Type III-L Solar Radio Bursts and Solar Energetic Particle Events

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Abstract.
A radio–selected sample of fast drift radio bursts with complex structure occurring after the impulsive phase of the associated flare (“Type III-L bursts”) is identified by inspection of radio dynamic spectra from 1 to 180 MHz for over 300 large flares in 2001. An operational definition that takes into account previous work on these radio bursts starting from samples of solar energetic particle (SEP) events is applied to the data, and 66 Type III-L bursts are found in the sample. In order to determine whether the presence of these radio bursts can be used to predict the occurrence of SEP events, we also develop a catalog of all SEP proton events in 2001 using data from the ERNE detector on the SOHO satellite. 68 SEP events are found, for 48 of which we can identify a solar source and hence look for associated Type III-L emission. We confirm previous work that found that most (76% in our sample) of the solar sources of SEP events exhibit radio emission of this type. However, the correlation in the opposite direction is not as strong: starting from a radio–selected sample of Type III-L events, around 64% of the bursts that occur at longitudes magnetically well–connected to the Earth, and hence favorable for detection of SEPs, are associated with SEP events. The degree of association increases when the events have durations over 10 minutes at 1 MHz, but in general Type III-L bursts do not perform any better than Type II bursts in our sample as predictors of SEP events. A comparison of Type III-L timing with the arrival of near–relativistic electrons at the ACE spacecraft is not inconsistent with a common source for the accelerated electrons in both phenomena.

1. INTRODUCTION
Solar energetic particle (SEP) events are one of the most dangerous features of space weather. Large events can cause satellite failure due to particle strikes on computer chips, and are a radiation hazard to the health of astronauts. SEP events may be the single most hazardous aspect of manned interplanetary space travel, because it is not feasible to launch the mass of shielding required to protect astronauts from penetrating radiation. For this reason, there continues to be great interest in understanding the causes of SEP events and identifying phenomena that can forecast their occurrence.

SEP events are primarily energetic protons accelerated in the Sun’s corona to energies of tens to hundreds of MeV. Since the conditions that lead to acceleration of protons are also likely to be conducive to electron acceleration, and electrons are more efficient than protons at producing electromagnetic radiation that will reach the Earth faster than any proton can, it is natural to look for an electromagnetic tracer of proton acceleration. In particular, electrons are prolific emitters of radio waves, and there has been a long tradition of looking for associations between radio bursts and particle events [e.g., 1; 2].
Recently a class of solar radio bursts now known as “Type III-L” bursts has been reported to show a high degree of association with SEP events [3–6]. These radio bursts are fast–drift bursts (i.e., with frequency–time drift rates that are similar to conventional Type III bursts) that occur in groups significantly after the impulsive phase of a flare. A reliable association of such radio bursts with SEP events would have two consequences: (i) study of the properties of the electron acceleration mechanism and site may reveal information about the mechanism and location of proton acceleration; and (ii) the radio bursts may be useful as a predictor of SEP events. Both possibilities have high value for space weather studies.

To date, most studies of this class of radio burst have started with lists of SEP events and looked for associated radio properties. This is appropriate for the first application described above. However, the resulting samples do not represent a test of the predictive power of these bursts: if Type III-L bursts are to be useful as a predictive diagnostic, it is crucial that we be able to identify them from the radio domain alone, and then study the association of a radio–selected sample of Type III-L events with SEP events. The purpose of this paper is to carry out such a study.

An immediate issue is the identification of Type III-L bursts. Type II, isolated Type III and Type IV bursts have very different physical origins that produce such different properties in the frequency–time domain that they can usually be reliably identified in dynamic spectra of radio bursts. However, as their label suggests, Type III-L bursts are related to Type III bursts, and their identification requires a distinctive operational definition that will both avoid confusion with conventional Type III bursts, and provide a process that all observers can apply and agree on. To date, the definitions used in studies of Type III-L bursts have varied from one study to the next in order to improve the degree of correlation with SEP events. In this paper we develop an operational definition based on the previous work, and apply this definition to all large flares in 2001 for which radio dynamic spectra are available (which is all but a small fraction of the events). This produces a large sample of radio–selected Type III-L bursts (acknowledging that not everyone is likely to agree with the definition used to obtain the sample), and we compare this list with the occurrence of SEP events and other phenomena.

In addition to the predictive possibilities of Type III-L bursts, they are important for what they may reveal about the acceleration site. If we can assume that electrons and protons are accelerated in the same region of the corona (but not necessarily by the same mechanism), then the highest frequency at which we observe Type III-L emission indicates the minimum electron density in the acceleration site (since Type III bursts radiate by the plasma emission mechanism). This is important for addressing the ongoing debate over the relative contributions to SEP events of particles accelerated in the low corona, possibly in the main flare site, and particles accelerated by coronal mass ejections (CMEs) at much greater heights. We address this question later in the paper. The next section reviews previous work on Type III-L bursts, and we then go on to justify the definition that we use. The sample of flares is presented, and examples of events are shown. The sample of SEP events in 2001 is described, and we then proceed to summarize the results of correlation studies.

2. TYPE III-L BURSTS

2.1. Previous definitions

The interest in Type III-L bursts began with the observation by [7] of groups of Type III bursts appearing to emerge out of Type II bursts in radio dynamic spectra (frequency–versus–time plots). Type II bursts are slow–drift narrowband features that are nearly horizontal in dynamic spectra below 30 MHz, while Type III bursts are fast–drift features that appear nearly vertical, at least at higher frequencies (above 50 MHz). [3] present an excellent summary of typical radio burst characteristics of solar flares. As in other wavelength domains, the concept of a separation into impulsive and gradual events has been applied to the radio burst properties exhibited by flares. In the radio domain, this separation is often portrayed as the difference between “III/II” events that show a bright Type III burst at the onset of the impulsive phase of the flare followed by a Type II burst several minutes later, and “II/IV” events that do not exhibit an impulsive–phase Type III burst: rather, they produce a Type II event, usually close in time to the soft X–
Figure 1. A radio burst from a GOES class M9 flare on 2001 December 29. The displayed image is a radio dynamic spectrum produced by merging data from the USAF/RSTN network in the frequency range 25–180 MHz and data from the WAVES/RAD2 instrument on the WIND satellite in the 1.1–14 MHz range. The label in the top right corner indicates the date and the RSTN observatory supplying the ground–based data (in this case, Learmonth). The frequency axis has a nonlinear scaling (channel widths scale as frequency$^{2/3}$), and there is a gap in the spectrum between 14 and 25 MHz where we have no data. The bottom panel shows the GOES 1–8 Å soft X–ray light curve. In the range above 25 MHz, Type III bursts have a fast frequency drift rate and appear as nearly vertical features, while Type II bursts have a slower drift rate and appear as diagonal features.

Joya peak, followed by a Type IV burst (broadband structured continuum emission typically between 10 and 100 MHz that may continue for an hour or more). However, Type IV bursts are much less common than Type III or Type II bursts, and there are different classes of Type IV burst that can cause confusion. Many large flares produce no low–frequency radio bursts at all.

Figure 1 shows an example of an event similar to those studied by [7]. This is a classic “impulsive Type III/II” event (except for the double–peaked structure of the GOES light curve), i.e., it features a fast–drift Type III burst at the onset of the impulsive phase at 09:40 UT, followed by slower–drift Type II emission starting at about 09:44 UT (fundamental at about 65 MHz, second harmonic at 130 MHz, with both bands showing splitting) and drifting downwards in frequency with time. Type III bursts appear in the WAVES spectrum (below 14 MHz) after 10:00 UT and their upper frequency limit appears to coincide with the frequency of Type II emission (unfortunately in the data gap), as if they emerge out of the Type II burst.

The importance of the suggestion by [7] that the later–appearing Type III bursts did in fact originate in
the Type II burst was the implication that the energetic electrons producing the Type III-L emission were accelerated by the shock responsible for the Type II burst (speeds inferred for Type II bursts based on their frequency drift rate and coronal density models are of order 1000 km s$^{-1}$, similar to the Alfvén speed in the corona). [7] linked the observation of these Type III bursts at frequencies above 20 MHz to the controversial “SA” bursts observed with spacecraft at much lower (kilometric) frequencies [2 MHz, i.e., much further out in the solar wind; 8–13]. The controversy surrounding SA events involved their origin: the low–frequency bursts first identified as SA events showed no evidence for Type III emission at higher frequencies, and [8] argued that they were the low–frequency extension of “herringbone structure” (fast–drift but usually short–lived features known to originate in Type II bursts and therefore likely to be due to shock–accelerated electrons). However, [9] argued that the SA events were more closely associated with microwave bursts that originate in the flare sites, suggesting instead that SA events are produced by electrons accelerated in the flare itself. [13] later argued that some of the SA events occurring later in the flare could be shock–accelerated.

[3], in the paper that coined the term “Type III-L”, noted that there were numerous events in which the kilometric emission had properties identical to those studied by [7] but where the highest frequency observed for the fast drift bursts was actually higher than the frequency of the associated Type II at the time, i.e., they had to be accelerated at a location in the corona that was at a higher density and therefore likely to be physically below the height of the Type II shock. [3] concluded that the electrons producing these fast–drift bursts could not be accelerated in the Type II shock but were more likely to be produced in reconnection regions associated with post–flare loop systems below the associated CMEs.

[3] also established a connection between Type III-L events and SEPs: they started with a sample of SEP events and found that nearly all were preceded (presumably by a period corresponding to the time required for the protons to propagate to Earth at nonrelativistic velocities) by Type III-Ls. The characteristics of these radio bursts were

- at kilometric wavelengths (i.e., frequencies below 0.3 MHz) they are long–lasting and very intense fast–drift bursts;
- they originate at around the time that Type II and/or Type IV bursts are visible above 20 MHz, some 5 to 10 minutes after the start of the associated soft X–ray flare;
- they have starting frequencies in the 100–500 MHz range, well above the corresponding Type II frequency;
- and they can occur even in the absence of Type II bursts.

These features again focus attention on the location of the acceleration site of the electrons radiating in Type III-Ls and, by implication, of SEPs if they prove to be associated with such bursts: the high starting frequency of the Type III-L bursts points to an acceleration site low in the corona, well below any shock (CME–associated or not) present at that time.

The importance of these results led to a dedicated study as part of a Living With a Star Coordinated Data Analysis Workshop in 2002, summarized by [4]. The study started with a list of 47 intense SEP events in the period 1997–2001 and investigated associated data. [4] looked for criteria that would produce a high degree of association between Type III-L bursts and SEP events and derived the following conditions:

- a duration at 1 MHz in WIND/WAVES RAD1 data exceeding 10 minutes;
- a peak intensity in 100–200 kHz WIND/WAVES RAD1 data exceeding 20 dB above background;
- Type III appearance in RAD2 more complex than just multiple individual Type III bursts, i.e. presence of bursty features or narrowband features with little frequency drift.

Note an important distinction between this set of criteria and the previous discussions summarized above: unlike [3], who infer a connection between Type III-Ls and low altitudes in the solar atmosphere, these criteria refer to phenomena only visible from space at frequencies well below the ionospheric
cutoff, i.e., phenomena at heights well out into the solar wind (the 1 MHz plasma level is typically at 10R⊙ or higher in solar atmospheric density models). The set of criteria used by [4] is compatible with acceleration at a shock well away from the flare site, but does not address the possibility of acceleration low in the corona since it ignores emission at higher frequencies. Note that [14] independently studied radio events identified as complex and long–lasting at 1 MHz, and argued that they were likely due to shock acceleration in a secondary process rather than being primary flare particles.

Two more recent studies have used similar criteria to identify Type III-L bursts. [5] focus on the radio properties of 26 SEP events from 1997 to 2002: their events were chosen to have durations longer than 20 minutes at 1 MHz, and to exhibit at least two components at 14 MHz. They investigated the spatial properties of these events using data from the Nançay Radio Heliograph at five frequencies from 164 to 432 MHz. [6] started from a list of SEP events and looked separately at the radio properties of impulsive and gradual events at 1 MHz and lower as seen by the WAVES/RAD1 receiver on WIND, but did not try to “type” the radio emission. They found that for the same time–integrated level of 1 MHz emission (i.e., fluence), gradual events produced far more energetic protons than did impulsive events. On the other hand, [15] studied 3 events associated with WIND/WAVES Type III-L events and argued that since one of these events did not produce SEPs, it casts doubt on the use of Type III-Ls as predictors of SEP events.

The other important feature of most previous studies is that they have started from lists of SEP events, usually intense, and looked for suitable features in radio dynamic spectra ([3] did a radio–selected survey by inspecting dynamic spectra for 89 more-or-less randomly chosen days, but their radio-selected sample consisted of only 6 Type III-L events, of which 5 were associated with SEPs). If Type III-Ls are to be a useful diagnostic for Space Weather purposes, then we must understand the properties of radio–selected samples of these events. That is the goal of this paper.

2.2. Operational definition
Previous studies have employed the L in the Type III-L label to connote the following properties [3; 4]:

- **Late**: the initial Type III–like emission clearly starts after the impulsive phase of the flare. Thus Type III-L events must be distinguished from Type III bursts that commonly occur at the onset of the impulsive phase of a flare.
- **Long**: the emission is long–lasting and accordingly “complex”; and
- **Low** frequency: the emission extends well into the WIND/WAVES range, down to at least 1 MHz.

Using these properties and the previous definitions as a guide, and in conjunction with inspection of the data (in particular, the occurrence of impulsive Type III bursts at the onset of many flares that must be distinguished from Type III-L bursts), we chose the following operational definition for this study:

- The onset of the impulsive phase of each flare is identified as the beginning of the impulsive rise in the GOES 1–8 Å soft X–ray channel. In complex cases, we generally estimate the time of maximum second derivative of the light curve.
- In cases where the soft X–ray light curve is unavailable or confusing, impulsive–phase Type IIIIs, if present, can also be used to identify the onset of the impulsive phase.
- After inspection of data, we decided that a suitable (but arbitrary) means to distinguish a Type III-L burst from an impulsive–phase Type III is to require that the Type III-L begin no less than 4 minutes after the onset of the impulsive phase as defined above (the “late” condition).
- To avoid confusion with long–lasting impulsive phase Type III emission, we require that there must be at least a 1 minute gap between any impulsive phase Type IIIs and any candidate Type III-L burst at frequencies above 10 MHz.
- A Type III-L burst must be clearly distinguishable from an individual but late Type III burst: it must have a longer duration and show complexity (e.g., must be clearly not just two individual Type IIIs).
• We require that a candidate Type III-L clearly be associated with the event being investigated, and not possibly a random coincidence in time. In effect this criterion is applied if suitable radio emission occurs very late in the decay phase of the associated flare, or if there is an ongoing storm of Type III bursts of similar intensity that can explain the observed emission independent of any flare or CME.

These criteria clearly still leave room for two observers to disagree on the nature of an event: in particular, the condition that a Type III-L burst show complexity and not be a simple late Type III burst proves to be a difficult distinction in some cases. For this reason, we will include both “definite” Type III-L bursts and “marginal” Type III-L bursts in the final sample. In practice observers may also disagree on the correct onset time indicated by the GOES light curve, particularly for very gradual events, when several events are in progress simultaneously, or when there is a precursor soft X–ray event.

Unlike [4], we do not impose an intensity condition. [4] used such a condition to improve the association of Type III-L emission with large SEP events, but since we wish to define a radio–selected sample we will use the intensity as a secondary rather than as a defining characteristic. The requirement that events be identified by eye, rather than in an automated fashion as in [4], is undesirable for an operational forecast tool but appropriate for this initial survey in view of the need to satisfy (and investigate) the discrimination criteria given above.

3. THE EVENT SAMPLE
3.1. Data Preparation
Since, as far as we know, all major SEP events can be tied back to flares (although frequently behind the limb and then difficult to identify), and because our criteria for Type III-L bursts focus on flares, it is logical to choose our core sample to be based on a set of flares. We use NOAA's list of GOES M- and X-class flares for 2001: we know from previous statistical studies that both radio emission and SEP events are more likely to be associated with large flares.¹ This sample gives us a large number of events without becoming unmanageable. We choose events in 2001 because that year was close to the peak of solar activity in the last cycle, and because radio dynamic spectra are available in digital form from each of the US Air Force Radio Solar Telescope Network (RSTN) sites at Holloman (New Mexico), Pahala (Hawaii), Learmonth (Western Australia) and San Vito (Italy) for essentially the entire year. Digital spectra are not currently as widely available in adjacent solar maximum years. The RSTN dynamic spectra cover the range 25–180 MHz in 802 channels with a time resolution of 3 seconds. The observing sites are far from interference-free, and horizontal lines at fixed frequencies of interfering signals are present in the spectra. We supplement the RSTN data in a few cases with data from the OSRA spectrograph (40–200 MHz at 0.1 s time resolution) at Tremsdorf, Germany, and from the Culgoora spectrograph operated by Australia’s Ionospheric Prediction Service. In order to cover low frequencies (below the ionospheric cutoff) we use the WAVES/RAD2 data from the WIND satellite, which cover 1.1–13.8 MHz in 256 channels at 16 second time resolution. Unlike other studies we do not use the more sensitive RAD1 data [4] because RAD1 data have poorer time resolution (1 minute): since “complexity” is believed to be a condition of Type III-L emission, the higher time resolution of RAD2 is essential to identify Type III–like structure within a Type III-L burst.

There were 307 M–class flares and 22 X–class flares in NOAA's flare list for 2001. Of the total of 329 flares, 322 (98%) have “good” WIND/WAVES RAD2 data, 3 have contaminating interference in the RAD2 band that prevent its use, and 4 had no RAD2 data. Of the 322 MX events with good RAD2 data, 298 had coverage from RSTN ground–based radio data, 6 flares had coverage from OSRA ground–based radio data (40-200 MHz), and 5 flares had coverage from Culgoora. Thus we have radio dynamic spectra from 1 to 180 MHz for 92% of all MX flares in 2001. We will also consider the 13 events for which

¹ We are aware, as discussed further below, that a selection based on soft X–ray emission will necessarily exclude some large flares behind the limb that produced SEPs but little soft X–ray emission above the limb, such as the famous 2001 April 18 event described by [16], but this choice does provide a well–defined sample.
Figure 2. The M1 event of 2001 January 20, with clear Type III-L emission in the WIND/WAVES data below 14 MHz but less obvious in the ground–based data above 25 MHz.

we have RAD2 data but no ground–based data. All 322 RAD2 events had GOES SXR (1–8 Å) data coverage.

For each of these 322 MX events, a one–hour composite plot (of the form shown in Fig. 1) using merged ground-based and satellite–based radio data (upper panel, with a gap between 14 and 25 MHz) and GOES 1–8 Å SXR light curves (lower panel) was produced with each data window beginning roughly 5 minutes before the onset of the impulsive phase of the flare. In the case of very extended events for which a 1–hour window did not encompass all likely flare activity, we extended the plotted window appropriately. The original radio spectra were regridded onto a frequency axis with channel widths scaling as the 2/3 power of frequency, in order to be able to see structure at both high and low frequencies adequately.

3.2. Type III-L Events Associated with MX Flares
Two authors (RTD and SMW) both independently applied the Type III-L defining criteria described above to the 322 event images in order to identify Type III-L bursts. The criteria were applied separately to the upper and lower portions of the radio spectrum, in order to be able to address the question of whether ground–based radio observations alone can be used to identify Type III-L bursts, or whether, as argued by [4], the 1 MHz properties alone suffice. No information other than the event images was used in the identification. Note that this survey does not rely on reports from diverse observers as to the timing of Type III emission or the start and stop times of the flare soft X–ray emission, but rather from inspection of dynamic spectra and direct comparison with GOES light curves for every event in
Figure 3. The M7 event of 2001 March 10. In this event fast–drift emission is seen at 04:10 UT, 6 minutes after the impulsive Type III burst at 04:04.

the sample, resulting in a uniform and consistent survey of properties. The two authors achieved 90% agreement on their Type III-L lists. Where there was disagreement or a definitive yes/no answer was not possible, we labeled the event as a marginal Type III-L event. The resulting list of Type III-L bursts from MX–class flares in 2001 is presented in Table 1.

Figures 1–5 present a number of examples of bursts to illustrate the Type III-L identification process, and the issues that typically arise. Figure 2 shows an event with no impulsive Type III burst. We adopt the inflection point in the GOES light curve at 18:35 UT as the start of the impulsive phase. Poorly defined Type II emission starts above 30 MHz at 18:42 UT: it contains narrowband spines of emission with the appropriate drift rate for a Type II, harmonic structure in the RSTN Holloman frequency range, and a faint continuation of both fundamental (6.5 MHz) and harmonic (13 MHz) can be seen in the WAVES data from 19:14 to 19:18 UT. Type III–like emission begins below 14 MHz at about the time that we first see the Type II emission (about 7 minutes after the onset of the impulsive phase), and continues for about 20 minutes with fast–drift features superimposed on a complex background. The Type III-L emission in the ground–based spectrum above 25 MHz is not as clear due to the numerous interference features in the spectrum, but we can see evidence for it from 18:55 to 18:58 UT. We usually found it more difficult to identify Type III-L structure in the ground–based data above 25 MHz because of the combination of more complex solar emissions there than at lower frequencies, and the presence of interference. This event produced SEPs.

Figure 3 shows a classic impulsive III/II event that would not be regarded as Type III-L emission if we imposed a duration limit on the 1 MHz emission as did [4]. The fast–drift burst at 04:10 UT is more
Figure 4. The X1 event of 2001 April 2. This is a very complex event with Type II emission (11:10–11:18), Type IV emission (starting above 100 MHz at 11:18 UT), and fast–drift bursts. Both the emission starting at 10:59 UT and the emission at 11:13 UT are potential Type III-L emission.

than 4 minutes after the impulsive–phase Type III burst at 04:04 UT, and while it could easily be a single Type III burst in the WAVES data, the ground–based data show definite structure, and this satisfies our criterion that the emission clearly be complex. This event produced SEPs.

Figure 4 shows a complex event that we classified as marginal, and one that illustrates the difficulty of classification. This is essentially a “II/IV” event but with only short–lived Type II emission in the ground–based data (starting at 11:10). In the WAVES data the emission drifting into the WAVES frequency range starting at 11:27 UT could be a diffuse Type II emission or an extension of the Type IV emission seen in the San Vito RSTN data. The fast–drift emission starting at 10:59 UT could satisfy our Type III-L criteria if we takes the GOES impulsive onset to be 10:54, but the GOES light curve is complex and there is an inflection point at 10:59 UT that would exclude the early radio emission from consideration. At 11:13 UT more fast–drift emission is seen, clearly consisting of multiple components in the San Vito data, but relatively short–lived in the WAVES data. Note that the duration of the 1 MHz emission here is also less than 10 minutes. This event produced SEPs.

Figure 5 is another complex event featuring many fast–drift bursts. The problem with this event is one of timing: Type II emission is seen from about 22:32 to 22:36, before the impulsive onset implied by the GOES light curve (around 22:45 UT). This suggests that the Type II emission is not associated with the X1 flare but rather with some earlier event, and casts doubt on the appropriate association for other features. However, the CME seen in conjunction with this event is definitely produced by the X1 flare and not any earlier event. We identify the low–frequency emission from 23:10 to 23:30, with a mix
Figure 5. The X1 event of 2001 November 22. This event also has a complex GOES light curve and is odd in that Type II emission appears to precede the onset of the impulsive phase, but the likely Type III-L emission follows the impulsive phase.

of fast–drift and slow–drift features below 14 MHz and coincident with the Type IV emission above 25 MHz, as a candidate Type III-L based on our criteria, but it is listed as marginal because of the possibility that it may not be associated with the X1 flare. This event produced SEPs.

These examples and the notes in the table demonstrate the unsurprising result that coming up with suitable criteria to serve as an operational definition for Type III-L bursts that can be taught, e.g. to a forecaster, is far from easy. This follows from the fact that Type III-Ls have not yet been demonstrated clearly to constitute a phenomenon that is physically distinct in the way that Type II, Type III and Type IV bursts are clearly of different origins: Type III-L bursts appear to contain multiple Type III bursts, and making the distinction between Type III-L and Type III bursts will always be problematic. Nonetheless, two individual authors could agree on about 90% of the classifications. The result is a list of 52 “good” Type III-L events and 18 “marginal” Type III-L events (Table 1). Thus we find that 22% of all MX flares show a form of radio emission that can be classified as Type III-L using our criteria, including 17 of the 22 X flares in 2001 (77%). We include SXR class, timing and location, Type III-L timing, and Type II occurrence for both ground and WAVES data, duration at 1 MHz and association with a CME in the Type III-L table. Marginal Type III-L events are indicated by printing the date and time in italics.

Note that the Type II identifications used in Table 1 were carried out by author SMW using the event images and are not the same as the NGDC lists compiled from observatory reports. In particular, the NGDC list is for ground–based observations only, whereas we include those for which we can identify Type II bursts in the WAVES RAD2 data.
Figure 6. The 13–40 MeV proton count rate for 2001 measured by the ERNE telescope on the SOHO satellite. Each panel covers 36 days starting on the date indicated by the label; the entire year except for the period March 13-19 (no events) is plotted. Dashed vertical lines indicate SEP events identified from the combination of these data and energetic electron data.
3.3. Solar Energetic Particle Events

In order to determine the association between Type III-L bursts and SEP events, we need a list of all SEP events in 2001. Most existing lists focus on large events, whereas we need the most comprehensive list possible: excluding small SEP events from our study can only reduce the degree of association between Type III-L bursts and SEP events. Once an SEP event has been identified, we also need to establish the corresponding solar onset time if we are to compare it with the times of the events in our flare–based Type III-L list. The identification of SEP events and their associated solar phenomena has a long and tortured history, largely due to the fact that we observe protons when, and if and only if, they reach the Earth. Direct propagation from the Sun to the Earth along the Parker spiral magnetic field lines, see http://sd-www.jhuapl.edu/ACE/EPAM/BeamEventList.pdf, 18 events in 2001) have only 5 events in common (04/26 12:20, 06/15 15:50, 09/24 10:50, 10/09 07:50, 11/04 16:30). All 5 of these events are relatively large proton events, although the 10/09 event occurs during the decay of a prior event: in identifying onset times (of SEPs arriving at the Earth) we attempt to fit and subtract the decay of the previous event. We also used 175–315 keV electron data from the EPAM instrument on the ACE satellite to refine onset times (the electron data also contain events not associated with SEP proton events and thus we do not use them as a primary source of event identifications: several possible events that are clear in the electron data but not evident in the > 13 MeV proton data are excluded from our list). The electron data are useful for defining the onset times: a 200 keV electron typically arrives faster than a 10 MeV proton, with propagation times of order 10-20 minutes [17], so the electrons typically start to rise before the protons, closer in time to the originating event at the Sun. The time resolution in the electron data used here is 5 minutes in most cases, supplemented in suitable cases by 12-second data averaged to 2–minute resolution; times have been corrected for the known clock error in EPAM data.

The resulting list of 68 events is presented in Table 2. We regard 15 of these 68 events as being marginal identifications due either to very low intensity or short durations, and these are identified by printing the date and time in italics. Note that our list of proton SEP events and the ACE/EPAM list of “beam–like electron events” (highly anisotropic electron events beamed along the solar wind magnetic field, see http://sd-www.jhuapl.edu/ACE/EPAM/BeamEventList.pdf, 18 events in 2001) have only 5 events in common (04/26 13:20, 06/15 15:50, 09/24 10:50, 10/09 07:50, 11/04 16:30). All 5 of these events are relatively large proton events, although the 10/09 event occurs during the decay of a larger preceding event and is more pronounced in the electron data than in the proton data. Our list has no events in common with the list of $^3$He–rich impulsive (small) SEP events studied by [18], and hence is dominated by events that are now typically called “gradual” or proton–rich. Our list is very similar to but larger than that of [19], who searched for events associated with CMEs.

An important issue for identifying SEP events is the fact that during large events the proton flux can remain at extreme levels for many days. We can identify SEP events as small as .002 particles cm$^{-2}$s$^{-1}$sr$^{-1}$ in the ERNE 13–40 MeV data when the background level is low, while large events may reach many hundreds of particles cm$^{-2}$s$^{-1}$sr$^{-1}$ and last for days. Since the flux level can fluctuate due to local changes in propagation conditions or other conditions in the local solar wind, it is not possible to
identify small new SEP events against such high backgrounds. For this reason, we will impose blackout periods for the comparison of Type III-L and SEP events: when the ERNE 13–40 MeV level exceeds 3 particles cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\), we assume that we cannot detect any but very large events during these periods, and exclude Type III-L events occurring during these periods from the comparison. The excluded periods are listed in Table 3. The threshold is applied from onset of SEP events above the threshold until the levels have decreased below the threshold, with gaps to allow inclusion of obvious large SEP events. This exclusion, always occurring during periods of high solar flare activity, removes a number of MX events from consideration, including 4 Type III-L events in our sample. Note that the fact that we find 68 SEP events despite the highly variable detection threshold over the year suggests that many more events would be detected if the background level were uniformly low.

Table 2 includes our best estimate of the onset time at Earth for each event, but these times are not of uniform quality: for large events with a very rapid rise and good energetic–electron count rates, the onset time is accurate to better than 3 minutes\(^3\), but for events with a very gradual rise it is difficult to distinguish the event onset from the background, and the uncertainty may be of order many hours. Since our purpose is to identify the corresponding solar events, we have used the earlier electron onset times wherever they clearly precede the onset of protons: the electron onset times are typically at most 10 minutes earlier than the proton onsets for well–connected western events, but can be an hour earlier than the proton onsets detectable in the data for events with a gradual rise. The second last column of Table 2 gives a qualitative indication of the rate of rise of the event (fast or slow), as an indication of the likelihood that an event is well connected (western events, fast rise) or poorly connected (eastern events, slow rise) to aid in identifying the solar source. Note that in this paper we do not address the distinction between “impulsive” and “gradual” SEP events: these terms have come to reflect differences in SEP composition (gradual events have normal solar wind composition while impulsive events have high charge states of Fe and high ratios of \(^{3}\)He/\(^{4}\)He) rather than differences in the rate of change of the count rates [e.g., 20]. The three SEP events found using GOES proton flux data instead of ERNE data are indicated by italics in the comments column: their rates are GOES 10–50 MeV rates and cannot be compared directly with the ERNE rates.

As noted earlier, the onset time of SEPs arriving at Earth may be as little as 10 minutes after they are accelerated at the Sun, or as much as 12 hours, depending on the energy of the first–arriving protons and whether they have propagated 1.2 AU directly along a well–connected field line, or random–walked their way across the solar wind magnetic spiral from the east side of the Sun. This large uncertainty in extrapolating the arrival time at Earth back to a departure time from the Sun leads to major ambiguities in identifying the solar event that produced the SEP. In most of the cases involving large events with a very rapid rise, there is no ambiguity in identification, but events with a gradual rise, even when large, have a large uncertainty in their solar origin because a number of flares and CME eruptions may occur in a several hour window preceding the nominal arrival time of the first energetic protons. (We only need to identify the solar event in order to look for Type III-L bursts, so we can ignore the ongoing debate about the exact particle injection times at the Sun, e.g., see the review by [21].)

To identify the solar event producing each SEP, we looked at both the event lists compiled by NOAA and the CDAW CME catalog\(^4\). Where there was ambiguity in the association, we generally favored large events and/or bright fast CMEs as the solar origin because they were generally associated with SEPs in events where the origin was clear. It is necessary to use CME lists in order to catch solar events that may have occurred well behind the solar limb and therefore produced little or no detectable soft X–rays, such as the 2001 April 18 event. This does of course bias the associations in favor of events that also produced CMEs; e.g., for the large 2001 May 7 SEP event we regard the 1200 km s\(^{-1}\) CME from beyond the west limb as a more likely source than the C4 disk–flare attribution of [22]. Associations of the SEP events

\(^3\) We find that our onset times from the EPAM electron data are consistent with the onsets derived by [17] using higher–energy 0.3–1.2 MeV electrons detected by the COSTEP instrument on SOHO for the 14 events common to both studies.

\(^4\) The CME catalog is generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA.
Figure 7. The M4 event of 2001 December 14, a candidate source for the particle event starting on December 15. Although this event shows many Type III-like features that could be Type III-L bursts, we do not classify it as a Type III-L event because numerous bright Type III bursts occur throughout the 06:30 – 09:30 UT period, and so we cannot unambiguously identify any feature with the flare itself.

... that we regard as possible but uncertain are classified as marginal associations, denoted by italic type in the association column (column 3) of Table 2. We have produced radio dynamic spectra of each event with an association identical to those used for the Type III-L identification, and use these to also report the presence of Type II emission in the ground and WAVES frequency ranges in the table. The speed of any associated CME (taken from the CDAW catalog) is also given in the table.

Figure 7 shows an example of an event where strict application of our Type III-L criteria rules out a likely–looking Type III-L-SEP association: this flare occurred in the middle of a 3–hour period when numerous bright Type III bursts can be seen in the WIND/WAVES data. Due to the possibility that that III-like bursts occurring in conjunction with the Type II burst could be coincidental, we do not classify this as a Type III-L burst.

Of the 68 SEP proton events listed in Table 2 we find possible solar event associations for 62 events, but of these we regard 14 as marginal associations. The nature and location of the associated event is also listed in Table 2: 35, or just over half, are GOES class M or X flares and thus were included in our core sample, while 17 have no flare association but we can find appropriate CMEs. This implies that a quarter of all SEP events in 2001 originated in flares occurring beyond the solar limb (with most, 14 out of 17, beyond the west limb and thus having a better magnetic connection to Earth): this is not surprising because the detection of eastern–limb events shows that SEPs can diffuse very large distances in azimuth around the Sun. In 10 events the most plausible association was with a smaller GOES class C
Figure 8. The M1 event of 2001 March 20. This is a long–duration event with a complex GOES light curve. The Type III-L and Type II emission are coincident in time but occur late relative to the soft X–ray peak.

flare, some of which (01/26, 02/11) produced fast CMEs with speeds of order 1000 km s\(^{-1}\) or faster. In addition, 4 of the 10 C class flares linked to SEP events occurred at the limb and may have been larger flares that were partially obscured in soft X–rays. We regard 4 of the 10 C–flare associations as marginal: the strong associations all exhibit very bright and/or fast CMEs, consistent with our explicit bias towards such events. 12 of the 22 X–class flares in 2001 are associated with SEP events, including all 5 of the X–class flares that occurred in the W30–W90 longitude range.

4. RESULTS

After the SEP high–background exclusion, we had 50 “good” and 16 “marginal” Type III-L events for 2001. The results of associating these 66 events with the SEP list are given in Table 4. We break the associations down according to whether the Type III-L is “good” or “marginal”, and then whether the SEP event is “good” or “marginal”, or has a marginal association. Further, since SEP events occurring in the western hemisphere are more likely to be detected at Earth than those to the east, we break the association down by east (heliographic longitudes E30-90), center (E30-W30) and west (W30-W90) locations. We also report the association of Type II events in the MX flare list with SEP events as a comparison.

As expected, the Type III-L list shows no strong longitude preference (radio emission does not care about the Parker spiral), whereas about 60% of the SEP events occur limbwards of W30 (charged–particle propagation does care about the Parker spiral). There is very little association between Type III-L bursts
(or Type II bursts) with SEP events having marginal associations, so we focus here on associations with "good" SEP events with reliable solar event identifications. As shown in the first line of Table 4, of the 13 "good" Type III-L bursts in the W30–W90 range, 7 (just over 50%) are associated with SEPs, while 3 out of 9 "marginal" Type III-L bursts are associated with SEPs. A further 1 "good" and 3 "marginal" Type III-L bursts in the W30–W90 range are associated with marginal SEP events, so that 8 out of 13 (62%) "good" and 6 out of 9 (67%) "marginal" well–connected Type III-L bursts are associated with SEP events. In the E30–W30 longitude range the degree of association is poorer as expected, although the statistics are not compelling: 8 out of 21 "good" Type III-L bursts are associated with SEP events. These numbers suggest that the presence of a Type III-L burst from a flare in the well–connected region of the solar surface is a good but not a compelling predictor of an SEP event. Figure 8 shows an example of a well–connected event (longitude W54) that produced clear Type III-L emission in conjunction with a Type II burst, but no particle event was detected.

Furthermore, in our sample Type III-L bursts do not appear to be a significantly better predictor of SEP events than Type II bursts: 10 out of 17 (59%) MX flares in the W30–W90 longitude range exhibiting Type II bursts were associated with SEP events. However, these associations for Type II bursts are poorer if we remove the restriction to MX events: we find that 14 out of all 26 reported Type II bursts in the W30–W90 longitude range in 2001 and 13 out of 35 Type II bursts in the E30–W30 range are associated with SEPs. This reflects the fact that smaller flares are quite capable of producing Type II bursts, but are less likely to produce detectable SEP events.

On the other hand, we find that SEP events are quite well associated with Type III-L bursts (Table 5), as the previous studies have reported. In 31 out of 41 (76%) "good" SEP events with a reliable solar event association, the solar event (flare or CME) shows radio emission that fits our Type III-L criteria. For all levels of SEP event with an association, 41 out of 62 show Type III-L emission (66%). However, SEP events are equally well associated with Type II bursts: 32 out of 41 (78%) "good" SEP events with "good" associations and 42 out of all 62 SEP events with any associations (68%) show Type II emission.

The degree of association improves if, as argued by [4], we restrict our attention to Type III-L bursts with durations in excess of 10 minutes at 1 MHz: 11 out of 13 Type III-L events in the W30–W90 range and 9 out of 15 Type III-L events in the E30–W30 range with 1 MHz durations over 10 minutes are associated with SEP events (Table 4). The reverse association is also quite strong: in 33 out of 41 SEP events associated with Type III-L bursts, the 1 MHz radio emission has a duration of 10 minutes or more.

5. ANALYSIS AND DISCUSSION

In the previous sections we have demonstrated that an operational definition of Type III-L bursts, satisfying the previously–inferred (by other authors) properties of lateness, length and low–frequency, can be described and applied to suitable data to produce a catalog of such events. There remains considerable subjectivity in the classification, but this is true of other classes of solar radio burst as well.

We compared our list of Type III-L bursts with the list of all SEP events detected in 2001 by the ERNE instrument on the SOHO spacecraft at proton energies above 13 MeV. For well–connected events originating in the western hemisphere, the majority of Type III-L bursts are indeed associated with SEP events, but not all of them, consistent with the arguments by [15]. Furthermore, they do not seem to be better predictors of SEP events from MX–class flares than is the presence of a Type II burst, and SEP events are just as likely to exhibit Type II bursts in their radio spectra as they are Type III-L bursts.

The association between Type III-L bursts and SEP events does improve if we restrict attention to events in which the 1 MHz radio emission lasts 10 minutes or longer. However, the simplest interpretation of this collection of properties appears to be “big flare” syndrome (BFS). [23] describes this condition as follows: “the larger the energy release in a flare, the larger the statistically expected magnitude of any measured flare energy manifestation”. An alternative statement of BFS is that “big flares have everything”, i.e., correlations between any two properties will be large in big flares because any given property is more likely to be detected in a large flare and correlations will appear even though two
properties may not be physically connected. In the case of our study, the hypothesis is that SEP detection is predominantly a function of flare size and favorable magnetic connectivity from the acceleration site to Earth. The fact that Type III-L bursts and Type II bursts show similar degrees of association with SEP events, and vice-versa, is then explained as the result of SEP events generally being large flares that exhibit all phenomena, rather than Type III-L and Type II emission being physically linked to the production of energetic protons. We expect that 1 MHz emission will have a longer duration in large flares, and so the improved correlation with longer Type III-L emission at 1 MHz is also consistent with BFS. The issue that this discussion does not address, however, is what parameter is appropriate to measure the “size” of a flare: soft X-ray class, while useful, is not definitive since it measures the peak SXR flux rather than the fluence, does not represent the energy or speed of any associated mass ejection, and further is not reliable for over-the-limb events.

Nonetheless, the fact that we can find Type III-L emission distinct from the Type III bursts that typically occur at the onset of an impulsive flare (roughly one-quarter of the MX flares in our sample show such impulsive Type III bursts, and about 40% of the Type III-L bursts are preceded by impulsive-phase Type IIIIs) is a significant result and potentially highlights a phenomenon that is physically distinct, in the same way that Type IV emission (occurring at frequencies above the ionospheric cutoff, typically after any Type II burst and with longer duration) is clearly the result of a physical mechanism that is distinct from the impulsive Type III bursts and Type II emission. More work is clearly needed to establish such a case. One issue that occurred in classifying Type III-L bursts is that relevant to this question is the difficulty of identifying Type III-L emission in the ground-based dynamic spectra: frequently such emission was confused by both bright flare continuum emissions (Type II, Type IV or other continua) and by interference, e.g., Figs. 2 and 8, where Type III-L emission below 14 MHz clearly occurs at the time of Type II emission above 25 MHz, but it is difficult to discern whether the Type III-L emission is also present above 25 MHz. This makes it difficult for us to address the issue of the acceleration site for the electrons producing the Type III-L emission, but there clearly are a number of cases where the Type III-L emission starts at frequencies above that of concurrent Type II emission, implying an acceleration site relatively low in the corona.

6. FAST-ONSET EVENTS

An issue for the association between Type III-L bursts and SEP events is that if the acceleration of the Type III-L-emitting electrons is coincident with the acceleration of the SEPs, then the SEPs cannot leave the Sun before the Type III-L burst occurs. While inspecting the plots for the events in Table 2, we noticed that there are several events in which 175–315 keV electrons arrive at Earth very quickly, close in time to the Type III-L burst onset. Given the extra propagation time required by the electrons to reach Earth, this could pose a problem for the interpretation of a common acceleration site.

We note that there continues to be a debate about the source of the near-relativistic electrons measured by the EPAM instrument. This question is irrelevant to our main purpose of identifying the solar sources of SEPs in order to look for associated Type III-L emission, but is relevant to the issue of the relationship between the electrons emitting Type III-L bursts and damaging protons in SEP events. The debate has arisen largely because of studies [e.g., 24; 25] that found a delay between the launch time of the near-relativistic electrons at the Sun and Type III bursts attributed [26] to 2–20 keV electrons in the corona. Most of these studies concern “beam–like electron events” rather than the large proton–dominated SEP events that make up Table 2, and it is argued that the delays mean that the near-relativistic electrons measured at 1 AU cannot be the high–energy tail of the Type III–emitting electrons and thus require a different source. The delays can be attributed to a CME–driven shock–acceleration source for the near-relativistic electrons [27], to propagation conditions [28], or to an origin in low–coronal phenomena occurring after the impulsive phase [e.g., 29]. An association with the Type III-L bursts occurring after the impulsive phase would fall into the latter category. [30] has reviewed the nature of the solar sources of energetic electron events and has concluded that some appear to arise in the impulsive phase of flares while others (particularly those with relativistic energies) appear to be better associated with acceleration.
Figure 9. The X14 event of 2001 April 15. The figure has the same format except that the light curve of 175-312 keV electrons (from ACE/EPAM) is shown in the lower panel at 12 second resolution (red curve, logarithmic in the vertical axis, scaled to fit). The ACE/EPAM curve has not been shifted in time, i.e., it represents the arrival time of electrons at ACE at 1 AU).

by a CME–driven shock.

Table 6 lists 8 events from our sample where the latest time that the first–arriving electrons could have left the Sun is very close to the onset time of associated Type III-L emission. If a 200 keV (kinetic–energy) electron follows the minimum 1.2 AU–long Parker spiral trajectory from the Sun to the Earth with zero pitch angle and no scattering (fastest possible circumstances), it requires 860 seconds to propagate from the Sun to the Earth, while a 300 keV electron requires 770 seconds. The light travel time of radio waves (1.0 AU) is 500 seconds, so we can assume that electrons in the ACE/EPAM energy range of 175–315 keV leaving the Sun are delayed by a minimum of 6 minutes in arriving at Earth compared with the arrival of electromagnetic radiation departing the Sun at the same time. Table 6 reports the latest possible departure time for the first–arriving electrons leaving the Sun (measured with Earth clocks) by subtracting 6 minutes from the observed time of arrival of the first electrons at 1 AU: in practice we expect that electrons must have been accelerated before the time shown. All 8 events are beyond longitude W50 and hence well connected. In 5 of 8 events the latest SEP launch time is within 12 minutes of the (nominal) SXR onset. In one case, 2001 April 15 (shown in Figure 9), the SEP launch time is within a few minutes of the nominal SXR onset for the X14 flare but this event has a complex soft X–ray light curve with a possible precursor event starting at 13:37 UT, roughly 10 minutes before the latest SEP launch time. In 5 of 8 events the SEP launch time is well (typically 15 minutes) before the first observation of the CME associated with the event in the LASCO/C2 field of view, but in the case of
2001 August 15 event beyond the SW limb a CME is detected significantly before the onset time of the SEPs: radio emission observed at 23:30 UT suggests that the actual event start time was as early as 23:25 UT, well before the first CME observation and more than 40 minutes before the first electrons arrive at ACE.

In none of the events listed in Table 6 does the latest possible SEP electron launch time precede the onset of the Type III-L-burst, so these data do not rule out a common acceleration site for the Type III-L-emitting electrons and the SEP electrons. However, given that our correction for the difference in travel time between electrons and radio photons is very conservative, it is still possible that in some cases (e.g., April 15), SEP electrons may have left the Sun before Type III-L emission is observed. On the other hand, as noted above, it may also be the case that the SEP electrons have an origin quite different from that of the SEP protons that are the main concern for space weather effects.

7. CONCLUSIONS

We have two goals in carrying out this study: (i) to determine whether Type III-L–bursts can be used to help to predict SEP events; and (ii) to determine whether Type III-L–bursts can help us to identify the location of the acceleration site for SEP particles.

We have established a set of criteria that may be used operationally to identify Type III-L bursts and distinguish them from the impulsive–phase Type III bursts. We find that the requirement of a 4–minute delay between the onset of a flare in soft X–rays and subsequent Type III-L emission serves well in most cases to make this distinction. Applying the defining criteria to the set of 322 GOES–class M and X flares in 2001 for which we have radio dynamic spectra, we found that two observers can agree about 90% of the time in their classifications, and a set of 52 “good” and 18 “marginal” Type III-L bursts resulted. After exclusion of high particle background periods (listed in Table 3), we have 22 Type III-L bursts occurring in the well–connected W30–W90 longitude range, and about 64% of these bursts were associated with SEP events, including 100% of the X flares in this range with Type III-L emission. The association also improves if we require that emission have a long duration at 1 MHz: 11 out of 13 Type III-L bursts in the W30–W90 range are associated with SEP events.

We identified 53 “good” and 15 “marginal” SEP proton events during 2001, and were able to reliably associate solar sources (flares and/or CMEs) with 48 of these events. Of the 41 “good” SEP events with reliable associations, 31 (76%) show radio emission that fits our Type III-L criteria. For comparison, [4] found that 20% of the large SEP events in their sample did not exhibit suitable Type III emission at 14 MHz, although 91% exhibited emission lasting longer than 10 minutes at 1 MHz. Thus a large fraction of SEP events, but not all, do exhibit “late” Type III bursts. This raises the possibility that there is indeed a link between the acceleration mechanism that produces SEPs and the acceleration of the electrons in the beams that produce Type III-L emission. Investigation of the timing of arrival of energetic electrons at the ACE satellite at the L1 Lagrangian point indicates that we cannot rule out the scenario in which they are accelerated at the same time as the Type III-L-emitting electrons.

The more dangerous SEP protons need not be accelerated at the same site and with the same mechanism as the electrons, but we note that in all but a few of the 68 proton events in Table 2, 175-312 keV electrons were detected by ACE/EPAM: electron acceleration almost invariably accompanies ion acceleration. While there are numerous potential sources of accelerated electrons, as discussed earlier, the prevailing view is that the energetic protons in the “gradual” SEP events that dominate Table 2 have no contribution from flare processes in the low corona and are instead accelerated by shocks driven by CMEs [e.g., 20], and indeed many of the solar sources that we identify for the SEP events are associated with CMEs faster than 1000 km s$^{-1}$ (of the 19 CMEs in the western hemisphere in 2001 with speeds faster than 1000 km s$^{-1}$ and widths larger than 100$, at least 14 were associated with detectable SEP protons, and 20 out of 28 halo CMEs faster than 1000 km s$^{-1}$ were associated with detectable SEP protons irrespective of the flare location). If this is the case, it is difficult to understand how there can be any causal association between CMEs and Type III-L bursts originating in the low corona at plasma frequencies above 50 MHz tens of minutes after the impulsive onset of a flare, when any associated fast
CME is generally several solar radii above the surface. The association of 1 MHz emission with CMEs is more plausible in terms of height and timing, but again for those fast–drift bursts originating in the low corona this implies that somehow the fact that the CME shock is accelerating protons enhances the plasma emission of electrons at 1 MHz, typically 5–10 \( R_\odot \) above the solar surface, even though the electrons themselves were accelerated far below.

Unfortunately, however, the associations between SEP events and Type III-L bursts are almost identical to those between SEP events and Type II bursts, and it is well established that Type II bursts are a poor predictor of SEP events \([e.g., 2; 31]\) because quite small flares with no detectable SEPs can easily produce Type II bursts. This leads us to speculate that the high degree of association of Type III-L emission with SEP events may be due to big–flare syndrome: the detection of SEPs is largely a function of the total energy released by the flare, and large flares tend to exhibit all forms of solar activity, so that high degrees of correlation will appear even in the absence of a causal connection between two phenomena.

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Table 1. Type III-L bursts from MX flares in 2001

| SXR Onset | SXR Location | III-L Ground | III-L WAVES | Type II Ground | Type II WAVES | CME km/s | 1 MHz dur. | Comments |
|-----------|--------------|--------------|-------------|----------------|---------------|-----------|-----------|----------|
| (Date UT) | Class        | Location     | WAVES       | WAVES          |               |           |           |          |
| 20010120 / 1835 | M1 | S07 E40 | 1846 | 1846 | y | y | 840 | 34 | patchy Type II, prototype Type III-L |
| 200001020 / 2108 | M8 | S07 E46 | 2114 | 2115 | y | y | 1510 | 18 | |
| 20010128 / 1846 | M1 | S04 W59 | 1558 | 1558 | y | y | 920 | 20 | faint emission |
| 20010128 / 2204 | M2 | N09 E72 | 0004 | 2351 | y | y | 640 | 9 | |
| 20010130 / 0403 | M7 | N27 W42 | 0409 | 0409 | y | y | 820 | 6 | |
| 20010130 / 0216 | M1 | S05 W54 | 0242 | 0242 | y | y | 480 | 16 | |
| 20010215 / 1458 | M1 | S05 W61 | 1502 | 1503 | y | y | 410 | 6 | weak, individual bursts |
| 20010324 / 0135 | M1 | S14 W42 | 0141 | 0141 | y | y | 310 | 7 | impulsive-phase IIIs bright, Type III-L weak |
| 20010324 / 0145 | M2 | NE05 | 0445 | 0445 | y | y | 8 | 4 | |
| 20010325 / 1103 | M3 | N21 E59 | 1115 | 1115 | y | y | 580 | 6 | |
| 20010325 / 1150 | M3 | N15 E27 | 1323 | 1323 | y | y | 450 | 6 | long impulsive IIIs, weak III-L |
| 20010325 / 1201 | M1 | N14 E05 | 0210 | 0210 | y | y | 7 | 4 | |
| 20010326 / 2204 | M2 | N17 W01 | 2240 | 2240 | y | y | 150 | 6 | long impulsive IIIs, weak III-L |
| 20010328 / 1000 | X2 | S00 W19 | 1009 | 1009 | y | y | 940 | 15 | confused by ongoing continuum, not clearly fast-drift emission |
| 20010402 / 0526 | M1 | N13 W63 | 0533 | 0533 | y | y | 630 | 4 | nothing above 14 MHz, weak III-L |
| 20010402 / 1006 | X1 | W17 W60 | 1016 | 1016 | y | y | 5 | 4 | |
| 20010402 / 1054 | X1 | N15 W64 | 1113 | 1113 | y | y | 990 | 16 | GOES onset time uncertain, identify later IIIs as III-L |
| 20010402 / 2134 | X17 | N18 W82 | 2152 | 2147 | y | y | 2500 | 19 | |
| 20010405 / 0206 | M3 | W Limb | 0207 | 0207 | y | y | 1860 | 7 | weak III-L, mild SWF3 |
| 20010406 / 1914 | X6 | S21 E31 | 1923 | 1923 | y | y | 1270 | 16 | no RSTN data |
| 20010409 / 1523 | M8 | S21 W04 | 1529 | 1529 | y | y | 1190 | 17 | |
| 20010410 / 0509 | X2 | S23 W09 | 0514 | 0514 | y | y | 2410 | 22 | |
| 20010411 / 1259 | M2 | S22 W27 | 1315 | 1316 | y | y | 1100 | 16 | multiple III-L candidates |
| 20010412 / 1015 | X2 | S19 W43 | 1030 | 1031 | y | y | 1180 | 14 | multiple III-L candidates |
| 20010415 / 1344 | X14 | S20 W85 | 1347 | 1349 | y | y | 1200 | 24 | |
| 20010420 / 0504 | M1 | N18 E63 | 0520 | 0520 | y | y | 5 | 5 | very weak III-L, possibly storm |
| 20010423 / 2020 | M4 | N14 E23 | 2028 | 2028 | y | y | 5 | 3 | bright III-L over ongoing storm |
| 20010423 / 1342 | M3 | N18 W09 | 1348 | 1348 | y | y | 860 | 6 | short II, multiple IIIs |
| 20010512 / 2326 | M3 | S17 E00 | 2334 | 2334 | y | y | nd3 | 13 | multiple candidate III-Ls |
| 20010520 / 0506 | M6 | SW Limb | 0608 | 0609 | y | y | 550 | 15 | strong SWF3 |
| 20010604 / 0806 | M2 | S18 E57 | 0813 | 0813 | y | y | 760 | 6 | III-L very similar to impulsive III group |
| 20010605 / 0444 | M2 | S18 E44 | 0452 | 0452 | y | y | 840 | 5 | III-L very similar to impulsive III group |
| 20010613 / 1134 | M8 | S29 E66 | 1140 | 1140 | y | y | 1110 | 12 | no RSTN data |
| 20010615 / 1004 | M6 | S26 E41 | 1022 | 1022 | y | y | 1090 | 7 | no RSTN data, multiple III-L candidates |
| 20010623 / 0623 | M1 | N10 E21 | 0636 | 0636 | y | y | 4 | 4 | could be 2 individual IIIs |
| 20010823 / 2358 | M3 | S18 E44 | 0008 | 0008 | y | y | 480 | 23 | weak but long in WAVES |
| 20010825 / 1624 | X5 | S17 E34 | 1631 | 1631 | y | y | 1400 | 20 | GOES onset uncertain |
| 20010827 / 0634 | M2 | E Limb | 0702 | 0702 | y | y | 2 | 2 | very late, weak |
| 20010828 / 1556 | M1 | M15 E65 | 1606 | 1606 | y | y | 480 | 12 | |
| 20010831 / 1037 | M2 | N15 E37 | 1041 | 1041 | y | y | 4 | 4 | GOES onset uncertain, short |
| 20010831 / 2240 | M3 | N14 E25 | 2247 | 2247 | y | y | 480 | 5 | gradual and complex rise phase |
| 20010903 / 1824 | M2 | E Limb | 1829 | 1829 | y | y | 1350 | 11 | GOES onset uncertain |
Table 1—Continued

| SXR Onset (Date UT) | SXR Class | SXR Location | III-L Location | III-L Type | CME | 1 MHz dur. | Comments |
|---------------------|-----------|--------------|----------------|-----------|-----|-----------|----------|
| 20010907 / 1528     | M1        | N19 W65      | 1541           | 1541      | y   | 490       | weak III-L |
| 20010909 / 1511     | M3        | E22 W22      | 1516           | 1516      | y   | 8         | extended impulsive III |
| 20010918 / 0005     | M1        | S32 W78      | 0034           | 0034      | y   | 9         | III-L is very late |
| 20010920 / 1815     | M1        | N09 W11      | 1838           | 1838      | y   | 450       | III-L late, high-frequency cutoff suggests over the limb, not from M1? |
| 20010924 / 1018     | X3        | S16 E23      | 1034           | 1034      | y   | 2400      | very gradual rise, onset uncertain |
| 20011001 / 0456     | M9        | W Limb       | 0520           | 0511      |     | 1410      | 18 |
| 20011009 / 1048     | M1        | S28 E08      | 1056           | 1056      | y   | 970       | multiple III-L candidates |
| 20011017 / 1119     | M1        | S17 W22      | 1144           | 1144      | y   | 470       | very late III-L |
| 20011019 / 0054     | X2        | N16 W18      | 0104           | 0104      | y   | 560       | artefacts in WAVES |
| 20011019 / 1622     | X2        | N15 W29      | 1628           | 1628      | y   | 900       | 30 SWF3 |
| 20011021 / 0512     | M1        | W Limb       | 0522           | 0522      |     | 530       | 4 weak SWF3, individual III? |
| 20011022 / 0034     | M1        | N17 W57      | 0045           | 0045      |     | 770       | 6 very short III-L |
| 20011022 / 1445     | M7        | S21 E18      | 1501           | 1340      |     | 27        | 27 |
| 20011022 / 1747     | X1        | S18 E16      | 1754           | 1754      |     | 620       | 25 long-lived narrowband feature at 1 MHz |
| 20011026 / 1430     | M2        | N07 E18      | 1434           | 1434      |     | 5         | GOES onset uncertain |
| 20011029 / 1110     | M4        | N12 E25      | 1114           | 1114      | y   | 600       | 5 confused by storm |
| 20011031 / 2136     | M1        | W Limb       | 2146           | 2146      |     | 6         | much brighter than storm |
| 20011104 / 1605     | X1        | N06 W18      | 1618           | 1810      |     | 36        | 36 |
| 20011109 / 1820     | M2        | S21 W42      | 1824           | 1825      | y   | nd3       | 18 |
| 20011117 / 0442     | M3        | S13 E42      | 0504           | 0504      | y   | 1380      | 32 bright at 1 MHz |
| 20011122 / 2020     | M4        | S25 W67      | 2024           | 2024      | y   | 1440      | 26 very similar to 1117 event |
| 20011122 / 2245     | X1        | S20 W40      | 2306           | 1440      |     | 25        | radio emission mostly from C6 precursor, appropriate GOES onset uncertain, CME definitely from X1 flare not C6. |
| 20011128 / 1630     | M7        | N04 E16      | 1634           | 1635      | y   | 500       | 16 horizontal features in WAVES data |
| 20011213 / 1424     | X6        | N16 E09      | 1437           | 1437      | y   | 860       | 10 |
| 20011226 / 0504     | M7        | N08 W54      | 0514           | 0514      | y   | 1450      | 20 1 MHz features not clearly fast-drift |
| 20011228 / 2002     | X3        | E Limb       | 2008           | 2008      | y   | 2220      | 21 very gradual |
| 20011229 / 09394     | M9        | S07 W85      | 1000           | 1000      | y   | 630       | 20 two peaks in GOES |
| 20011229 / 11544     | M1        | S26 E87      | 1204           | 1204      |     | 4         | weak III-L |

1 Type III-L events in italics are marginal events.
2 Duration of continuous emission at 1 MHz in minutes, estimated from figures. This may be longer than the duration of the Type III-L emission at 1 MHz.
3 Short–wave fadeouts (SWF) occur when a strong flare overhead produces high ionization in the lower layers of the atmosphere and frequencies above the normal ionospheric cutoff are strongly absorbed.
4 Event excluded from comparisons due to high SEP background level.
5 No LASCO CME data at the appropriate time.
| SEP Onset¹ | SEP max² | SEP assoc.³ | SXR/CME Location | Type II Location | Type II WAVES | CME (km s⁻¹) | Comment⁴ | Type III-L⁵ |
|------------|----------|-------------|-------------------|----------------|---------------|--------------|----------|------------|
| (Date UT) |          |             | SXR/CME (Date UT) | Type          | type          |              |          |            |
| 20010105 / 1740 | 3        | CME 0105 / 1700 | W Limb            | Slow rise      | m             | 830          |          |            |
| 20010110 / 2000 | 0.08     |              |                   |               |               |              |          |            |
| 20010115 / 1600 | 0.01     | CME 0114 / 0630 | NW Limb           | Slow rise      | n             | 945          |          |            |
| 20010121 / 0200 | 3        | M8 0129 / 2108 | S07 E46           | 2112           | 2122          | 1510         | Slow rise | y          |
| 20010126 / 1300 | 0.06     | C2 0126 / 1149 | S23 W57           | 1157           | 1206          | 930          | Slow rise | m          |
| 20010128 / 1540 | 8        | M2 0128 / 1540 | S04 W59           | 1558           | 1558          | 920          | Slow rise | m          |
| 20010211 / 0120 | 0.9      | C7 0211 / 0054 | N24 W57           | 0105           | 1180          |           | Slow rise | y          |
| 20010226 / 0610 | 2        | CME 0226 / 0530 | W Limb            | 850            |               | Slow rise     | n          |
| 20010308 / 1330 | 0.002    | M6 0308 / 1116 | N30 W18           | 1126           |               | 630          | Slow rise | n          |
| 20010310 / 0500 | 0.01     | M7 0310 / 0403 | N27 W42           | 0409           | 0416          | 820          | Slow rise | y          |
| 20010325 / 1200 | 0.3      | M3 0325 / 1103 | N21 E59           | 580            |               | Slow rise     | y          |
| 20010329 / 1015 | 60       | X2 0329 / 1000 | NW Limb           | 903            | 1012          | 940          | Fast rise | m          |
| 20010402 / 1140 | 0.4      | X1 0402 / 1054 | N15 W64           | 1110           | 1122          | 990          | Fast rise | y          |
| 20010404 / 2155 | 300      | X17 0402 / 2134 | N14 W82           | 2151           | 2159          | 2500         | Fast rise | y          |
| 20010409 / 1600 | 0.7      | M8 0409 / 1523 | S21 W04           | 1527           | 1542          | 1190         | Fast rise | y          |
| 20010410 / 0600 | 20       | X2 0410 / 0509 | S23 W09           | 0513           | 0522          | 2410         | Slow rise | y          |
| 20010412 / 1050 | 8        | X2 0412 / 1015 | S19 W43           | 1020           | 1035          | 1180         | Fast rise | y          |
| 20010415 / 1359 | 100      | X14 0415 / 1344 | S20 W85           | 1347           | 1357          | 1200         | Fast rise | y          |
| 20010418 / 0230 | 20       | CME 0418 / 0213 | W Limb            | 0217           | 0255          | 2470         | Fast rise | y          |
| 20010426 / 1320 | 0.3      | M8 0426 / 1306 | N17 W31           | 1335           |               | 840          | Fast rise | n          |
| 20010507 / 1215 | 5        | CME 0507 / 1206 | NW Limb           | 1220           |               | Fast rise     | n          |
| 20010520 / 0615 | 20       | M6 0520 / 0602 | NW Limb           | 0605           |               | 550          | Fast rise | y          |
| 20010530 / 1600 | 0.004    | CME 0530 / 0000 | W Limb            | 0012           | 2000          | Slow rise     | y          |
| 20010601 / 2030 | 0.05     | CME 0601 / 1730 | W Limb            | 800            |               | Fast rise     | n          |
| 20010604 / 1635 | 0.4      | C3 0604 / 1622 | N24 W59           | 1622           |               | 460          | Fast rise | y          |
| 20010611 / 1300 | 0.4      | CME 0611 / 0445 | SE Limb           | 1650           |               | Slow rise     | n          |
| 20010612 / 0545 | 0.05     |              |                   |                |               |             | Fast rise | n          |
| 20010615 / 0700 | 0.01     | C4 0615 / 0634 | S26 E48           | No              |               | Fast rise     | n          |
| 20010615 / 1040 | 0.02     | M6 0615 / 1004 | S26 E41           |               | 1090          | Fast rise     | y          |
| 20010615 / 1550 | 5        | CME 0615 / 1530 | W Limb            | 1700           |               | Fast rise     | y          |
| 20010619 / 0340 | 0.3      | CME 0619 / 0354 | NW Limb           | 0335           |               | Fast rise     | y          |
| 20010705 / 0930 | 0.005    |              |                   |               |               | Slow rise     |            |
| 20010712 / 0130 | 0.2      | CME 0712 / 0006 | SW Limb           | 740            |               | Fast rise     | n          |
| 20010719 / 1020 | 0.2      | M2 0719 / 0956 | SW Limb           | 1670           |               | Fast rise     | n          |
| 20010721 / 2000 | 0.002    | C6 0730 / 2039 | E Limb            | 2045           |               | no data       | Slow rise | n          |
| 20010809 / 1610 | 1        | CME 0809 / 1030 | W Limb            | 480            |               | Fast rise     | n          |
| 20010814 / 1200 | 15       |              |                   | no data         |               | Slow rise     |            |
| 20010816 / 0010 | 500      | CME 0815 / 2354 | SW Limb           | 2331           |               | 1600         | Fast rise | y          |
| 20010821 / 1120 | 2        | C3 0821 / 1036 | SW Limb           | 620            |               | Slow rise     | n          |
| 20010911 / 0130 | 0.02     | M3 0911 / 0448 | S28 E09           | 300            |               | Fast rise     | n          |
| 20010912 / 2330 | 0.06     | C9 0912 / 2106 | SW Limb           | 2139           |               | 670          | Fast rise | n          |
| 20010915 / 1150 | 5        | M2 0915 / 1106 | S21 W49           | 1129           | 1207          | 480          | Fast rise | n          |
| 20010917 / 1200 | 0.03     | M2 0917 / 0820 | S14 E04           | 0828           | 0834          | 1010         | Slow rise | n          |
| 20010918 / 0145 | 0.08     | M1 0918 / 0005 | S32 W78           |               |               | Fast rise     | m          |
| 20010919 / 0830 | 0.1      | C7 0919 / 0650 | SW Limb           | 0700           |               | 420          | Slow rise | m          |
| Date UT | Max | RA | DEC | Date UT | Max | RA | DEC | Type II | Type II | CME (km s<sup>-1</sup>) | Comment | Type III-L |
|---------|-----|----|-----|---------|-----|----|-----|---------|---------|---------------------|---------|-------------|
| 2001/10/24 | 1050 | 70 | X3 | 0924 / 1018 | S16 E23 | 1038 | 2400 | Fast rise | y |
| 2001/10/1 | 0800 | 70 | M9 | 1001 / 0456 | W Limb | 1405 | Slow (?) rise | m |
| 2001/10/5 | 1900 | 3 | CME | 1005 / 1000 | SW Limb | 1540 | Slow rise | y |
| 2001/10/9 | 0750 | 1 | C7 | 1009 / 0726 | W Limb | 0737 | Fast rise | y |
| 2001/10/9 | 1500 | 2 | M1 | 1009 / 1048 | S28 E08 | 1055 | 1110 | Slow rise | y |
| 2001/10/19 | 0140 | 5 | X2 | 1019 / 0054 | N16 W18 | 0101 | 0117 | 560 | Fast rise | y |
| 2001/10/19 | 1700 | 6 | X2 | 1019 / 1622 | N15 W29 | 1624 | 1639 | 900 | Fast rise | y |
| 2001/10/22 | 0100 | 0.05 | M1 | 1022 / 0034 | N17 W37 | 770 | Slow rise | m |
| 2001/10/22 | 1530 | 8 | M7 | 1022 / 1445 | S21 E18 | 1453 | 1505 | 1340 | Fast rise | y |
| 2001/11/4 | 1630 | 60 | X1 | 1104 / 1605 | N06 W18 | 1614 | 1627 | 1810 | Fast rise | y |
| 2001/11/9 | 1900 | 3 | M2 | 1109 / 1820 | S21 W42 | 1837 | 1841 | No data | Slow rise | y |
| 2001/11/17 | 0600 | 4 | M3 | 1117 / 0442 | S13 E42 | 0450 | 1380 | Slow rise | y |
| 2001/11/22 | 2045 | 8 | M4 | 1122 / 2020 | S25 W67 | 2022 | 1445 | Fast rise | y |
| 2001/11/22 | 2315 | 70 | X1 | 1122 / 2245 | S20 W40 | 2231 | 2235 | 1435 | Fast rise | m |
| 2001/11/25 | 2040 | 11 | | | | | Slow rise | |
| 2001/11/21 | 1220 | 0.3 | CME | 1211 / 1000 | W Limb | 890 | Slow rise | n |
| 2001/11/21 | 1730 | 0.2 | M4 | 1214 / 0842 | N06 E90 | 0853 | 1510 | Slow rise | n |
| 2001/12/18 | 2100 | 0.02 | CME | 1218 / 1830 | W Limb | 1030 | Slow rise | n |
| 2001/12/25 | 2100 | 0.2 | CME | 1225 / 1130 | SE Limb | 1123 | 1770 | Slow rise | m |
| 2001/12/26 | 0525 | 700 | M7 | 1226 / 0504 | N08 W54 | 0455 | 0517 | 1450 | Fast rise | y |
| 2001/12/28 | 2200 | 20 | X3 | 1228 / 2002 | E Limb | 1959 | 2025 | 2200 | Slow rise | y |
| 2001/12/30 | 1120 | 30 | | | | | Slow rise | |

1. Events in italics are marginal SEP events. The onset time is the earliest time that either energetic protons or electrons are detected at Earth distance, with an uncertainty of order 10 minutes for events with a rapid rise but typically much larger uncertainties for events with a gradual rise.

2. Maximum count rate measured by ERNE in the 13–40 MeV range in cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>

3. Associations in italics are marginal associations. The times reported for associated events are the GOES onset time for flares, as described in the text, or the first reported detection in the case of CMEs.

4. Comments in italics are events during ERNE data gaps that were determined from GOES proton data.

5. “y” denotes a “good” Type III-L event, “m” denotes a marginal event, “n” denotes absence of a Type III-L.
Table 3. **SEP exclusion periods**

| Interval       | Interval       |
|----------------|----------------|
| Jan-28 23:47 to Jan-29 12:23 | Sep-24 12:50 to Sep-25 21:01 |
| Mar-29 19:57 to Mar-30 00:56 | Sep-25 23:25 to Sep 30 20:00 |
| Mar-30 02:05 to Mar-30 13:22 | Oct 01 12:00 to Oct-05 11:45 |
| Mar-30 17:37 to Mar-30 17:46 | Oct-06 18:35 to Oct-07 23:29 |
| Apr-03 00:10 to Apr-05 22:22 | Oct-19 18:14 to Oct-20 13:25 |
| Apr-10 10:00 to Apr-12 06:00 | Oct-22 18:38 to Oct-23 00:09 |
| Apr-12 12:00 to Apr-13 01:50 | Nov-04 17:46 to Nov-05 16:12 |
| Apr-15 15:02 to Apr-17 02:41 | Nov-06 05:35 to Nov-09 12:00 |
| Apr-18 03:31 to Apr-19 12:58 | Nov-19 08:50 to Nov-20 06:28 |
| May-07 19:23 to May-08 08:23 | Nov-23 00:00 to Nov-24 02:33 |
| Jun-15 17:19 to Jun-15 22:54 | Nov-24 08:25 to Nov-25 16:00 |
| Aug-10 08:58 to Aug-10 14:00 | Nov-25 23:00 to Nov-28 05:35 |
| Aug-16 01:00 to Aug-18 14:00 | Dec-26 06:28 to Dec-28 14:18 |
| Sep-15 13:31 to Sep-15 17:31 | Dec-29 02:13 to Dec-30 11:09 |
Table 4. Association of Type III-L and Type II\(^1\) bursts with SEP events

| Association with good SEP events | E90-E30 | E30-W30 | W30-W90 |
|----------------------------------|---------|---------|---------|
| Good Type III-L with good SEPs/Total good Type III-L | 5/16    | 6/21    | 7/13    |
| Marginal Type III-L with good SEPs/Total | 0/3     | 1/4     | 3/9     |
| Type II with good SEPs/Total Type II | 3/16    | 7/30    | 10/17   |
| Good SEP (good association) E-W distribution | 6       | 8       | 27      |

| Association with marginal-association (mA) SEP events | E90-E30 | E30-W30 | W30-W90 |
|------------------------------------------------------|---------|---------|---------|
| Good Type III-L with mA SEPs/Total good Type III-L | 0/16    | 1/21    | 0/13    |
| Marginal Type III-L with mA SEPs/Total | 0/3     | 0/4     | 0/9     |
| Type II with mA SEPs/Total Type II | 1/16    | 2/30    | 0/17    |
| mA SEP E-W distribution (good or marginal SEP) | 5       | 3       | 6       |

| Association with marginal SEP (mSEP) events | E90-E30 | E30-W30 | W30-W90 |
|------------------------------------------|---------|---------|---------|
| Good Type III-L with mSEPs/Total good Type III-L | 0/16    | 1/21    | 1/13    |
| Marginal Type III-L with mSEPs/Total | 0/3     | 0/4     | 3/9     |
| Type II with mSEPs/Total Type II | 0/16    | 2/30    | 2/17    |
| mSEP E-W distribution (good or marginal assoc.) | 2       | 3       | 7       |

| Association with all SEP events | E90-E30 | E30-W30 | W30-W90 |
|---------------------------------|---------|---------|---------|
| Good Type III-L with all SEPs/Total good Type III-L | 5/16    | 8/21    | 8/13    |
| Marginal Type III-L with all SEPs/Total | 0/3     | 1/4     | 6/9     |
| Good Type III-L, 1 MHz duration > 10 min/Total | 3/10    | 8/14    | 7/9     |
| Marginal Type III-L, 1 MHz duration > 10 min/Total | 0/0     | 1/1     | 4/4     |
| Type II with all SEPs/Total Type II | 4/16    | 10/30   | 12/17   |
| SEP E-W distribution | 11      | 13      | 38      |

\(^1\)Type II bursts are limited to those observed from the ground and produced by MX flares, excluding the high–particle–background periods of Table 3.
Table 5.  **Association of SEP events with radio bursts**

| Quality                        | Good IIIL | Mar. III | No III | III/I Total | II/Total<sup>1</sup> |
|-------------------------------|-----------|----------|--------|-------------|----------------------|
| Good SEP/good association     | 24        | 7        | 10     | 31/41       | 31/41                |
| Marginal SEP/good association | 3         | 3        | 1      | 6/7         | 4/7                  |
| Good SEP/marginal association | 2         | 1        | 6      | 3/9         | 5/9                  |
| Marginal SEP/marginal association | 1       | 0        | 4      | 1/5         | 2/5                  |
| Totals                        | 30        | 11       | 21     | 41/62       | 42/62                |

<sup>1</sup>In this Table Type II bursts include events in which Type IIs occurred either in ground–based data or in WAVES spectra, or both.

Table 6.  **Fast–onset SEP events**

| Flare/CME (SXR onset) | SEP onset (corrected)<sup>1</sup> | III-L onset | CME - first observation | CME speed (km/s) | Location       |
|-----------------------|------------------------------------|-------------|-------------------------|-----------------|----------------|
| 20010329 / 10:00      | 10:09                              | 10:04       | 10:26                   | 940             | N20W19         |
| 20010415 / 13:44      | 13:53                              | 13:50       | 14:06                   | 1200            | S20W85         |
| 20010418 / 02:12      | 02:24                              | 02:20       | 02:30                   | 2460            | Beyond W Limb |
| 20010604 / 16:12      | 16:29                              | 16:22       | 16:30                   | 460             | N24W59         |
| 20010615 / 15:30      | 15:44                              | 15:35       | 15:56                   | 1700            | W Limb         |
| 20010815 / 23:54      | 00:04                              | 00:02       | 23:54                   | 1580            | SW Limb        |
| 20011109 / 07:26      | 07:44                              | 07:34       | 08:06                   | 530             | W Limb         |
| 20011226 / 05:04      | 05:19                              | 05:14       | 05:30                   | 1450            | N08W54         |

<sup>1</sup>This is the latest time that the first 200 keV electrons could have left the Sun measured in the Earth observing frame. It results from correcting the actual arrival time at Earth by subtracting 6 minutes to compensate for the minimum possible difference in propagation time between 200 keV electrons following a minimum (1.2 AU) Parker spiral path and direct-path electromagnetic radiation.