002	2125–2130	2105	37	18N 49E	M6	2150
	July 14	11	>500	10	1020–1050	1003	19	22N 07W	X6	1054
	July 22	12	>120	0.19	1130–1135	1117	17	14N 56W	M4	1154
	July 27	24	>120	0.031	~1930	...	...	N 120W	...	1954
2000	Aug. 09–Aug. 16	<50	60	B0.0001	1525–1545?	1519	62	11N 11W	C2	1630
	Aug. 12	11	70	.003	1000–1005*	0945	11	17S 79W	M1	1035
	Sept. 07	21	70	0.001	~2055	2032	23	06N 47W	C7	2130
	Sept. 09	10	70	0.003	~0830	0828	21	07N 67W	M2	0856
	Sept. 12	13	>120	0.64	1145–1150	1131	42	17S 09W	M1	1154
	Sept. 16	**	**	**	0410–0430	0406	20	14N 07W	M6	0518
	Sept. 19	11	70	0.004	0810–0820	0806	20	14N 46W	M5	0850
	Oct. 09–Oct. 14	<30	70	0.002	2320–2345?	2319	24	01N 14W	C7	2350
	Oct. 16	07	>120	0.12	~0650	0640	48	N 95W	M2	0727
	Oct. 25	13	>120	0.065	~0955	0845	160	S 120W	C4	0826
	Oct. 29–Nov. 04	<12	70	0.0003	0150–0210	0128	29	25S 35E	M4	dg
	Nov. 08	23	>120	10	2255–2335	2242	46	10N 75W	M7	2306
	Nov. 24	06	>120	0.07	0500–0525	0455	7	22N 03W	X2	0530
	Nov. 24	16	>120	0.9	1455–1525	1451	22	22N 07W	X2	1530
	Nov. 25–Nov 30?	<18	>120	dg	0100–0135	0059	32	07N 50E	M8	0131
	Dec. 28	15	>120	0.007	~1205	...	...	N 150W	...	1206
2001	Jan. 05	19	70	0.007	~1650	...	...	N 120W	...	1706
	Jan. 10–Jan. 13	<21	60	0.0002	0045–0110	0023	40	13N 36E	C6	0054
	Jan. 20–Jan. 26	<29	>120	0.003	2115–2125	2106	14	07S 46E	M8	2154
	Jan. 28	17	>120	0.3	1540–1605	1540	20	04S 59W	M2	1554
	Feb. 11	03	70	0.003	0100–0110	0057	26	24N 57W	C7	0131
	Feb. 26	08	60	0.003	~0505	...	...	N 120W	...	0530
	March 10	08	60	0.0005	0400–0410*	0400	5	27N 42W	M7	0426
	March 25–March 29	<22	30	0.0002	1635–1700	1625	11	16N 23E	C9	1706
	March 29	12	>120	0.2	1000–1015	0957	18	16N 12W	X2	1026
	April 02	13	>120	0.02	1100–1105*	1058	38	16N 62W	X1	1126
	April 02	23	>120	4.3	2145–2215	2132	19	17N 78W	X20	2206
	April 09	16	>120	dg	1525–1545	1520	14	21S 04W	M8	1554
	April 10	07	>120	0.9	0510–0540	0506	20	23S 09W	X2	0530
	April 12	12	>120	0.3	1015–1045	0939	49	20S 42W	X2	1031
	April 15	14	>500	11	1345–1415	1319	31	20S 84W	X14	1406
	April 18	03	>500	2.7	0220–0240	0212	64	S 120W	C2	0230
	April 26–April 29	<22	30	0.001	1305–1310	1126	106	17N 23W	M8	1230
	May 07	13	70	0.1	~0855	...	...	N 140W	...	1006
	May 20	08	>120	0.06	0605–0615	0600	3	S 120W	M6	0626
	May 29–June 5	<24	50	B0.0002	2355–2415	...	...	S E95	...	~0000

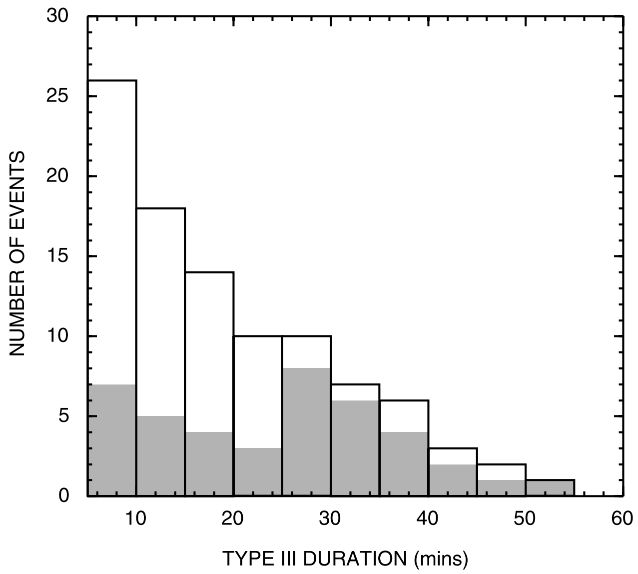


Figure 1. A histogram showing the durations of 14 MHz type III activity associated with SEP events. The shaded histogram is for those events in which protons were detected above ~120 MeV.

at 1 MHz. In all but two cases these events did not originate on the visible disk of the Sun and so the high frequency radio emissions were occulted. Figure 1 shows a histogram of the durations of the 14 MHz type III activity for the events where it was observed. The shaded histogram is the subset of events in which the SEP event extended above 120 MeV; these tend to be associated with longer duration emission. Some of the events in the 5–10 and 10–15 minute bins (9 and 5 events, respectively) are groups of normal type III bursts. The distribution is similar to that derived by *MacDowall et al.* [1987, Figure 3] for type III activity and SA events, although the durations they obtained were slightly longer because of using 1 MHz activity. Note that some of their longer duration "metric III only" events are likely to have been type III-*l*.

[21] Listings of ground-based radio burst observations and Hα flares, available from NOAA, were examined at the times of the radio emission seen at the upper frequencies (≳10 MHz) of the WAVES experiment. Radio events observed from the ground occurred in association with all the events of Table 1 except for 12 that occurred during ground-based observations but were determined to be from behind the Sun's limbs. (From the total list of 123 SEP events 43 were determined to be backside.) Most of the radio events included type II bursts and/or type IV bursts, as would be expected based upon previous studies. What was surprising was how different the reports were from the different observatories. They differed particularly in the duration of type II bursts, the presence of type III bursts concomitant with type II bursts, and whether the emission was type IV or a sequence of type IIIs. Of course the observing range is important as well as the frequency and temporal resolution of the observations. Nevertheless it is clear that the reports are subjective and that the emission types are not clearly distinguishable. Also, the bursts associated with proton increases are particularly complex. From a limited comparison of the Culgoora reports with those from other observatories it would appear that type III bursts are often not reported by other observers when they occur during type II–like activity.

[22] Flare associations were made primarily on the basis of the timing information; that the fast-drift radio bursts occurred during the Hα and soft X-ray emissions, that the flare events were generally of long duration and intense, and also that the Hα area was large. The tables list the coordinates of the Hα flares. The values prior to July 2000 are from the Solar Geophysical Data Part II group listings. The later values are from the NOAA internet site. Also listed are the start and rise times of the soft X-ray events; the rise time is the number of minutes between the start of the flare and the maximum intensity. The maximum soft X-ray intensities are also listed using the CMX system (see Table 1). All the frontside events and many of the backside events were associated with soft X-ray flares as recorded by the GOES satellites and listed on the NOAA Web site. For the backside events an estimate of the likely source region is given. This was determined by considering the Carrington longitudes of strong active regions that were previously sources of SEPs when on the visible disk. Note that the backside events deemed furthest from the limb were the ones with no X-ray events or high frequency radio emissions, suggesting that these are reasonable source longitudes.

[23] Compilations of CMEs as observed by the LASCO coronagraph on SOHO (PI R. A. Howard) were obtained from the LASCO internet site at (http://lasco-www.nrl.navy.mil/cmelist.html). These lists were assembled by O. C. St. Cyr, S. P. Plunkett and G. R. Lawrence. These researchers have provided the authors with assessments of which CMEs are likely to have been frontside based on SOHO EIT UV observations. Speed and angular size estimates of all CMEs have been made by S. Yashiro and G. Michalek and available

Notes to Table 1

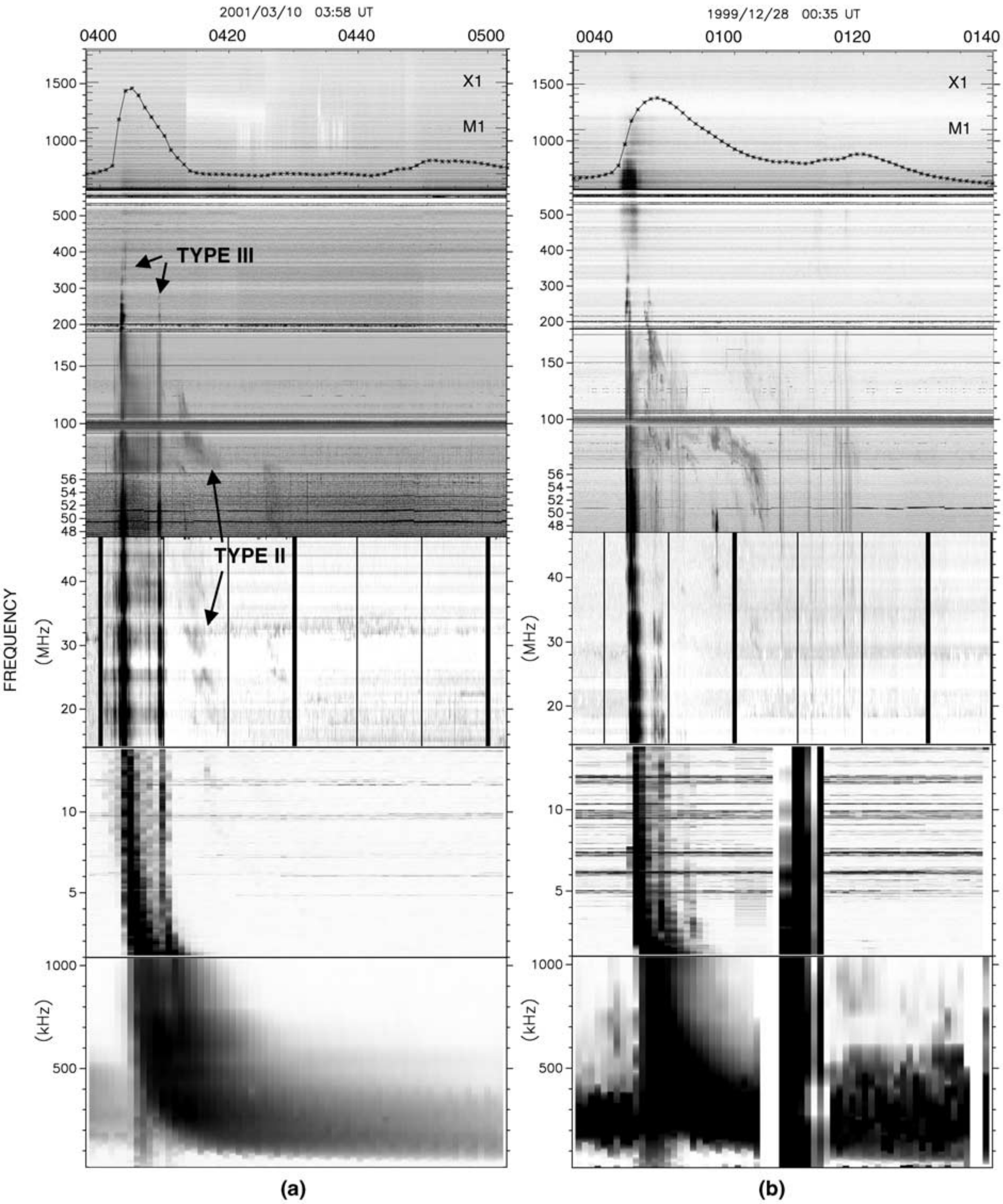
[a] Onset time of particle event. A range of days indicates that the event did not reach peak intensity at any energy within the first 12 hours of the solar event. Dates with ** in the Hours column indicate solar events which probably produced particle events but new injections were masked by particles from preceding events.

[b] Maximum energy to which protons detectable in the GSFC IMP 8 experiment. Events seen in neutron monitor data are given >500 MeV.

[c] Peak proton intensity within the first ~12 hours in the 24–29 MeV energy range in units particles/(cm^2-sec-ster-MeV). The notation dg means that there was a data gap in the IMP 8 data. Values preceded by a B indicate the background level above which the event did not rise within the first 12 hours after the solar event.

[d] Start and end times of type III burst (at 14 MHz) to nearest 5 minutes. Times followed by * indicate bursts that are likely to be normal type III bursts. The remainder are type III-*l*. A "?" after the times indicates that there is some uncertainty in determining which part of the observed emission is important. Single times preceded by a "~" are ones in which there is no emission at 14 MHz and the time is the start time at 1 MHz. In the two events with "???" in this column there was some weak radio emission at the time of ground-based activity but the situation was confused by the presence of many other radio bursts.

[e] The 1–8 Å soft X-ray peak intensity in terms of B, C, M, and X nomenclature, where these represent intensities of 10^{-7}, 10^{-6}, 10^{-5}, and 10^{-4} W m^{-2}, respectively. The notation "..." means that no event was observed.


2001/03/10 03:58 UT
0400
0420
0440
0500
1999/12/28 00:35 UT
0040
0100
0120
0140
X1
M1
TYPE III
TYPE II
FREQUENCY
(MHz)
(kHz)
(a)
(b)

from a NASA internet site (http://cdaw.gsfc.nasa.gov/) for the period until the end of June 2001. When it was operating, LASCO observed that a CME preceded every SEP event apart from two cases when there was sustained activity. In one case (September 23 1997) a clear CME was observed but had not been cataloged because it had occurred too close in time to preceding events. Most (85%) of the CMEs were large with angular extents >120°. Table 1 give the time that each CME was first observed in the C2 coronagraph, which occults below 2 solar radii. In all but two cases the CME was first observed after the start of the X-ray event, typically by about 20 to 40 minutes.

2.2. Fast-Drift Radio Bursts Associated With SEP Events

[24] In this section radio data in the complete frequency range from 1.8 GHz to 20 kHz are illustrated. Data from the WAVES experiment were obtained from the CDA Web. The WAVES experiment has three receivers: RAD2 covers the range 13.825 to 1.075 MHz, RAD1 covers 1040 to 20 kHz, and the "thermal noise" receiver (TNR) covers the range 245 to 4 kHz. Higher frequency data were obtained from the Culgoora radio observatory [*Prestage et al.*, 1994] and the Bruny Island Radio Spectrometer (BIRS) [*Erickson*, 1997]. The former has antennae operating in the frequency ranges 1800–570, 570–180, 180–57 and 57–18 MHz. Specific events may be viewed at the solar/(Culgoora)historical data section at http://www.ips.gov.au. BIRS operates in the frequency range 47 to 3 MHz and the data may be viewed at (http://fourier.phys.utas.edu.au/birs/). BIRS data in the range 47–14 MHz were first combined with the RAD2 and RAD1 data from WAVES. Note there is no gap in the frequency coverage between BIRS and WAVES. The BIRS and RAD2 data have been placed on the same intensity scale using the method discussed by *Dulk et al.* [2001]. Information required for calibration of the RAD1 data does not exist so the grey scale for these data has been arbitrarily adjusted to approximately match that of RAD2 near 1 MHz. Similarly, the Culgoora data are uncalibrated and the grey scales were adjusted to match BIRS.

[25] The BIRS and RAD2 frequency ranges overlap from 14 to 3 MHz. However, the BIRS data are subject to ionospheric absorption in this range so the RAD2 data are illustrated. Similarly, the BIRS and Culgoora frequency ranges overlap from 47 to 18 MHz, but in this range the effective sensitivity of BIRS is much higher than that of Culgoora, so the BIRS data are presented. Before November 15, 1997, BIRS data extended only to 37 MHz.

[26] Figures 2–5 illustrate the radio data for 8 particle events that get successively more energetic as determined by the peak intensity above 100 MeV, or above 20 MeV for the less intense events. The complete frequency coverage allows us to track back the origins of the fast-drift bursts seen below 14 MHz. Also illustrated are the GOES 1–8Å soft X-ray data. Each of the figures covers two events with 65 minute time spans; the start times of the period illustrated are indicated at the top. In our discussion of the figures we also summarize the relevant features as they were given by the Culgoora observers in the NOAA listings and mention some of the inconsistencies with the reports from other observers. This is done in order to emphasize the fact that it is impossible to properly describe these complex phenomena with a few numbers and letters; one must examine the dynamic spectra themselves to have a good appreciation of the true phenomena. At the small scale that we must use to portray these complete spectra some of the reported features are practically invisible. Interested readers must consult the dynamic spectra on the Web sites specified above in order to fully appreciate the complexities of the data. It will be seen that the reported type II bursts are often minor features in the dynamic spectra.

[27] Figure 2 shows that for the least intense particle events the fast-drift bursts in the WAVES data are the continuations of "normal" type III bursts seen in the ground-based data; they begin at about 500 MHz at the start of the flare. For the other events, examples of which are shown in subsequent figures, the radio activity is complex with vestiges of type II bursts being present in all but one event, but superimposed on these slow drift features are type III bursts that start at frequencies usually below 200 MHz and sometimes below 100 MHz late in the event. In some cases the activity is diffuse and better described as a continuum.

[28] Figure 2a shows X-ray and radio data for a small >20 MeV SEP event on March 10, 2001. This event was barely detectable above 60 MeV and lasted less than 2 days. The start of the interval illustrated is 0358 UT. Culgoora data extend from 1800-47 MHz with the GOES 1–8 Å soft X-ray profile superimposed on the 1800-570 MHz panel. BIRS data are plotted from 47 to 14 MHz and these data have 10 minute time lines with the hour and half hour lines being thicker. The first dark line is 0400 UT. WAVES data are plotted from 14 MHz to 20 kHz. In this event the WAVES emission is the low-frequency extension of two groups of type III bursts that both lasted about 3 minutes and started at 0402 and 0407 UT. The first group started at 700 MHz and the second at 300 MHz. The first group is

Figure 2. (opposite) Complete radio spectra combining Culgoora (1800 MHz to 47 MHz), BIRS (47 MHz to 14MHz), and WAVES (13.875 MHz to 20 kHz) data. The frequency scales are linear within the ranges 1800–570 MHz, 570–180 MHz, 180–57 MHz, 57–14 MHz, 13.875–1.075 MHz, and 1040–20 kHz and changes of scale occur at the boundaries of these ranges. A burst that drifts smoothly in frequency will exhibit a change of slope at these boundaries. The BIRS data contain heavy vertical time marks at 00^m and 30^m of each hour and thin marks each 10 minutes. A profile of the GOES soft X-ray data is superimposed upon the 1800–570 MHz radio data. On Figure 2a, which shows radio data for a small particle event on March 10, 2001, we have indicated the type III and type II activity. More details are given in the text. Figure 2b shows data for another relatively small particle event on December 28, 1999. Note that in both events of Figure 2 the fast-drift bursts seen at the lowest frequencies are continuations of the groups of type III bursts seen at frequencies up to more than 200 MHz which started close to the start of the soft X-ray increases. The soft X-ray events reached maximum intensity within 10 minutes. These are "normal" type III bursts associated with impulsive flares. In both events the type III bursts are followed by weak type II bursts. The dark band across the lower part of Figure 2b, in the frequency range 400–100 kHz, is radio emission from the Earth's magnetosphere.

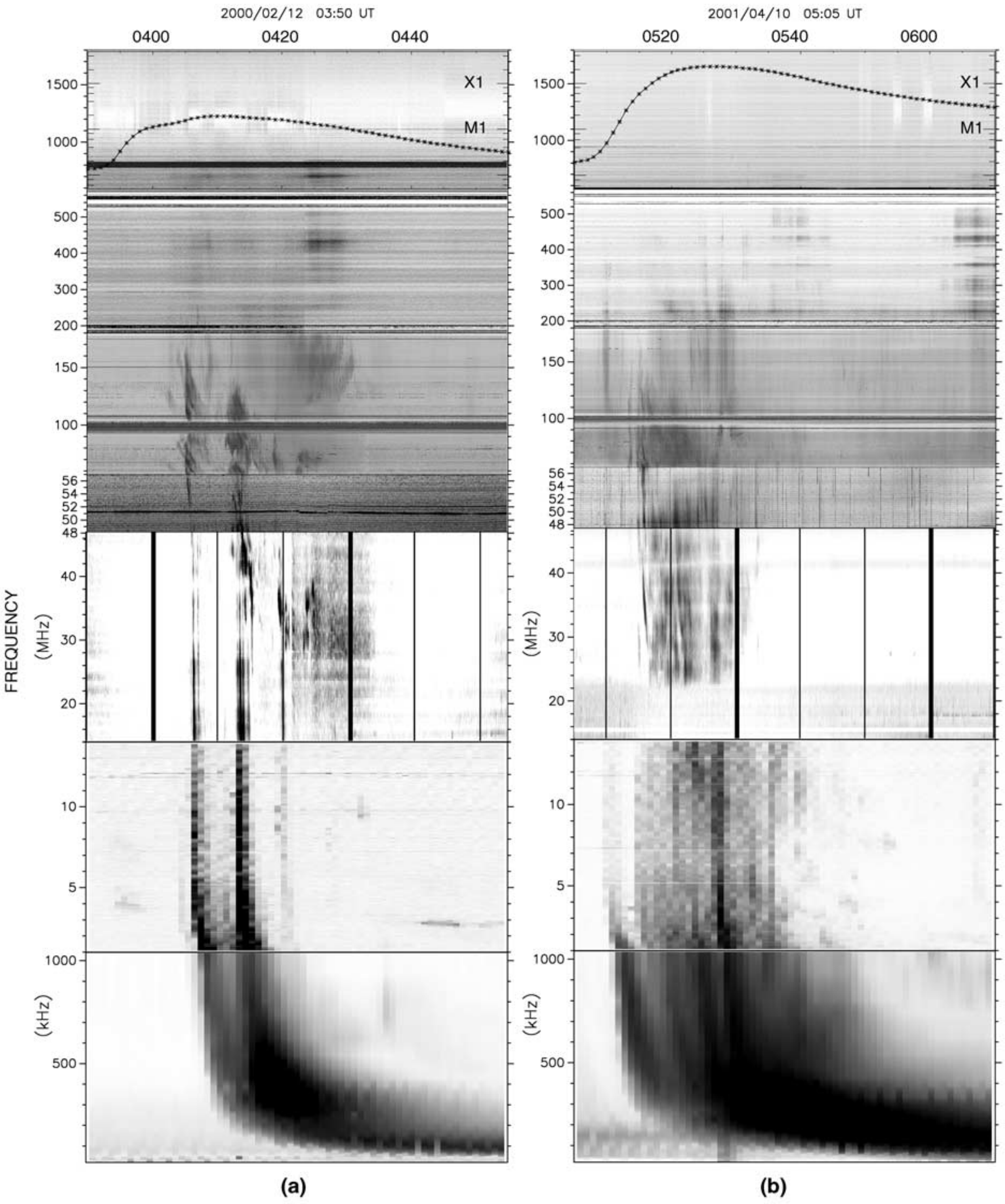


Figure 3. This figure shows data in the same format as Figure 2. Neither of these events include a significant contribution from impulsive phase "normal" type III bursts. Note the less abrupt rise of the X-ray intensity compared with the events of Figure 2. In Figure 3a there are three groups of type III bursts which are superimposed on slow drift features. On a larger scale there are many short duration slow-drift and fast-drift features. Figure 3b shows an extended period of type III activity. Only during a brief, four minute, period (0513–0517 UT) is there type II-like emission. Most of the activity was reported as type IV emission. The lack of signal between 24 and 14 MHz is caused by ionospheric absorption.

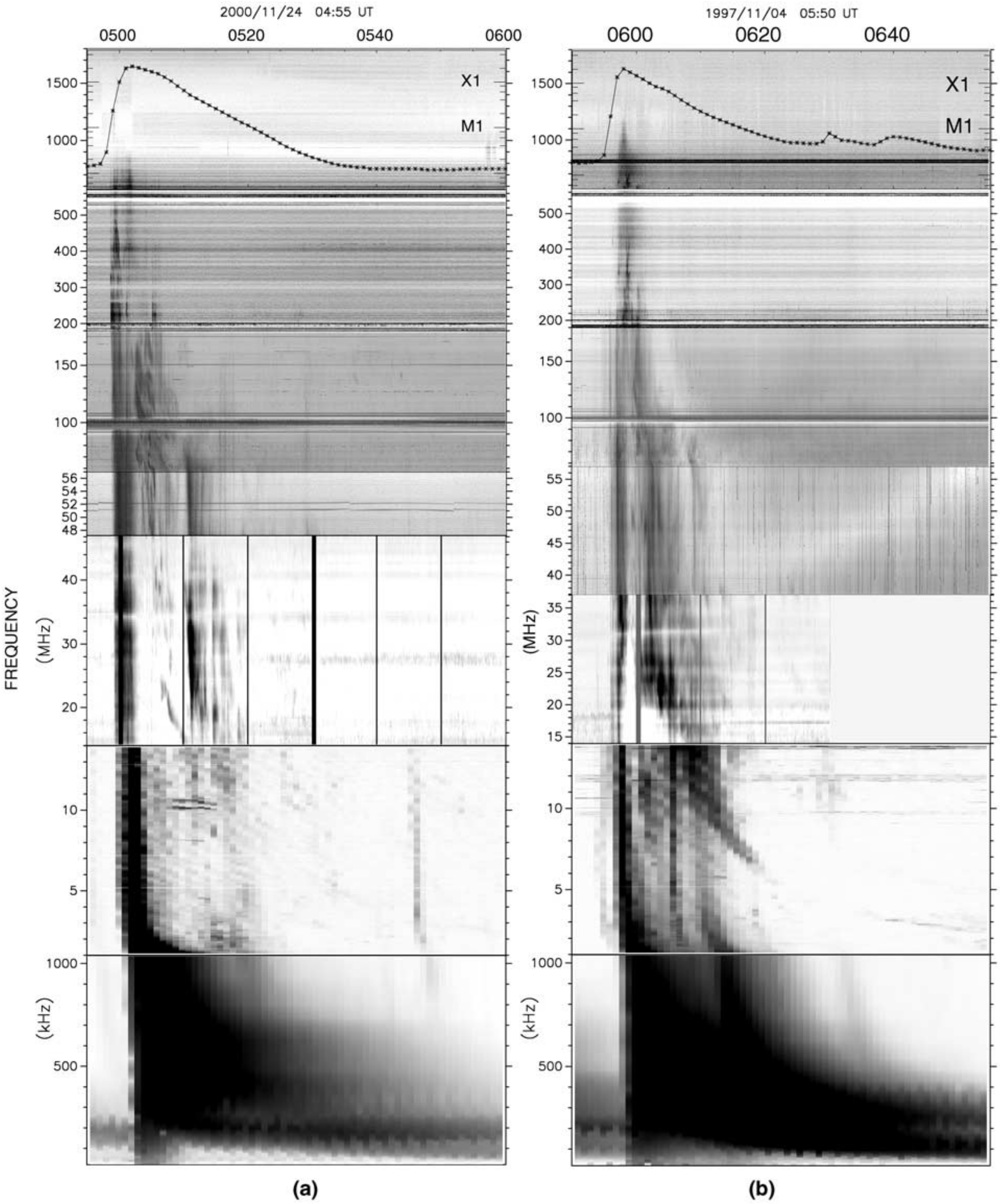


Figure 4. This figure shows radio data in the same format as Figure 2 for two SEP events that were observed above 120 MeV. In these events the type III emission lasts from the beginning of the flare X-ray emission and beyond maximum intensity starting at successively lower frequencies. The soft X-ray events are more impulsive than those of Figure 3. In both events the type II emission was reported to occur in two periods with different drift rates. In Figure 4a type II emission is clearly seen in the 25–14 MHz range. In Figure 4b a type II burst is clearly seen below 10 MHz. The very faint feature near the right hand edge of Figure 4b just above 1 MHz is likely emission generated in front of the CME.

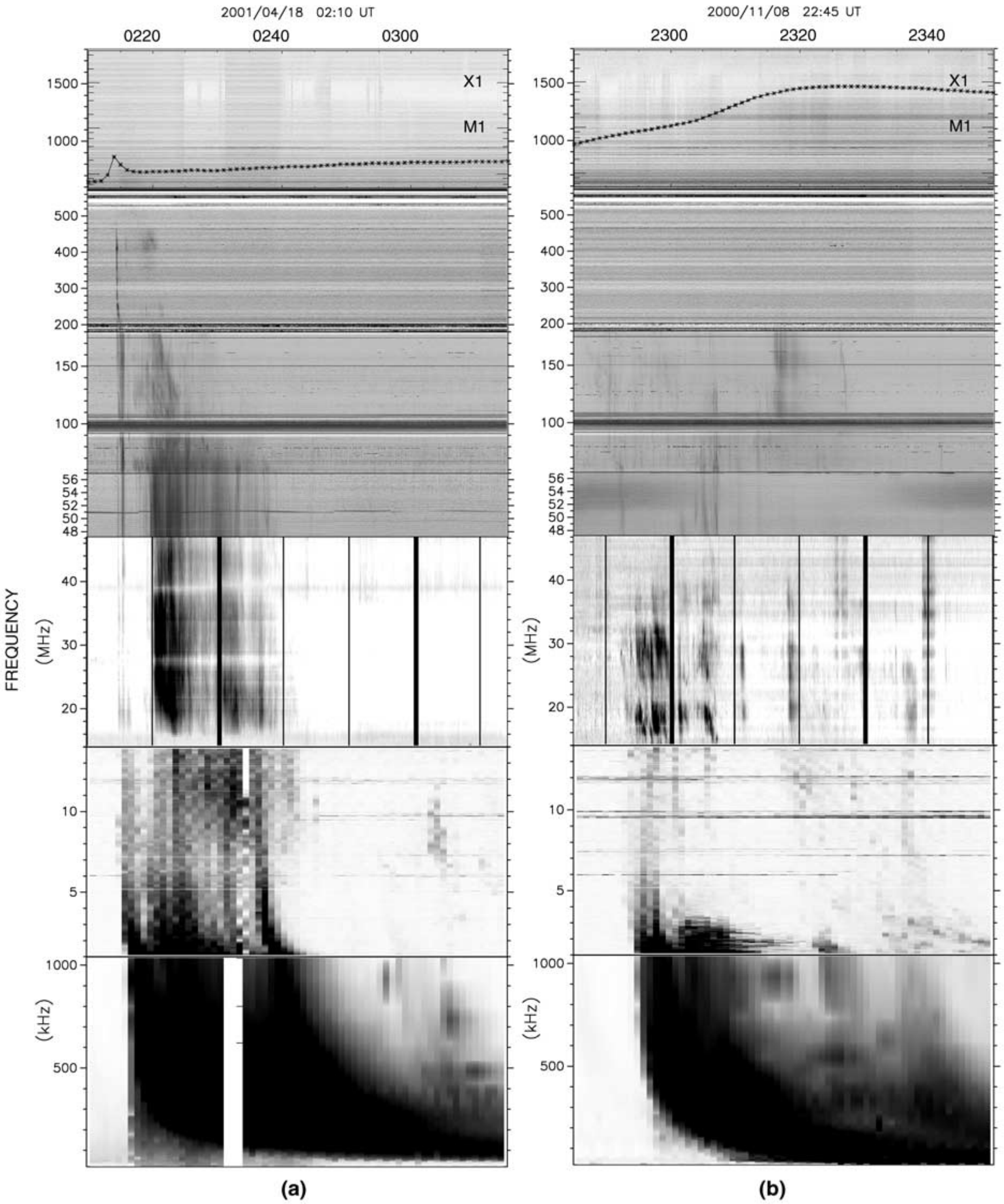


Figure 5. This figure shows data in the same format as Figure 2. The associated SEP events were very energetic. The November 8, 2000 event was one of only two in the study period that saturated the IMP 8 instrument above 24 MeV and the April 18, 2001 event was detected by neutron monitors and thus extended above 500 MeV. Note the long duration of the radio emission below 1 MHz. The April 2001 event occurred well behind the west limb of the Sun, thus accounting for the weak soft X-ray intensity. In neither event is there any emission above 5 MHz that looks like a clear type II burst. In Figure 5b the faint feature near the right hand edge of the figure just above 1 MHz is likely emission generated in front of the CME.

more intense and is followed by type V continuum in the frequency range 160 to 40 MHz between 0404 and 0408 UT. The two type III groups occurred during a short duration M7 soft X-ray flare at 27°N 42°W that started at 0400 UT, reached maximum intensity at 0405 UT and ended at ∼0415 UT. The radio data also show a faint type II burst between 0411 and 0419 UT starting at 70 MHz and ending at about 20 MHz. Here, and in describing other type II events, the times and frequencies are for the fundamental (i.e. lower frequency) band. There are no type III bursts at the time of the type II burst.

[29] Only the first type III group in Figure 2a was reported by the HiRaS observers in Japan. The HiRaS instrument covers the frequency range 2500–25 MHz. It is more sensitive above 500 MHz than the Culgoora instrument but less sensitive below 50 MHz. (The reader is encouraged to look at that data at (http://sunbase.crl.go.jp/solar/denpa/hiras/).

[30] Figure 2b shows data for another relatively short duration (<2 days) particle event on December 28, 1999. At 0043 UT there was a strong type III group that started at 400 MHz and lasted for about 3 minutes. The extension of this type III group is responsible for most of the emission seen in the WAVES data. However there is a contribution from a second, weaker type III group that started at 0046 UT and 170 MHz and lasted 7 minutes. In addition to the type III groups there were also two type II bursts reported during the intervals 0046–0055 UT and 0057–0105 UT. The first one was in the frequency range 150–30 MHz and the second in the 50–25 MHz range. Some continuum emission between 0059 and 0111 UT in the frequency range 170–90 MHz was also reported. The flare was located at 20°N 56°W. For this event also the HiRaS observers did not report the second group of type III bursts. The Learmonth observers reported type III activity during the whole period 0043–0120 UT. Note how in this event, and in the preceding one, the initial strong type III groups start close to the start of the soft X-ray increases and that the X-ray events reached maximum intensity within 10 minutes. These are ‘‘normal’’ type III bursts associated with impulsive flares.

[31] The event of Figure 3a occurred February 12, 2000 and was associated with an M1 flare at 26°N 24°W. The soft X-ray flare increased more gradually than in the previous events (the rise time was 19 minutes) and in this event there were no initial type III bursts starting above 300 MHz. Instead there were three type III burst groups (0406–0410 UT, 0413–0415 UT and 0419–0421 UT) all of which occurred during type II activity and well after the start of the flare event. The starting frequencies of the type III groups were reported to be 250, 180 and 110 MHz and all extended to below 1 MHz. The middle one was the strongest at low frequencies. Type II bursts are very hard to see in this representation but two were reported; from 0403 to 0411 UT (90–35 MHz) and from 0412 to 0419 UT (70–30 MHz). The smooth emission above 50MHz between 0403 and 0435UT is type IV. For this period HiRaS observers did not report any type III emission. Learmonth only reported the first type III group along with one type II burst. The SEP event associated with this complex radio activity had an intensity in the 24–29 MeV range more than an order of magnitude greater than the March 10 2001 event of Figure 2a.

[32] The radio signatures associated with the SEP event of April 10, 2001 are shown in Figure 3b. A careful examination of the record shows many type III emissions that extend to very low frequencies, as may be seen in the figure. Much of the activity was reported as type IV and ‘‘continuum’’ based on its broad bandwidth. A small moderate intensity type III burst in the 70–420 MHz range at the onset of the flare was reported; it lasted only a minute at 0510 UT. Another group of type III bursts occurred in the interval 0525–0530 UT starting at 500 MHz and continuing down into the kHz range. This group was not reported by the HiRaS observers although it became the most intense feature in the 14–2 MHz range. Barely visible was a very fast drifting type II burst (from 70–∼23 MHz) that was reported during the short time interval 0513–0517 UT. (HiRaS reported type II emission but for a more restricted time and frequency interval.) Note the gap in the data between 14 and 24 MHz. This is ‘‘short wave fadeout’’ caused by the high intensities of X rays impinging on the ionosphere and resulting in increased ionospheric absorption. The April 10, 2001 SEP event was a major one with protons being detectable above 120 MeV. Nevertheless the type II activity is an insignificant feature in comparison with the type III bursts.

[33] Figure 4a shows data for the X2 flare at 22°N 03°W that occurred on November 24, 2000 at 0457 UT. The Hα flare lasted only 38 minutes and the soft X-ray event was more ‘‘impulsive’’ than the previous two events; the rise time was only 7 minutes. There was an intense type III group during the initial phase of the flare extending from 900 MHz down into the kHz range. Two other type III groups were reported at 0505–0507 UT and 0510–0516 UT with starting frequencies of 750 and 80 MHz. Both are visible below 10 MHz but do not appear to add significantly to the lowest frequency emission. Two type II bursts in the time intervals 0502–0510 UT (90–18 MHz) and 0519–0528 UT (25–20 MHz) were reported. For this event the HiRaS observers reported similar burst types and durations. There is no inconsistency in the reporting of the late type III bursts; both HiRaS and Culgoora observatories reported type III emission during type II emission and also when no type II–like emission appeared. Nevertheless in this event the dominant contribution to the low-frequency emission is the intense ‘‘normal’’ type III burst at the start of the flare.

[34] Figure 4b shows radio and X-ray characteristics very similar to those of the event of Figure 4a. Again the WAVES event is primarily the low-frequency extension of a strong group of type III bursts occurring at the start of the flare at 0552 UT on November 4, 1997. The Culgoora observer reported that the burst started at 240 MHz but HiRaS give a starting frequency of 410 MHz. The apparent activity above 570 MHz near 0600 UT in Figure 4b is caused by a receiver problem and is largely spurious. Two type II bursts were reported by both Culgoora and HiRaS observers. The first one was reported in the frequency range 230–30 MHz between 0558 and 0607 UT and the second one starting at 60 MHz at 0600 UT. Only the second one, continuing into the WAVES data to end at about 6 MHz at 0620 UT, is clear in Figure 4b. The event was complex and included type IV emission starting at 0606 UT at about 200 MHz and extending beyond the period illustrated. The data from 20

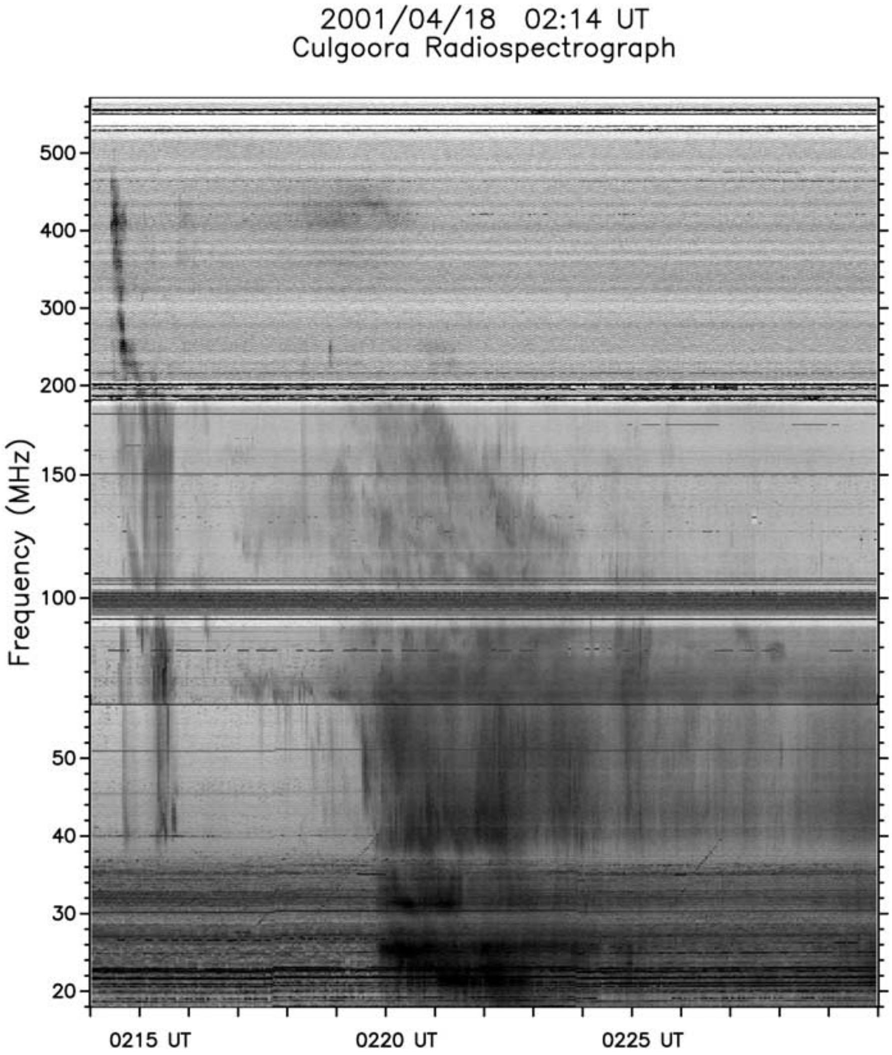


Figure 6. This figure shows some of the Culgoora data of Figure 5a using magnified time and frequency scales in order to show the details of the emission in the 570–18 MHz range. Notice that the only slow drift features, between 200 and 100 MHz, are not harmonically related. Part of the initial type III group does show fundamental and harmonic emission.

to 14 MHz appear to be affected by ionospheric absorption between 0558 and 0607 UT.

[35] Figures 5a and 5b illustrate the radio events associated with two of the most energetic proton events in the study period. The event of April 18, 2001, of Figure 5a, was seen in neutron monitor data. The November 8, 2000 event of Figure 5b did not extend above 500 MeV but was more intense below 120 MeV and saturated the IMP 8 MED telescope. In both cases the type III emission lasts longer than 20 minutes in the WAVES data. The April 18, 2001 event originated beyond the west limb of the Sun, probably at about W120°. Four large SEP events from the same active region occurred in the period April 9–15 including the one associated with the radio event in Figure 3b. The soft X-ray event reached only the C1 level, presumably because it was occulted, but lasted for more than 4 hours. There was a small impulsive component to the soft X-ray event and a short duration type III group starting at 480 MHz at this time (0214 UT). For this event BIRS recorded only fast-drift bursts that extended into the WAVES frequency range to become a large outburst. At higher frequencies Culgoora and HiRaS report type II emission from 0217–0233 UT (130–18 MHz) and 0217–0246 UT (500–23 MHz) respectively. However, a close examination of the data only shows drifting bands between 0220 and 0225 UT above 100 MHz and there are no fundamental/harmonic pairs of bands. Rather than type II, the event looks like an extended group of type III bursts with starting frequencies drifting downward in a way similar to the events in Figure 4. To illustrate that there is no clear type II burst, Figure 6 shows a subset of the data with a magnified scale.

[36] Figure 5b illustrates the event of November 8, 2000. The flare event associated with this SEP increase was rather unusual. As may be seen the X-ray emission was very gradual and long lasting. This was one of the few SEP events with no type II burst reported by ground–based

observers although in the BIRS data between ∼2258 and 2306 UT in the frequency range 39 to14 MHz there are brightenings in the type III bursts that drift downward in frequency at a rate characteristic of a type II burst. The ground–based data reveal only a series of relatively weak type III bursts while the event seen in the WAVES data was very intense and long lasting. Two active regions were flaring at the time of the radio bursts but the timing suggests an association with the 20°N 66°W 1F flare that started at 2240 UT, reached maximum at 2323 UT and ended at 0030 UT the next day. (Note that most SEP events are associated with bright flares so the "F" category is also unusual.)

[37] The slow drift feature between 2333 and 2350 UT and 4 and 1 MHz in Figure 5b is likely to be emission from the CME-driven shock i.e. an IP type II event. Only the data in Figure 4b show a similar feature; the weak emission between 3 and 2 MHz from 0635 to 0700 UT. However many of the other WAVES radio events not illustrated have IP type II emissions. This is consistent with the ISEE-3 results wherein those interplanetary shocks that produce radio emission are preceded by SEP events [*Cane and Stone*, 1984]. Many of the SEP events are also associated with type II bursts that extend from the ground-based frequencies down to frequencies below 14 MHz. These events are illustrated on the WAVES internet site. The emissions are often rather weak and consisting of just some intermittent brightenings. In almost all cases the dominant feature on the plot is the preceding intense type III emission.

[38] It is clear that the fast-drift bursts seen in the WAVES data are the continuations of type III or type III–like radio bursts seen in the ground-based data and do *not* originate in clearly distinguishable type II bursts. Type II bursts are usually present (often multiple ones), but with the type III emission superimposed. The type III bursts have starting frequencies that often progress to lower frequencies as a function of time. In order that these features may be made more apparent a special section on the Culgoora Web site displays all the radio events in the eastern Australian time frame associated with the SEP events listed in Table 1. The downward drift of the starting frequencies is a feature that is only readily apparent in the data from the Culgoora and HiRaS observatories (the highest frequency characteristics are more clearly defined in the data from HiRaS than from Culgoora because it is more sensitive above 500 MHz) because these produce the only data that extend over a sufficiently broad frequency range. It can be seen that after the initial strong type III component at the start of the flare (which is often absent) the emission is intermittent and diffuse. This is far more apparent on the colored images available on the Culgoora Web site than in our representations. Often the emission is more or less a continuum. It is important to note that the radio spectra associated with SEP events are complex and that clear type II bursts are absent. Simple type II bursts, i.e. ones without overlying type III activity, do not appear to be associated with the solar events that produce long lasting SEP events.

[39] The long lasting radio events seen at frequencies below about 60 MHz in Figures 3–5 would previously have been called SA events. Since a direct connection with type II emission appears to be weak, at best, we propose to rename this type of event type III-*l*; the emission lasts for a long time, extends to low-frequencies and includes components late relative to the start of the flare. In most cases type III-*l* bursts are obvious in the WAVES daily plots by being of long duration and very intense, particularly in the Thermal Noise Receiver. Type III- *l* bursts are also likely to be identifiable in the ∼50–1 MHz range based on the intensity-time profiles because they are composed of a number of individual burst components, but this aspect was not examined in this study. *Cane et al.* [1981] found this to be a distinguishing characteristic of SA events [see also *MacDowall et al.*, 1987]. *Kahler et al.* [1986a] and *Reiner et al.* [2000] illustrated that the intensity-time profiles of "normal" type III bursts have a rapid rise to maximum intensity followed by a slower exponential-like decay whereas the "SA events" above ∼1 MHz are more complex.

[40] To determine if a radio event is type III-*l* it is desirable to have complete frequency coverage. However this is only possible for about 8 hours per day when BIRS is able to observe the Sun. Using the Culgoora data (and so having a gap between ∼18 MHz and 14 MHz) extends the interval to about 10 hours. The frequency coverage is particularly poor between about 1500 and 2000 UT which is the time frame of observatories in the USA. A careful examination of the NOAA listings of radio bursts can often be used to determine if a low-frequency event is type III-*l* by looking at the timing of bursts and their frequency extent. Type III bursts at the beginning of the flare event start at several hundred MHz and typically last 5–10 minutes. If the $\gtrsim$1 MHz emission lasts longer than this emission then it is type III-*l*. Also if only type II or type IV emission is reported and there is a fast-drift burst seen by WAVES then it is type III-*l*. It is usually possible to determine if type III emission is a type III-*l* burst using just the WAVES dynamic spectra and flare data and by noting that the type III emission occurs more than 10 minutes after the start of the flare. The distinguishing characteristic of type III emission associated with long lasting, high energy SEP events is that it occurs after the flare impulsive phase.

2.3. Relationship Between CMES, Type III Bursts, and Proton Events

[41] To further investigate the relationship between type III bursts, SEP events and CMEs, the WAVES data were examined at the times of a large sample of front-side, large CMEs that occurred in the years 1997 through 2000. The list comprised 169 events and was as complete as possible for events with angular extents >140° but, undoubtedly, some events are missing. Only the large CMEs were considered because it is such CMEs that are predominantly associated with >20 MeV SEP events. Type III bursts (that were determined to be type III-*l* by comparing the WAVES 14 MHz duration with flare observations and the activity reported by the ground-based observers) were seen for many of the large CMEs but in quite a few cases (66) there were no fast-drift bursts at all. Thus a large CME is not a sufficient condition for the occurrence of a type III-*l* burst. The large CMEs without any associated type III or type III-*l* bursts were nearly all slow; 85% (56/66) of the events had sky-plane speeds of <600 km/sec. *None* had associated >20 MeV proton increases. This suggests that type III-*l* bursts result from the departure of large, fast CMEs. Note that there were some large CMEs with associated type III-*l* bursts that are not in Table 1 because it is not possible to

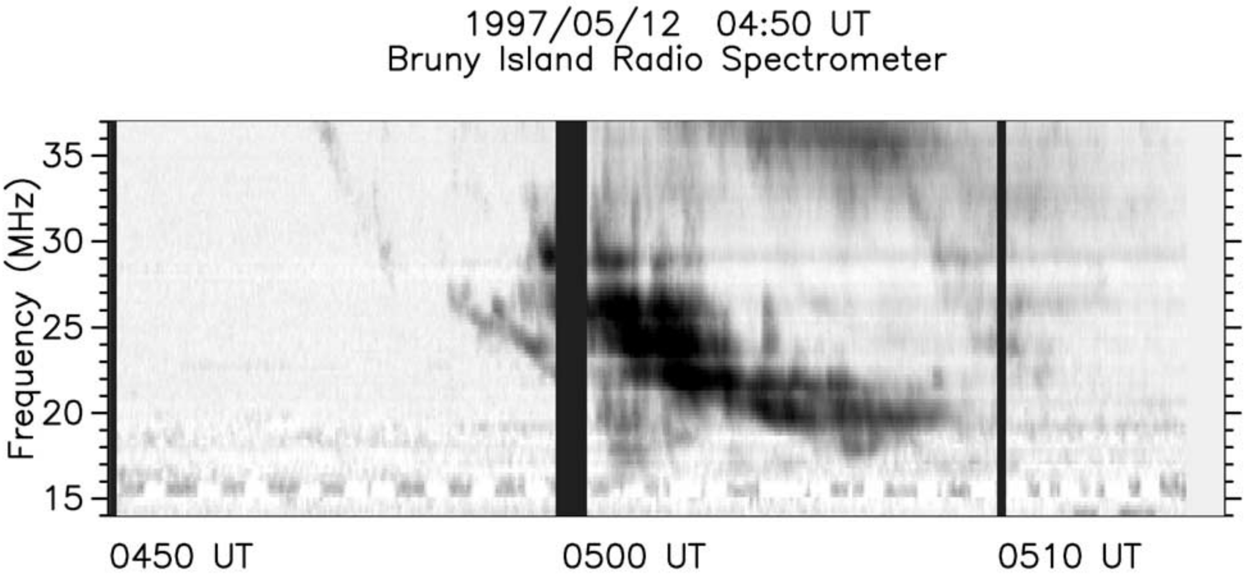


Figure 7. The BIRS data for the May 12, 1997 event are displayed in order to show that there is fast drift emission starting above 30 MHz just after 0500 UT (the thick vertical line). The representation of these same data by *Dulk et al.* [2000] did not show any emission at frequencies above the type II backbone at 30 MHz. Note that the type II burst looks like a sequence of narrow-band type III bursts.

determine whether there was an SEP event or not because of a high background caused by previous events.

[42] Finally it was investigated whether type III-*l* bursts occur without associated proton events. A random sample of 89 24-hour intervals that occurred on the 10th, 20th and 30th of each month (and March 1) for a period of 2.5 years was considered. The durations and times of all the fast-drift bursts clearly visible and lasting five minutes or longer at 14 MHz were recorded using the daily spectra available on the WAVES internet site. Next the 14 MHz activity was compared with soft X-ray reports and also with the activity reported by ground-based observers. There were ~110 type III burst groups in the >2000 hour study period. Only six events were found that satisfied the type III-*l* criteria; five were associated with SEP events. The sixth event was associated with an eastern hemisphere flare and the radio burst did not extend to low frequencies, indicating that the Earth was not magnetically connected to the flare region. This part of the study suggests that type III-*l* bursts only occur in association with proton acceleration at the Sun.

3. Discussion

[43] This study finds, as has been previously established, that SEP events are well associated with flares. In general those events with high intensities early in the event were associated with large, bright Hα flares and intense, long duration soft X-ray events. For example, all the >500 MeV events in the study period that originated on the disk were preceded by soft X-ray flares of at least X1 peak intensity. All the SEP events were associated with CMEs. The new result is the finding that essentially all SEP events are preceded by type III bursts that extend to frequencies generated in the interplanetary medium. For the majority of the particle events, in particular those that lasted longer than 36 hours, the type III activity is not just an extension of "normal" type III bursts that occur in the initial, impulsive, phase of flare events but, rather it continues or starts some 5–10 minutes later. The type III emission lasts on average about 20 minutes at 14 MHz as compared with "normal" type III groups at flare onset that last about 5 minutes.

[44] It is important to address the question of whether the electrons responsible for these bursts, named type III-*l*, are shock-accelerated as might be implied if they originate at type II bursts as originally proposed by *Cane et al.* [1981] and recently suggested by *Dulk et al.* [2000]. One good argument against the proposal is the existence of those events in which a type II burst is not present. This could not be established by *Cane et al.* [1981] because of the gap in frequency coverage that existed at that time between ground-based and space-based observations. *Dulk et al.* [2000] do not consider or mention events that have no type II emission. Another argument is that the type III-*l* emission often occurs after, or continues beyond, the end of the type II bursts. Figures 2–5 provide evidence that many type III-*l* bursts actually start at frequencies above type II bursts and thus the critical question is why *Cane et al.* [1981] and *Dulk et al.* [2000] concluded differently. From the present study it is apparent that the observed features depend greatly on the instrumentation and the presentation of the data. The old, pre-1990's records were photographic rather than digital and they were displayed in a very compressed format. This may account for the different conclusion reached by *Cane et al.* [1981]. Note that *Kundu and Stone* [1984], *Klein and Trottet* [1994], and *Reiner et al.* [2000] have challenged the shock acceleration hypothesis on the basis of simultaneous

activity at higher frequencies. The fast-drift bursts from which the WAVES events originate only drift to lower frequencies and so cannot originate at "herringbone structure" as originally suggested. *Dulk et al.* [2000] specifically state that the type III-like bursts associated with type II bursts are "distinct from herringbones".

[45] In addition to large format digital displays the dynamic range and the contrast that are used in the presentation are also important. This is probably the reason for the different conclusions derived from spectra recorded on film, as cautioned by *Klein and Trottet* [1994]. Limited dynamic range is likely to be part of the reason why *Dulk et al.* [2000] concluded that the fast-drift bursts start at the type II bursts. This is illustrated in Figure 7 that shows the BIRS data for one of the events illustrated by *Dulk et al.* [2000]. The thick vertical band on the plot is the time mark for 0500 UT on May 12, 1997. Immediately after this band (that is actually a small data gap while the system carries out interference reduction procedures) there is a group of fast drift bursts that extend from the top of the range at 37 MHz down to about 17 MHz. This group is seen to extend into the kHz range on the WAVES data. In the *Dulk et al.* [2000] Figure 2b there is no visible emission at frequencies higher than 30 MHz, which is the upper edge of the type II burst that is also evident in the figure. This missing emission above 30 MHz appears to be caused by the high contrast employed by *Dulk et al.* [2000] that greatly reduces the visibility of weaker features.

[46] Another problem is the limited frequency range that *Dulk et al.* [2000] employed. Four of their 8 events were only displayed at frequencies below 70 MHz. Dynamic spectra extending to 800 MHz for these 4 events have been published in a catalog from the Potsdam group [*Klassen et al.*, 2000]. From these data it can be seen that there are fast-drift emissions starting above 70 MHz. In the four events for which *Dulk et al.* [2000] do show higher frequency data, the present authors think that the fast-drift bursts clearly start at frequencies higher than the type II burst in May 3, 1999 and June 4, 1999. In the November 3, 1999 case, that is the weakest event illustrated and not on the present list because it was not associated with a >20 MeV SEP event, it does seem that the fast-drift elements might start at the type II. The final event was that of November 4, 1997 which was also shown in our Figure 4b. (Note that we use lower resolution WAVES data, available from the CDA Web site, than did *Dulk et al.* [2000].) In this event most of the WAVES emission is a continuation of the strong type III burst at the start of the flare. A careful examination of the dynamic spectrum suggests that the later components start at frequencies higher than the type II–like activity. The unambiguous cases of type III-*l* activity that we illustrated, such as November 8, 2000 when no type II burst was observed, occurred after the time period analyzed by *Dulk et al.* [2000].

[47] If the fast-drift bursts that precede SEP events are not shock accelerated, then they are basically the same as other type III bursts. Whether they are shock accelerated or not, the presence of type III bursts in association with SEP events proves the existence of open field lines from regions low in the corona ($\lesssim$0.5 solar radii above the solar surface) into the interplanetary medium and means that it is possible that some ions in all SEP events could have their origins in such low-lying regions. The direct association with fast, large CMEs, and the indirect association by virtue of flare phenomena well associated with CMEs (e.g. long duration soft X-ray flares), suggests that type III- *l* bursts result from reconnection following CMEs.

[48] It is of interest to review the reasons that have been proposed to reject a role for particles from flares or from post-CME reconnection in long duration SEP events. That flares do accelerate energetic particles is not under debate but in the current paradigm the interplanetary intensities of flare-produced particles are believed to be low and the particle events, which are of short duration, are considered to constitute a separate class. Nevertheless several of such events were sufficiently energetic that they were detectable above 20 Mev and are in our event list, but the topic of classes of particle events is beyond the scope of the present paper. *Kahler*, in his 1992 review article on CMEs and flares, states the following: "More convincing evidence that the sources of SEPs lie outside flare regions would be SEP events associated either with flares lacking an impulsive phase or with a nonflare source". He gives as examples of these two situations the SEP events of August 21, 1979 and December 5, 1981. However both these events had associated low-frequency type III bursts seen by the ISEE-3 experiment. In the first event *Cliver et al.* [1983] used this type III emission (called an SA event in that paper) to tie the >500 MeV proton event to a C7 flare with a "weak impulsive phase". At that time it was thought that the particles were accelerated at the type II shock and that this shock had to be preceded by strong "normal" type III bursts and a hard X-ray event at flare onset. The idea was that the "impulsive phase" explosion created the type II shock or even provided a seed population for shock acceleration. Thus it was common practice at that time to use characteristics of the impulsive phase microwave bursts to predict proton events. *Cliver et al.* [1983] used the August 21 1979 event to point out that a strong impulsive phase was not a requisite for a major SEP event. We have shown other events with "weak impulsive phases." In fact in many of the largest events the impulsive phase type III emission is missing. This is a property of the more gradual flares, as can be seen particularly well in Figures 3a, 3b, and 5b and was found in a statistical study of type III bursts and soft X-ray time scales by *Cane and Reames* [1988].

[49] The December 5, 1981 SEP event is frequently quoted as a "pure" event in which there was "no accompanying flare" [*Reames*, 1999]. The departure of the associated CME was signaled by a disappearing filament away from an active region *but also* by a weak ($\sim$C4) soft X-ray flare and parallel ribbons seen in Hα. This SEP event was the most energetic of six such "disappearing filament" events discussed by *Cane et al.* [1986]. It was the only one with a clear "SA event" (i.e. type III- *l* burst) and it was this low-frequency radio emission that enabled *Kahler et al.* [1986b] to link the SEPs to the solar event. (A similar event occurred on December 6, 1997 and is listed in Table 1.) Thus neither of the *Kahler* [1992] statements quoted above provide good arguments against a non-shock source of energetic particles.

[50] The results of the study by *Kahler et al.* [2000] are also of interest. In that paper a search was made for SEP events associated with large, bright soft X-ray arcades

associated with noise storms. Such arcades are indicative of the occurrence of a CME and were used as a CME proxy for a period with no coronagraph observations. The distinguishing characteristic between SEP and non-SEP arcades was found to be the presence of a type II burst. Only one non-SEP event had a reported type II burst. An examination of the Culgoora dynamic spectrum for this event reveals a type II burst with no overlying type III activity, i.e. there was no type III-*l*. In contrast the Culgoora spectrum for the >500 MeV SEP event of February 20, 1994 (which was an SEP event added to the *Kahler et al.* [2000] study "for comparison") reveals type III activity for more than 30 minutes (see the Culgoora Web site), i.e. this event was type III-*l*.

4. Conclusions

[51] The results of this study have been obtained by an extensive analysis of several data sets. The radio data have been collected by three different observatories and, for each single event, involve large amounts of data. The figures in this paper do not do justice to the complicated phenomena that are under study. Neither do conventional written reports. The readers are *urged to look at the larger format displays* available on the internet and particularly those that we have made available the solar/(Culgoora)historical data/SEP related events section http://www.ips.gov.au. Using all of these available data we have concluded that:

1. Proton events detected above ~20 MeV are always accompanied by type III bursts, by CMEs and, for events originating on the disk or not too far behind the limb, by flare signatures in Hα and soft X-rays. For the majority of these $\gtrsim$20 MeV events the type III bursts either commence or extend beyond 5–10 minutes after the start of the associated flares. These bursts are called type III- *l*. They often have progressively lower starting frequencies as a function of time. SEP events become more intense as the type III activity becomes longer lasting.

2. Although type III-*l* bursts usually occur at the same time as reported type II bursts they usually commence at frequencies above the type II bursts. Thus the causative electrons are likely to be accelerated in the same manner as for normal type III bursts in the, as yet not fully understood, "flare process".

3. The dynamic spectra of events associated with interplanetary solar energetic particles are very complex and rarely show well defined type II bursts i.e. slowly-drifting, harmonically-related pairs of narrow bands. The type II features that are observed appear to be composed of limited frequency type III bursts. The dominant feature is overlying wideband type III emission, i.e. type III-*l*.

4. The association of type III-*l* bursts with CMEs suggests that the acceleration of the causative electron beams occurs in reconnection regions in the aftermath of CMEs.

5. These results suggest the possibility that flare particles could be present in all SEP events, i.e. the existence of energetic particles in addition to those generated by any CME-driven shock. Most importantly, the presence of type III bursts proves the existence of open field lines along which flare electrons, at least, escape to the interplanetary medium.

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