DECIOMETRIC TYPE III RADIO BURSTS
AND ASSOCIATED HARD X-RAY SPIKES

B. R. DENNIS
Goddard Space Flight Center, Greenbelt, M.D., U.S.A.

A. O. BENZ
Institute of Astronomy, ETH, Zürich, Switzerland

M. RANIERI
Instituto Astrofisica Spaziale, CNR, Frascati, Italy
and

G. M. SIMNETT
University of Birmingham, Birmingham, England

(Received 2 June; in revised form 19 October, 1983)

Abstract. A detailed comparison is made between hard X-ray spikes and decimetric type III radio bursts for a relatively weak solar flare on 1981 August 6 at 10:32 UT. The hard X-ray observations were made at energies above 30 keV with the Hard X-Ray Burst Spectrometer on the Solar Maximum Mission and with a balloon-born coarse-imaging spectrometer from Frascati, Italy. The radio data were obtained in the frequency range from 100 to 1000 MHz with the analog and digital instruments from Zürich, Switzerland. All the data sets have a time resolution of \( \sim 0.1 \) s or better. The dynamic radio spectrum shows many fast drift type III radio bursts with both normal and reverse slope, while the X-ray time profile contains many well resolved short spikes with durations of \( \leq 1 \) s. Some of the X-ray spikes appear to be associated in time with reverse-slope bursts suggesting either that the electron beams producing the radio bursts contain two or three orders of magnitude more fast electrons than has previously been assumed or that the electron beams can trigger or occur in coincidence with the acceleration of additional electrons. One case is presented in which a normal slope radio burst at \( \sim 600 \) MHz occurs in coincidence with the peak of an X-ray spike to within \( 0.1 \) s. If the coincidence is not merely accidental and if it is meaningful to compare peak times, then the short delay would indicate that the radio signal was at the harmonic and that the electrons producing the radio burst were accelerated at an altitude of \( \sim 4 \times 10^6 \) cm. Such a short delay is inconsistent with models invoking cross-field drifts to produce the electron beams that generate type III bursts but it supports the model incorporating a MASER proposed by Sprangle and Vlahos (1983).

1. Introduction

Type III radio bursts and hard X-ray bursts are both produced by electrons with similar energies and both tend to occur during the impulsive phase of solar flares with fluctuations on time scales of \( < 1 \) s. Consequently, many comparative studies have been conducted in an attempt to understand the relationship between the two phenomena and between the electrons that produce them. Most of the previous work has concentrated on groups of metric type III bursts and multiple X-ray spikes (Kane and Raoult, 1981; Kane et al., 1980; Kane, 1981; Kane et al., 1982). Kane et al. (1982) claim to have
established a clear one-to-one association between single type III bursts and hard X-ray peaks, but in general this is difficult to do especially for the more intense flares with a multiplicity of type III bursts and X-ray peaks. Thus, most of the correlation data are of a statistical nature. In this paper we present digital radio and hard X-ray data with \( \leq 0.1 \) s time resolution on a relatively weak event, where the problem of identifying associated X-ray spikes and type III bursts is simplified. Moreover, the type III bursts are in the decimetric wavelength range, where the statistical data have shown better correlations with X-ray bursts (Kane, 1981).

Previous observations have shown that there appear to be two distinct classes of flare-associated fast-drift radio bursts: (i) the classical type III bursts that start at meter (or occasionally decimeter) wavelengths and extend sometimes to kilometer wavelengths, and (ii) decimetric type III bursts usually confined to the 400 to 800 MHz frequency range (Young et al., 1961; Kundu et al., 1961; Kundu, 1965).

Both the metric and the decimetric classes of type III bursts are believed to be produced by beams of 10 to 100 keV electrons moving through the corona. The majority of bursts in both classes drift towards lower frequencies and are produced by beams moving from higher to lower densities; that generally means that they are moving upwards in the corona. The more rare reverse slope or RS bursts drift towards higher frequencies and are produced by beams moving from lower to higher densities i.e. generally downwards in the corona. Some bursts show both normal and reverse slopes at different times. These are the U-bursts and mixed-slope bursts. A U-burst results when an electron beam moves along a closed magnetic arch in the corona, firsts up one side, then over the top and down the other side. The interpretation of the other mixed slope bursts is not so clear and may have to involve more than one beam in certain cases.

One possible explanation for RS bursts is that they are the second branch of a U-burst. It is postulated that the first leg of the U-burst is not observed for some reason (Tarnstrom and Zehntner, 1975; Tang and Moore, 1982). LaBonte (1976) suggested that the first leg may be obscured by a coronal density enhancement in the line of sight. Another possible explanation of RS bursts is that the electrons are accelerated or are stored high in the corona prior to their precipitation into the lower corona (LaBonte, 1976; Simnett, 1982).

It is not clear why there should be a separate class of decimetric type III bursts. Certainly, we know from their higher starting frequencies that they originate from regions of higher densities, presumably lower in the corona. The electron beams are, consequently, more likely to be on closed field lines. This set of circumstances may be sufficient to explain their limited frequency range, shorter duration, higher fraction of reverse slope and mixed slope bursts, and their higher correlation with X-ray bursts (Kundu, 1965; Kane, 1981; Benz et al., 1983b).

Estimates of the number of electrons required to produce a type III burst are difficult to obtain. Wentzel (1982) used a value of \( 10^{33} \) electrons in his discussion of possible theories of type III bursts. Observationally, in situ observations in Earth orbit of the electrons that produce the type III bursts extending to frequencies of 40 to 60 kHz have shown that the beams contain \( \sim 10^{33} \) electrons with energies between 10 and 100 keV.
(Lin, 1974). Kane (1972) showed from upper limits on the flux of thin-target X-rays that less than $10^{34}$ electrons above 22 keV are required to produce a strong type III burst at 500 MHz.

The hard X-ray bursts may also be generated by beams of fast electrons but in this case the beams are assumed to move downwards into the lower corona. A comparison of the numbers of electrons involved shows immediately that the same electron beams do not produce both the observed X-ray spikes and the type III bursts. In order to produce a 1 s wide X-ray spike detectable with current instrumentation, an electron beam must contain $\geq 10^{35}$ electrons with energies above 20 keV, i.e. at least two orders of magnitude more than the number in the beams producing the metric type III's. We have no reason to suspect that the decimetric type III's should require a greater number of electrons.

One might expect a better chance of detecting X-rays from electron beams that produce RS bursts since they must penetrate the lower corona. Indeed, Tang and Moore (1982) report Hα brightenings at sites remote from the main flare in coincidence with RS bursts. They attribute the brightenings to the effect of the electron beams impacting the lower corona and the subsequent thermal conduction along the same closed magnetic flux tube from the flare site. Also, Crannell et al. (1978) reported an X-ray spike in coincidence with what appeared to be a decimetric RS burst making up the second leg of a U-burst (Simnett, 1982). Thus, it may be possible that RS decimetric type III bursts indicate the presence of significantly higher numbers of electrons than had previously been thought. An alternative explanation is that the electron beam that produces the RS burst is capable of triggering an already metastable loop as it reaches the lower corona. Further magnetic energy is then released and more electrons are accelerated to produce the observed X-ray spike and type III bursts.

Correlation studies of X-ray bursts and decimetric type III bursts can provide unique information on the dynamics of the electron populations produced during the impulsive phase of flares. Decimetric type III bursts may well originate closer to the source of X-rays than do metric type III's. Consequently, Kane's conclusion that the radio and X-ray data are consistent with the different electron populations being accelerated in a single process can be tested more precisely with higher time resolution than is possible for metric type III's. The problem of the origin and nature of beams producing RS bursts can also be addressed advantageously by studies of decimetric type III's since they contain a far greater fraction of RS bursts than do metric type III's.

In this paper, we begin to investigate in detail the relationship between X-ray bursts and decimetric type III's with a view to understanding the dynamics of the electron populations and the possible acceleration mechanisms. We have selected a relatively simple event for which digital radio and X-ray data are available with a time resolution of 0.1 s or better. Several RS bursts are apparently associated with X-ray spikes and possibly also with subsequent normal-slope type III bursts. An X-ray spike and a normal-slope type III burst were observed in coincidence to within 0.1 s thus suggesting that the radio emission was at the harmonic and that models of type III bursts that predict delays of 1 to 2 s are not valid for this particular event.
Fig. 1. Radio and X-ray fluxes as a function of time. Top: Dynamic radio spectrum of the burst recorded on film with the Zürich DAEDALUS analog spectrometer. The time is accurate to 0.25 s. The thick vertical white bar at 10°32'00" is a timing marker. The horizontal white lines result from interference at fixed frequencies. Middle: X-ray counting rate in the energy range from 30 to 527 keV measured with the HXRBS on SMM. The time resolution is 0.128 s and the ± 1σ error bars were computed from the square-root of the observed number of counts. The numbered intervals refer to the 7 X-ray spikes or groups of spikes discussed in the text. Interval 4 is shown on an expanded scale in Figure 4 and interval 6 is shown in Figure 5. Bottom: X-ray counting rate in the energy range from 20 to 150 keV measured with the balloon-borne proportional counter from Frascati, Italy. The time resolution is 0.125 s and the ± 1σ error bars were computed from the square-root of the observed number of counts.
2. Observations

We present observations of a relatively weak but impulsive flare on 1981 August 6 at 10h32m UT, which showed a remarkable array of well correlated hard X-ray and radio features (Figure 1). The event was barely detectable in soft X-rays with the GOES satellite reaching less than the C2 level in the 1–8 Å range, i.e. $< 2 \times 10^{-6}$ W m$^{-2}$. A small Hz flare was observed from active region 3257 (Boulder number) at a location of S 08 E 52 and with a peak brightness at 10h29m46s $\pm$ 28s UT (Tang, private communication). This is 1–2 min before the start of the hard X-ray event thus making any connection uncertain. (The general data on the flare, here and below, were taken from Solar-Geophysical Data, 1982.)

2.1. Instrumentation

The radio data were obtained with the two Zürich spectrometers operating between 100 and 1000 MHz (Perrenoud, 1981, 1982). The analog instrument, DAEDALUS, recorded data on 35 mm film with a time resolution of 0.25 s over the full frequency range. The computer-controlled digital instrument, IKARUS, recorded data on magnetic tape in selected frequency ranges with a time resolution of 0.1 s. During the observations reported here, the frequency ranges of interest were 229–394, 425–464, 580–646, and 725–740 MHz.

The hard X-ray observations were made with two separate instruments. The Hard X-Ray Burst Spectrometer (HXRBS) on the Solar Maximum Mission (SMM) provided 15 channel spectra from 30 to 527 keV every 128 ms and counting rates over the same energy range every 10 ms (Orwig et al., 1980). The balloon-borne Frascati telescope (Cardini et al., 1983) consists of a position-sensitive proportional counter and a pseudorandom mask. It gives the counting rate above 20 keV every 15.625 ms and the location of the X-ray source to within $\sim 1^\circ$. This confirmed that the X-rays were in fact from the Sun. The SMM was in Earth orbit at an altitude of 540 km over the Gulf of Mexico and the Frascati telescope was flown on a balloon at an altitude of 130000 feet over France. The difference in location resulted in the negligible time difference of 21 ms.

2.2. The radio data

The radio event was confined to the decimetric range from > 200 to $\leq 880$ MHz and was observed from 10h25m30s UT until 10h35m at 536 MHz at Ondřejov. The peak flux recorded in Zürich was $380 \times 10^{-22}$ W m$^{-2}$ Hz$^{-1}$ at 443 MHz at 10h31m30s. No activity was detected with the Zürich spectrometers until 10h28m49s with the appearance of an isolated type III burst. The final activity was a series of decimetric blips at 10h33m. Figure 1 shows the analog record obtained by the Daedalus spectrometer of that part of the event associated with the X-ray bursts. It was classified as DCIM emission at Zürich since it occurred in the decimetric range and the bursts had a narrow bandwidth (the half power bandwidth of single events was less than 100 MHz). Such activity has been termed ‘blips’ by Benz et al. (1981) and Fürst et al. (1982). Blips with both normal and reverse slopes can be clearly resolved. Table I gives the times, frequency ranges and drift rates of the identifiable bursts. Note that the isolated type III burst at 10h28m49s
TABLE I
Characteristics of decimetric bursts and hard X-ray spikes for the event on 1981, August 6

<table>
<thead>
<tr>
<th>Time</th>
<th>Frequency MHz</th>
<th>Drift rate MHz s⁻¹</th>
<th>Radio</th>
<th>X-rays</th>
<th>Time of peak</th>
<th>Width s</th>
<th>HXRBS c s⁻¹</th>
<th>Frascati c s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:28:45</td>
<td>390–420</td>
<td>&gt;400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>320–370</td>
<td>&gt;400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>240–290</td>
<td>−27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:31:31</td>
<td>430–560</td>
<td>+180</td>
<td>10:31:32.2</td>
<td>0.1</td>
<td>120</td>
<td>256</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10:31:33.7</td>
<td>0.1</td>
<td>130</td>
<td>−</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10:31:34.3</td>
<td>+150</td>
<td>34.1</td>
<td>1</td>
<td>120</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10:31:35.0</td>
<td>0.1</td>
<td>110</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35.8</td>
<td>0.5</td>
<td>100</td>
<td>296</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36.5</td>
<td>0.1</td>
<td>120</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>37.6</td>
<td>0.5</td>
<td>150</td>
<td>288</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>38.5</td>
<td>0.5</td>
<td>120</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>420–600</td>
<td>+131</td>
<td>42.0</td>
<td>1.0</td>
<td>270</td>
<td>368</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:31:38.7–41.8</td>
<td>420–600</td>
<td>+131</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>43.8–43.9</td>
<td>−350</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>44.4–44.6</td>
<td>650–710</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:31:51.1–51.2</td>
<td>430–720</td>
<td>−700</td>
<td>10:31:49.8</td>
<td>0.2</td>
<td>150</td>
<td>248</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51.8</td>
<td>600–740</td>
<td>&gt;700</td>
<td>51.0</td>
<td>2.0</td>
<td>280</td>
<td>384</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>52.5</td>
<td>440–480</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:31:58</td>
<td>410–430</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:32:05</td>
<td>400–470</td>
<td>−365</td>
<td>10:32:05</td>
<td>0.1</td>
<td>140</td>
<td>−</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>07</td>
<td>390–460</td>
<td>−490</td>
<td>07</td>
<td>0.2</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:32:10</td>
<td>460–470</td>
<td>?</td>
<td>10:32:10.5</td>
<td>0.1</td>
<td>90</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.4</td>
<td>570–740</td>
<td>+247</td>
<td>11.5</td>
<td>1.5</td>
<td>130</td>
<td>272</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td>390–460</td>
<td>−60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>390–460</td>
<td>−80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.7</td>
<td>390–460</td>
<td>−240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.0–13.8</td>
<td>530–660</td>
<td>+164</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:32:16.4</td>
<td>420–460</td>
<td>?</td>
<td>10:32:16.6</td>
<td>0.1</td>
<td>120</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.2</td>
<td>450–460</td>
<td>?</td>
<td>17.0</td>
<td>1.5</td>
<td>150</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.0</td>
<td>400–460</td>
<td>330</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.7</td>
<td>400–470</td>
<td>−990</td>
<td>20.0</td>
<td>1</td>
<td>280</td>
<td>368</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>20.9</td>
<td>590–700</td>
<td>+330</td>
<td>21.0</td>
<td>0.8</td>
<td>420</td>
<td>544</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.5</td>
<td>590–650</td>
<td>+267</td>
<td>22.3</td>
<td>1</td>
<td>450</td>
<td>584</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.2</td>
<td>390–460</td>
<td>&gt;500</td>
<td>23.1</td>
<td>0.5</td>
<td>340</td>
<td>536</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.5</td>
<td>400–430</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Numbers in this column refer to the intervals containing the 7 X-ray spikes or groups of spikes discussed in the text. Radio and X-ray data for interval No. 4 are plotted in Figure 4 and data for interval No. 6 are plotted in Figure 5.
is not shown in Figure 1 but the drift rate changes dramatically from $-400\ \text{MHz s}^{-1}$ at frequencies between 320 and 370 MHz to $-27\ \text{MHz s}^{-1}$ between 240 and 290 MHz. A gap of $\sim 150\ \text{s}$ exists between this burst and the next sign of activity: two RS-bursts starting at $10^h31^m31^s$ (see Figure 1). This commencement of activity with RS-bursts is curious but not unprecedented (Slottje, private communication). Drift rates of 100 to 500 MHz s$^{-1}$ can be measured for most of the subsequent bursts except for the burst at $10^h31^m51^s$ where a drift rate of $\gtrsim 700\ \text{MHz s}^{-1}$ is measured.

2.3. **The X-ray Data**

The counting rates of the HXRBS and of the Frascati telescope are plotted as a function of time in Figure 1 for direct comparison with the dynamic radio spectrum. Most of the X-ray spikes and other features appear in both time profiles, thus confirming their common solar origin. The spikes appearing in only one data set, e.g. the spike at $10^h32^m05^s$ in the HXRBS data set, may be instrumental resulting from electronic saturation following a cosmic ray interaction in the detector. For convenience we will concentrate on the HXRBS time profile and use the Frascati data to confirm or reject individual features.

No X-rays above 30 keV were detected with either instrument at the time of the isolated type III burst at $10^h28^m45^s$. The first hard X-rays were not detected until

![Diagram](image-url)

**Fig. 2.** Results of power-law fits to the deconvolved HXRBS spectral data plotted as a function of time. The $\pm 1\sigma$ error bars are based on the observed numbers of counts in each interval.
10\textsuperscript{h}31\textsuperscript{m}32\textsuperscript{s}, the time of the first RS-burst. The highest counting rate of over 400 counts s\textsuperscript{-1} occurred at 10\textsuperscript{h}32\textsuperscript{m}22\textsuperscript{s}. Three or four peaks separated by \(\sim 1\) s are well resolved during the \(\sim 9\) s duration of this major increase in rate. All significant and resolved X-ray peaks are listed in Table I with an indication of possible correlations with radio bursts.

The X-ray spectra obtained from the HXRBS 15-channel counting-rate data were fitted with a simple power-law expression of the form

\[
dN(E)/dE = A(E/50)^{-\gamma} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1},
\]

where \(dN(E)/dE\) is the differential photon flux incident on the detector, \(E\) is the photon energy in keV, and \(A\) and \(\gamma\) are parameters determined from the least-squares fitting procedure. Plots of \(A\) and \(\gamma\) versus time are shown in Figure 2, and two spectra obtained at different times during the event are shown in Figure 3. The value of \(\gamma\) lies between 3 and 6 for the whole event, a typical range for hard X-ray bursts. Assuming that the X-rays were produced in thick-target interactions, then the total number of electrons above 25 keV involved in the flare is estimated to be \(5 \times 10^{35}\) with a total energy of \(10^{27}\) ergs.

2.4. RADIO AND X-RAY CORRELATIONS

A total of 7 X-ray spikes or groups of spikes are identified in Figure 1. These are now discussed in detail. The suggested correlations with the type III bursts are indicated in Table I.

![Graph](link)

Fig. 3. Deconvolved HXRBS spectra at two different times during the flare. ○ 10\textsuperscript{h}32\textsuperscript{m}11.2\textsuperscript{s}–10\textsuperscript{h}32\textsuperscript{m}11.6\textsuperscript{s}, ○ 10\textsuperscript{h}32\textsuperscript{m}21.5\textsuperscript{s}–10\textsuperscript{h}32\textsuperscript{m}22.5\textsuperscript{s}. The vertical lines are \(\pm 1\sigma\) error bars derived from the observed numbers of counts. The horizontal lines indicate the channel widths. The least-squares power-law spectrum is drawn through each set of data points.
(1) The first X-ray spike, at $10^{h}31^{m}32.2^{s}$, is labelled 1 in Figure 1. It was $\leq 128$ ms wide and occurred 0.7 s after the first RS burst traversed the 500 MHz level. Unfortunately, this spike is not confirmed in the Frascati data, possibly because it is so weak. Also, the radio data are not digital at this time so that the timing is uncertain to $\sim 0.25$ s. The drift rate is $\sim 180$ MHz s$^{-1}$, relatively low compared to the average value for type III bursts of 700 MHz s$^{-1}$ at 550 MHz quoted by Kundu (1965). The total number of electrons above 20 keV required to produce the X-ray spike (if it is of solar origin) assuming thick-target interactions is $4 \times 10^{33}$.

(2) The second X-ray spike, again $\sim 128$ ms wide, also occurs in close temporal proximity to a much more intense type III-RS burst although in this case apparently 0.5 s before the RS burst crosses the 500 MHz level. A slightly wider X-ray burst follows immediately afterwards, however, with a width at its base of $\sim 1$ s and a similar amplitude. The total number of electrons above 20 keV required to produce the X-ray spike by thick-target interactions is $4 \times 10^{34}$.

(3) The X-ray flux continues at an elevated level of $\sim 100$ c s$^{-1}$ between $10^{h}31^{m}35^{s}$ and $10^{h}31^{m}44^{s}$ with a major spike at $10^{h}31^{m}42^{s}$. Several reverse drift bursts are evident in this time interval together with a prominent normal drift burst crossing the 450 MHz level at $10^{h}31^{m}43.1^{s}$. The 1.1 s delay from the peak time of the X-ray spike is consistent with the electron travel time to the altitude at which the plasma frequency is 450 MHz, i.e. $\sim 10^{10}$ cm, assuming a velocity of 0.3 c.

(4) Little further X-ray or radio emission is evident until $10^{h}31^{m}51^{s}$ when a relatively strong X-ray spike and two or three type III bursts occur in coincidence. An expanded view of the X-ray and radio fluxes for 5 s about this time is shown in Figure 4 to highlight the coincidence to within 0.1 s of the radio peak at the 616 MHz level and the hard X-ray peak. The X-ray flux begins to rise a second or more before any increase is seen in the radio signal. The HXRBS memory data with 10 ms time resolution plotted at the bottom of Figure 4 show a single high point 0.8 s before the start of the radio burst. This ultrafast spike results from 8 counts when $\leq 2$ were expected in the 10 ms interval. This large a fluctuation above the expected number has a probability of occurrence of $< 1$ in 1000 according to Poisson statistics. If this spike is of solar origin, it would be the fastest variation ever reported in hard X-rays, a factor of 2 to 4 faster than the fluctuations reported by Kiplinger et al. (1983). Unfortunately, we cannot rule out the possibility of an instrumental cause for this single-point spike. Such spikes are occasionally seen in the HXRBS high time resolution data when no flare is occurring as the result of cosmic-ray interactions. Nevertheless, it occurs at an intriguing time when the lower time resolution data show a small peak lasting 0.3 to 0.4 s.

Significant and believable fluctuations do occur during the time interval covered in Figure 4 on time scales of 20 to 50 ms. The rise and fall of the peak in coincidence with the radio bursts at $10^{h}31^{m}51^{s}$ both occur in $\leq 50$ ms and a sharp spike lasting 20 to 30 ms occurs at $10^{h}31^{m}51.7^{s}$.

The radio burst at 616 MHz begins to rise $\sim 0.2$ s before the rapid rise in the X-ray flux to its peak value. The radio and X-ray peaks, however, occur simultaneously to within the 0.1 s time resolution of the data. The 10 ms memory plot does not have high
Fig. 4. An expanded version of the five-second interval (interval No. 4 in Figure 1) centered on the X-ray peak at 10h31m51s showing the radio fluxes at three different frequencies and the HXRBS X-ray counting rates with two different time resolutions. The bottom plot is the number of counts in the energy range from 30 to 527 keV recorded in each 10 ms interval. Note that the single high point at 10h31m49.8s may be instrumental. The error bars on the 30–137 keV count rates are ± 1σ obtained from the square-root of the observed number of counts in each 128 ms interval.
enough counts to define the peak time more precisely but it does show that the X-ray peak is not narrower than \( \sim 0.25 \) s.

It is difficult to interpret the radio spectrum during this time interval but it appears from close examination of the original film used to make Figure 1 that there are two closely spaced type III bursts. The first starts at \( \sim 700 \) MHz and is seen in Figure 4 as the first peak at 616 MHz in close coincidence with the X-ray peak. It extends down to 430 MHz with an average drift rate of \( -700 \) MHz s\(^{-1}\). The second burst starts at \( \geq 740 \) MHz, 0.8 s after the first, and is seen in Figure 4 as the single peak at 734 MHz and the second peak at 616 MHz. The burst extending from 480 to 440 MHz, a further 1.4 s later, may be a third separate burst or it could be the extension of the second burst down to these frequencies, in which case the average drift rate would be \(-280\) MHz s\(^{-1}\). Thus, although the radio bursts are not clearly distinguished even with the 0.1 s time resolution, we believe that this time interval contains a primary and a secondary type III burst similar to those reported by Benz et al. (1982).

The spectrum of the X-ray spike at the time is not significantly harder or softer than the spectrum at other times although there is a tendency to soften through the burst with \( \gamma \) changing from 3 \( \pm 1 \) to 5.2 \( \pm 0.8 \) in \( \sim 3 \) s (see Figure 2).

(5) Two X-ray spikes occur at \( 10^3 \)32\(^m\)05\(^s\) and \( 10^3 \)32\(^m\)07\(^s\) with two or more type III bursts in the same 2 s interval. Note that the first of these spikes is not confirmed by the Frascati data, but the HXRBS memory data suggest that it is not instrumental since it is \( \sim 0.1 \) s wide. Again there is some ambiguity in the drift rates from the digital data for these relatively short bandwidth bursts, possibly caused by multiple bursts occurring in a short time interval.

(6) A five-second interval centered at \( 10^3 \)32\(^m\)11.5\(^s\) is plotted in Figure 5 to show the temporal relationship between the X-ray peak at this time and the radio bursts. The spectrum of the X-ray peak is shown in Figure 3. It is consistent with a power law with a similar spectral index \( (\gamma = 4) \) to that measured throughout the rest of the flare (see Figure 2). A clearly resolved RS burst crossing the 734 MHz level at \( 10^3 \)32\(^m\)11.3\(^s\) precedes the X-ray spike by \( (0.2 \pm 0.1) \) s. A group of three normal-slope type III bursts cross the 450 MHz level in a span of 2 s immediately following this spike. A strong RS burst crosses the 616 MHz level at \( 10^3 \)32\(^m\)13.4\(^s\) but there is no indication of a corresponding X-ray spike at this time or of any following normal-slope bursts.

(7) The final grouping of bursts corresponds to the period including the highest X-ray counting rate from \( 10^3 \)32\(^m\)16\(^s\) to the end of the event. This time profile is typical of a flare, with three or four clearly resolved peaks followed by a more gradual exponential decay. Four or five normal-slope type III bursts occur during this period together with two weak RS bursts. The number of bursts and their close temporal proximity make it difficult to be sure of the correlation between a given X-ray spike and any of the type III bursts. The spectral fits show a hardening trend with \( \gamma \) decreasing from \( 5.2 \pm 0.6 \) at the start of the burst to \( 3.5 \pm 1 \) at the end (see Figure 2). The number of electrons above 20 keV required to produce the observed X-ray flux in this interval by thick-target interactions is \( \sim 4 \times 10^{35} \), whereas we can assume that \( 10^{32} - 10^{33} \) electrons are required to produce each type III burst. Thus, we get that \( \lesssim 1\% \) of the electrons accelerated in

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
the flare appear in the beams producing the type III bursts, a result similar to that previously obtained.

3. Discussion

We do not have a detailed understanding of the dynamic radio spectrum shown in Figure 1. In particular, we do not know why the emission, that is evidently from electron beams, should extend over such short bandwidths. The overall spectrum does, however, suggest turbulence at densities corresponding to plasma frequencies of 400 to 500 MHz, i.e. densities of 2 to $3 \times 10^9$ cm$^{-3}$ if the emission is at the fundamental or 5 to $8 \times 10^8$ cm$^{-3}$ if it is at the first harmonic. At higher densities corresponding to plasma
frequencies of 500 to 750 MHz (i.e. 3 to $7 \times 10^9$ cm$^{-3}$ if fundamental and a factor of four smaller if it is harmonic), less turbulence is apparent as evidenced by the well-defined fast-drift bursts extending over a wider frequency range.

In spite of this lack of understanding, several topics can be addressed with the radio and X-ray data presented in this paper. These include RS bursts and their connection with X-ray spikes, primary and secondary type III bursts, and possible models for the production of the electron beams that generate type III bursts.

3.1. RS BURSTS

The data presented in this paper support the model for RS bursts in which electrons are accelerated at high altitude and stream down towards the chromosphere. The idea that they are the second leg of a U-burst cannot, however, be ruled out. As evidence for the high-altitude acceleration model we present the following observations:

(1) RS bursts are as short in duration at a given frequency as are normal type III's. This is in contrast to U-bursts where the second leg usually lasts longer than the first at a given frequency.

(2) Reverse-slope and normal-slope type III bursts are often seen during the same flare over similar frequency ranges.

(3) Tarnstrom and Zehntner (1975) report observations of so called Y-bursts in which an RS burst is closely followed by a normal-slope type III or group of type III's. Examples of such associations are shown in Figure 1 at 10$^h$31$^m$42$^s$ and at 10$^h$32$^m$11$^s$. The explanation suggested by Tarnstrom and Zehntner is that the electron beam is reflected magnetically back upwards.

(4) The 0.1 s duration of the X-ray spike at 10$^h$31$^m$32$^s$ (marked as No. 1 in Figure 1), if it can be associated with the electron beam generating the RS-burst, is consistent with a very short beam length. Velocity dispersion between 20 keV and 100 keV electrons would give a longer duration than this in $2 \times 10^4$ km – rather a short loop for a U-burst. However, Coulomb scattering, anisotropic pitch-angle distributions, an accelerated electron spectrum lacking in low energy electrons, or non-linear wave-particle interactions could overcome this problem.

The strength of the X-ray spikes observed in near coincidence with RS bursts and the occurrence of type III bursts immediately following some RS bursts leads us to suggest that further particle acceleration is triggered by or is in coincidence with RS bursts. The number of electrons above 25 keV required to generate the observed X-ray spikes by thick-target interactions is $1–2 \times 10^{34}$. This is at least an order of magnitude more than can be expected in the beams producing the RS bursts unless there are more electrons in downward directed beams than in the upward directed beams that generate the classical type III bursts. The absence of any enhanced X-ray flux in exact coincidence with the reverse slope bursts at 10$^h$32$^m$11$^s$ and 13$^s$ places an upper limit of $\sim 10^{34}$ on the number of electrons in the beam using the same arguments about thin-target X-ray production as Kane (1972). Consequently, we must assume that most of the electrons required to produce the X-ray spike are not supplied by the beam generating the RS
burst. Thus, if the coincides between RS bursts, X-ray spikes and type III bursts are
not merely accidental, further electrons must have been accelerated.

3.2. TYPE III DELAYS

Previous observations have shown that normal-drift type III bursts are delayed from
associated X-ray spikes by $\sim 1$ s (Benz et al., 1983a; Kane et al., 1982). Benz et al.
(1983a) showed that for 18 such associations the delay increased with decreasing
frequency as expected from the drift rate of the radio signal. The data are consistent with
no delay between the X-ray spike and the generation of the electron beam that later
produces the observed type III burst.

In all attempts to show one-to-one correlations between type III bursts and X-ray
spikes there are always ambiguities as to which of several X-ray spikes are correlated
with a given type III burst. Even in time interval No. 4 in Figure 1 at $10^3 31^m 51^s$ where
there appears to be a clear association between a type III burst and an X-ray spike as
shown in Figure 4, it is difficult to assign a unique delay time to the radio burst. The
X-ray spike peaks within 0.1 s of the peak of the radio burst at 616 MHz but it begins
up to 1.5 s before the radio burst. In fact, the X-ray burst is made up of multiple narrow
spikes and there are at least two type III bursts within 3 s during this interval. However,
if the main X-ray spike at $10^3 31^m 51.0^s$ and the first type III burst seen in the 616 MHz
time profile were associated as suggested by Figure 4, the short time delay of $\lesssim 0.1$ s
has some interesting implications and these will now be explored.

A longer delay between a type III burst and an associated X-ray spike would be
expected based on simple considerations of radio and electron propagation times. If the
radio signal were at the fundamental, a longer delay would be expected since the radio
group velocity would initially be much lower than the velocity of the X-rays. Alternatively,
if the radio signal were at the harmonic, a delay equal to the electron propagation time
to an altitude of $10^{10}$ cm would be expected.

The delay of the radio signal in propagating through the corona can be computed as
follows. The radio signal propagates from the point of origin with a group velocity

$$v_g = \frac{\partial \omega}{\partial k} = cn ,$$

where $\omega$ is the frequency, $k$ is the wave number, $c$ is the velocity of light, and $n$ is the
refractive index equal to $(1 - \omega_p^2/\omega^2)^{1/2}$ where $\omega_p$ is the plasma frequency. If the radio
signal is at the fundamental, it is generated near the plasma frequency and consequently
has a very low initial velocity. Its velocity increases as it propagates out through the
corona to lower densities but there is a delay compared to the X-rays, which propagate
at the velocity of light. This total group delay $\Delta t$ is given by integrating the differential
delay along the line of sight to the Earth,

$$\Delta t = \int \frac{1}{v_g} \left( \frac{1}{c} - \frac{1}{n} \right) ds = \frac{1}{c} \int \frac{1}{n} \frac{dh}{\cos \theta} ,$$

where $\theta$ is the angle of the line of sight to the local vertical on the Sun. We assume a
simple exponential coronal density model with the scale height \( \lambda \) dependent on the temperature \( T \) (K) according to the relation

\[
\lambda = 9.4 \times 10^9 \left( \frac{T}{2 \times 10^6} \right) \text{ cm}.
\]

The expression for \( \Delta t \) then simplifies to the following:

\[
\Delta t = \frac{2\lambda}{c \cos \theta} \int \frac{dn}{1 + n} = \frac{0.44}{\cos \theta} \frac{T}{2 \times 10^6} \text{ s}.
\]

Thus, the expected delay is \( \gtrsim 0.5 \text{ s} \). If the radio signal is at the harmonic, however, the delay is much less than this since the frequency is always \( \gtrsim \) twice the plasma frequency.

The propagation time of the electrons to reach the altitude at which the type III burst is produced can be computed assuming that the electron velocity is 0.3 \( c \). If the emission is at the harmonic, then the 600 MHz level corresponds to an altitude of \( \sim 10^{10} \) cm above the chromosphere. This gives a delay time of \( \sim 1 \) s if the electrons are accelerated at altitudes of \( \leq 10^9 \) cm. If the source is at a longitude of 52° E as suggested by the \( H\alpha \) pictures, the simplest way to reconcile the observation of a decimetric type III burst and an X-ray spike occurring within 0.1 s is if the radio signal is at the harmonic and the electrons are accelerated at an altitude of \( \sim 4 \times 10^9 \) cm.

Various models for type III bursts have been proposed in which longer delays after the X-rays emission are predicted. These involve the production of the X-rays in thick-target interactions of electrons streaming down to the lower corona and the reflection of some of these electrons on to open (or higher closed) field lines as a result of curvature drift or anomalous Doppler resonance (Emslie and Vlahos, 1980; Vlahos, 1979). However, this drift across field lines tends to be a relatively slow process taking as long as 1–10 s, and is, thus, inconsistent with the observed X-ray to radio delay of \( \leq 0.1 \) s.

A different model proposed recently by Sprangle and Vlahos (1983) would be consistent with such a short delay. The X-rays in this model are produced by precipitating electrons as in previous models, but these electrons excite narrow-band electromagnetic waves which escape from the flaring loop and become the driver for secondary electron acceleration inside an open (or higher closed) flux tube. These secondary fast electrons produce the type III burst as they stream out along the flux tube. Since the electromagnetic wave propagates at the speed of light, the delay between the X-rays and the type III burst can be very short depending on the magnetic field geometry. Consequently this model is consistent with the observation of a time delay of \( \leq 0.1 \) s.

The explanation of the secondary type III burst with a slower drift rate delayed from the X-ray spike by 0.8 s at 616 MHz (see Figure 4) could be that the electromagnetic wave accelerates secondary electrons in two separate flux tubes. This may be a general explanation of the primary and secondary type III's reported by Benz et al. (1982) and it may also explain how the acceleration region appears to cover a wide range of diverging magnetic field lines (Kane et al., 1980).
4. Conclusions

We can draw several important conclusions from the X-ray and radio observations presented in this paper of a relatively weak but impulsive flare. Most of these conclusions could not have been made without the fine time resolution (≤0.1 s) of the data sets.

1. We have confirmed the existence of short spikes in the X-ray flux with total durations of ≤0.1 s from simultaneous observations by well separated detectors.

2. We report for the first time observations of X-rays in association with reverse slope type III bursts.

3. We suggest that in some cases type III-RS bursts result from the precipitation of electrons accelerated or stored in the corona at an altitude of >10^4 km.

4. We suggest that type III-RS bursts can occur in coincidence with the acceleration of additional electrons.

5. We present further evidence for the existence of primary and secondary bursts in type III emission first suggested by Benz et al. (1982).

6. We present an observation of a fast drift type III burst which has its peaks intensity at ~600 MHz within 0.1 s of a peak in the X-ray flux. If this type III burst is in fact delayed by such a short time from the associated X-ray event, then the radio signal must be at the harmonic and the electrons producing both the X-rays and the type III burst must be accelerated at an altitude of ~3 × 10^9 cm above the chromosphere. The short delay is inconsistent with models invoking cross-field drifts but supports the model incorporating a MASER proposed by Sprangle and Vlahos (1983).

The close correspondence of fast-drift radio bursts with short duration hard X-ray bursts demonstrated in this paper suggests that there is an intimate association between the electron populations responsible for the two types of emission. Similar studies of other flares showing decimetric and X-ray emission are urgently needed to further define this association.

Acknowledgements

B. Dennis acknowledges the financial support of the United Kingdom Science and Engineering Research Council and the hospitality of the Department of Space Research at the University of Birmingham, where much of the work for this paper was carried out. He is also grateful to Drs Larry Orwig and Alan Kiplinger for assistance in analyzing the HXRBS data. The construction of the Zürich radio spectrometer was supported by the Swiss National Science Foundation (Grant 2.640–0.80).

References


