FLARE FRAGMENTATION AND TYPE III PRODUCTIVITY IN
THE 1980 JUNE 27 FLARE

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Abstract. We present observations of the solar flare on 1980 June 27, 16:14–16:33 UT, which was observed by a balloon-borne 300 cm$^2$ phoswich hard X-ray detector and by the IKARUS radio spectrometer. This flare shows intense hard X-ray (HXR) emission and an extreme productivity of (at least 754) type III bursts at 200–400 MHz. A linear correlation was found between the type III burst rate and the HXR fluence, with a coefficient of $\approx 7.6 \times 10^{27}$ photons keV$^{-1}$ per type III burst at 20 keV. The occurrence of $\approx 10$ type III bursts per second, and also the even higher rate of millisecond spikes, suggests a high degree of fragmentation in the acceleration region. This high quantization of injected beams, assuming the thick-target model, shows up in a linear relationship between hard X-ray fluence and the type III rate, but not as fine structures in the HXR time profile.

The generation of a superhot isothermal HXR component in the decay phase of the flare coincides with the fade-out of type III production.

1. Introduction

Is a solar flare made by one single energy release process as suggested from the smooth soft X-ray time profile? Or does it consist of a couple of ‘elementary flare bursts’, as implied from hard X-ray features on time-scales of 4–24 s (de Jager and de Jonge, 1978)? Is there an even more elementary level in the hierarchy of flare mechanisms, as conjectured from fine structures, down to 30 ms in HXRBS/SMM data where fast

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structures on a time-scale < 1 s are found in \( \lesssim 10\% \) of the flares (Kiplinger et al., 1983; Desai et al., 1987)? The search for the most elementary time structure in solar hard X-ray data is handicapped by the deconvolution problem (superposition of many overlapping components with different time-scales). Different parts of a hard X-ray burst may also occur from slightly different locations, as hard X-ray images (HXIS) have shown (Duijveman, Hoyng, and Machado, 1982). As a trend, the analysis of numerous HXRBS/SMM events reveals fewer fine structures for higher hard X-ray count rates. An individual elementary burst may be quite weak, as is shown by the 30 ms time variations observed by Kiplinger et al. (1983), as well as by the detection of 1–2 s microflares by Lin et al. (1984), which all have small integrated fluxes. If we hypothesize that large flares are made of such elementary processes which occur with a higher rate than their typical duration, the resulting HXR time profile would be a featureless envelope without much fine structure. Hence, time profiles of intense hard X-ray bursts may not reveal the elementary acceleration events.

Here we present radio observations of the well-observed 1980 June 27 flare which provide complementary information to the HXR data, obtained by balloon-borne hard X-ray detectors with very high sensitivity (Lin et al., 1981; Bai et al., 1983; Lin et al., 1984; Schwartz, 1984; Lin and Schwartz, 1987). Despite the excellent time resolution down to 8 ms, and the compelling quality of the energy spectra, only a few rapid components varying over 1–4 s have been identified in the HXR data (Schwartz, 1984). However, the metric and decimetric radio data during the flare reveal 2–3 orders of magnitude more fine structure than is observed in hard X-rays. The observation of \( \approx 10^3 \) metric type III bursts and \( \approx 10^3 \) ms spikes before and during the flare suggests a release of energetic particles in a highly quantized pattern (Benz, 1985, 1987). Every type III burst requires an individual acceleration or a fragmentation of the original electron population. Also the clustered appearance of the numerous millisecond spikes suggests either a quantized injection of energetic particles or a spatial fragmentation inside the magnetic flux tube. In both cases, either for a quantized accelerator or for bifurcations of the magnetic field, the consequence is a high fragmentation of the accelerated electron population.

The observations presented show not only an extreme richness and clustering of type III bursts, but also a linear relationship between the type III burst rate and the hard X-ray fluence. Although the radio signatures and the hard X-ray emission might not necessarily be produced by the very same electrons, the correlation suggests a causal relationship, which is most naturally interpreted by a common acceleration source. A productivity of up to 10 type III bursts per second is measured, thus implying a duty cycle for the accelerator of < 0.1 s during a couple of \( \approx 5 \) s-flashles in the impulsive flare phase. If one assumes a thick-target model, the injected power is possibly quantized on a similar time-scale. Individual injected electron beams are not resolved in the HXR time profile despite the excellent count rate statistics, perhaps because of the smearing effect of energy loss times significantly longer than the time between discrete injections. The only measureable consequence is the correlation of HXR flux with the rate of electron beams. The energy involved in the HXR emission, in terms of the thick-target model,
corresponds to $\approx 10^{28}$ ergs per observed type III beam (assuming a 15 keV electron cutoff). This is similar to the estimated energy per microflare ($\approx 10^{27}$ ergs) derived from observations of decimetric millisecond spikes (Benz, 1985).

2. Observations

The hard X-ray observations were performed with a 300 cm$^2$ NaI/CsI phoswich scintillator designed for high sensitivity and time resolution. A co-aligned cooled array of four intrinsic germanium detectors provided high spectral resolution with $\approx 1$ keV FWHM from 15–300 keV. The balloon-borne instrumentation, developed at the University of California at Berkeley and San Diego, was flown on 1980 June 27 from Palestine, Texas. The Sun was observed during the intervals 15:24–16:43 UT and 19:39–21:03 UT. Data were stored with 0.128 s time resolution before triggering by an enhanced scintillator rate and 8 ms and 32 ms thereafter. The five energy channels of the phoswich detector cover 22–33, 33–60, 60–120, 120–235, and $> 235$ keV. Peak fluxes of $\approx 4.5 \times 10^4$ counts s$^{-1}$ were measured at the flare maximum. Instrumental details and the data reduction procedure can be found in Schwartz (1984), Lin et al. (1981, 1984), and Lin and Schwartz (1987).

The metric and decimetric radio emission of this same flare was observed with the frequency-agile digital spectrometer IKARUS of ETH Zurich, Switzerland (Perrenoud, 1982). This instrument observed on 1980 June 27 in the frequency ranges 100–145, 160–172, 229–397, 425–464, 580–652, and 817–1000 MHz, with a frequency resolution of 3 MHz and a time resolution of 0.1 s. While the flare related from 16:14 to 16:33 UT, with a HXR maximum at 16:16 UT, IKARUS recorded data from 16:13:26 to 16:21:30 UT, i.e., covering the entire main flare phase. Bursts were observed at all intensities from the sensitivity threshold of $\approx 1$ s.f.u. up to 10 000 s.f.u. during this flare.

The same flare was also observed as an M6 soft X-ray burst by the GOES-2 spacecraft and in hard X-rays by the ISEE-3 spacecraft. The SMM spacecraft was in the nighttime part of the orbit during the flare. An H$\alpha$ flare started at 16:14 UT with importance SB at S 25 W 67 in Hale active region 16923 (Solar-Geophysical Data).

3. Data Analysis and Results

3.1. HARD X-RAY EMISSION

The evolution of the hard X-ray emission of the 1980 June 27 flare, lasting from 16:14 to 16:33 UT, is shown in Figure 2. The rise of the impulsive phase from 16:14–16:16 UT consists of at least 4 main peaks below 120 keV. The main impulsive phase from 16:16 to 16:17 UT consists of 3 major peaks visible in all energy channels. From the temporal variation of the hard X-ray spectra, the following two different non-thermal HXR components were derived: (i) individual spikes lasting 3–15 s with a hard spectrum and a break energy of 30–65 keV, and (ii) a slowly varying component.
characterized by a soft spectrum with a constant low-energy slope and a break energy which increases from 25 keV to $\gtrsim 100$ keV through the event. The double power-law spectrum was interpreted as a possible indication of DC electric field acceleration (Lin and Schwartz, 1987). In the high-energy range above 235 keV, a delay of 3 s with respect to the time profiles of the lower energy channels was found for the two most intense HXR peaks at 16:16 and 16:17 UT. This delay was interpreted as second-step acceleration, with first-order Fermi acceleration as the most likely mechanism (Bai et al., 1983). Smaller delays ($E > 120$ keV) were also found for 4 additional peaks during the impulsive phase (Schwartz, 1984). Besides these non-thermal components, there was also a superhot isothermal component of $34 \times 10^6$ K detected first in the main impulsive phase and later dominating the decay phase of the flare after 16:17:30 UT (Lin et al., 1981).

The HXR time profiles in Figure 2 show $\approx 13$ significant features with rise times of 3–10 s. Because we are interested in faster time structures, we investigated possible fine structures at higher time resolution, down to 32 and 8 ms. The search did not reveal more fine structures at higher time resolution. The number of flux increases with $dF > 3\sigma$ at higher time resolution (128, 64, 32, 16, and 8 ms) was found not to exceed the expected probability for Gaussian-distributed random fluctuations. Almost all of the $3\sigma$ peaks at $< 128$ ms time resolution did not occur in adjacent energy channels, or at comparable higher time resolution. Also, at lower flux levels at the beginning of the flare from 16:13:30–16:14:45 UT, where the separability of fine structures is expected to be optimum, no fine structure ($F > 3\sigma$) was detected.

We conclude from these considerations that the HXR emission of the 1980 June 27 flare is not significantly structured on time-scales of $\lesssim 1$ s, although observed with the highest ever available sensitivity. This conclusion is not inconsistent with the result reported by Kiplinger et al. (1983), that fast structures with time-scales of $< 1$ s occur in $\approx 10\%$ of the HXRBS/SMM flares.

3.2. Metric Type III Bursts

The 1980 June 27 flare is extremely rich in type III bursts in the metric range. During the time of the main flare, from 16:13:20 to 16:18:00 UT, 750 type III bursts were counted in the 229–397 MHz frequency range, 76 bursts at 160–172 MHz and 89 bursts at 100–145 MHz. There is no correlation between type III flux and HXR flux. Also, attempts to correlate individual type III bursts with HXR peaks failed because of the high density of the radio structures. Besides the amazing high type III productivity, the most striking result is the clustering of type III bursts around the HXR peaks. The metric type III bursts below 200 MHz do not show this clustering effect. It is most obvious in the enlarged representation of Figure 1 for the 227–398 MHz range. The four primary peaks in hard X-rays are accompanied by clusters of broadband metric type III bursts and narrowband weak fine structures (also called ‘blips’, Benz et al., 1983). Another striking feature of the type III distribution in the frequency-time plane is the alignment across the frequency band; groups of bursts have their leading edge near the same exciter path across the frequency band (Figure 1).

To perform a more quantitative analysis of the type III characteristics, we developed
an automatic structure recognition program, similar to the method used in Aschwanden and Benz (1986). Flux enhancements exceeding a minimal value in the second time derivative (filtering out the linear background) are traced along adjacent frequency channels and combined into coherent structures. The structure definition was given by six free parameters, which were adjusted until a selection of bursts was produced comparable to visual inspection. The number of type III structures exceeding a flux threshold of $\geq 1$ s.f.u. was determined to be 754 in the 229–397 MHz range. This is very close to the visually counted number. The time, duration, center frequency, bandwidth, peak flux, background flux, and frequency-time drift rate were also measured with the same algorithm for each burst.

We get the following characteristics for the 754 analyzed type III bursts in the 229–397 MHz range: 50% have a bandwidth $> 25$ MHz, 20% with $> 50$ MHz, and only 4% with $> 100$ MHz. Most of the analyzed bursts belong, therefore, to the category of ‘blips’ according to the definition $\Delta v < 50$ MHz (Benz, Bernold, and Dennis, 1983; Wiehl et al., 1985). Although the category of decimetric ‘blips’ differs statistically in bandwidth and starting frequency from the class of type III’s, the physical emission...
mechanism is believed basically to be the same (Benz, Bernold, and Dennis, 1983). Hence, we consider 'blips' as narrowband type III bursts and do not distinguish them from ordinary type III bursts in the following analysis. The high abundance of narrowband structures is mainly due to weak bursts and broadband bursts which break up into smaller substructures with different characteristics. The structure recognition program identifies bursts by (i) minimal flux, (ii) minimal frequency bandwidth, and (iii) coherence in drift rate; it discriminates substructures or superposed structures by (iv) time differences in the second derivative or (v) significant discontinuities in the flux spectrum. Some sequences of type III bursts, which are aligned across the frequency spectrum, may belong to the same exciter; the significant flux discontinuities may indicate either a relaxation of the beam instability and subsequent recovery, or exciters on different magnetic field lines.

The distribution of type III bursts in frequency is nearly homogeneous over the analyzed band from 229–397 MHz; 53% of the bursts have a starting frequency in the lower half of the band, or 64% have the center frequency in the lower half. A few bursts have a continuation at lower frequencies down to 100 MHz. The typical background-subtracted fluxes of the type III bursts are between 10–100 s.f.u. (50%); only 28% have fluxes > 100 s.f.u., and 1% have > 1000 s.f.u. In general, the type III fluxes at 100 MHz are much higher, up to 10000 s.f.u. during this flare. Although we detected type III bursts with flux intensities down to the noise limit of ≈ 1 s.f.u., the absolute number of type III bursts is uncertain. The abundance of type III bursts versus flux intensity increases monotonically towards weaker fluxes, reaching the maximum at the weakest fluxes required in the structure definition, i.e., the size spectrum is still rising at the weakest flux level.

3.3. CORRELATION OF HARD X-RAY EMISSION VERSUS TYPE III RATE

We investigate the coincidence of type III clusters with hard X-ray peaks. In Figure 2, the type III bursts in the 229–397 MHz frequency band are binned in 2 s intervals, yielding burst rates up to 16 per 2 s bin. For reasons of poor statistics, the number of significant peaks in the type III rate evolution may vary between 5 and 10. However, a comparison with the hard X-ray fluence also plotted in Figure 2 shows a remarkable coincidence of peaks. A total of about 9 hard X-ray peaks line up with peaks in the type III burst rate within 3 s, where the peaks are separated by 10–20 s. We emphasize that the type III radio flux does not correlate with the HXR fluence at any frequency. We quantify the correlation of the type III burst rate versus HXR counts in the scatterplot shown in Figure 3. Because there is a conspicuous evolution during the flare, we restrict a linear regression fit to the main flare phase at 16:15:20–16:17:10 UT; the preceding preflash phase shows a much lower HXR count rate; and in the decay phase the type III bursts fade out. We investigated the quality of this linear relationship as a function of the minimum radio peak flux, the HXR energy band, and the time bin width. The correlation was best (correlation coefficient = 0.99) for the case with type III bursts > 25 s.f.u., X-rays in the 22–33 keV energy range, and 20 s bins. Figure 3 shows a scatterplot for 2 s bins. In Table I, we summarize the linear regression for different
Fig. 2.  Top: The number of type III bursts, as shown partially in Figure 1, counted in 2 s bins, for threshold (background-subtracted) flux levels of 1, 25, and 100 s.f.u. About 9 peaks in the type III burst rate are visible at all three threshold levels. Bottom: Hard X-ray emission measured with the balloon-borne scintillator of the University of California. The displayed count rates cover the energy range of 22–235 keV and are integrated in bins of 1.024 s. The hard X-ray count rate shows 14 4σ peaks (indicated by the vertical broken lines) with a time-scale of approximately 10 s. Nine of these peaks line up with maxima in the type III burst rate within 3 s.

**TABLE I**

Linear correlation between the type III rate and HXR counts for different energy ranges

<table>
<thead>
<tr>
<th>Energy range (keV)</th>
<th>Linear regression</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_0$ (cts)</td>
<td>$N_0$</td>
</tr>
<tr>
<td>22–33</td>
<td>1400</td>
<td>6</td>
</tr>
<tr>
<td>33–60</td>
<td>1400</td>
<td>2</td>
</tr>
<tr>
<td>60–120</td>
<td>900</td>
<td>0</td>
</tr>
<tr>
<td>120–235</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>&gt; 235</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>&gt; 22</td>
<td>4000</td>
<td>3</td>
</tr>
</tbody>
</table>
Fig. 3. Scatterplot of the number of type III bursts per 2 s bin versus the hard X-ray counts per 2 s bin in the lowest energy range of 22–33 keV. Three intervals of the flare show different ratios of the type III rate versus the hard X-ray count rate. The ratio of the two rates during the main phase from 16:15:20–16:17:10 UT is fitted by linear regression, yielding \( \approx 1400 \) HXR counts per type III burst with a correlation coefficient of 77%.

X-ray energy ranges. We assume that the number of type III's \((N_{III})\) observed in a given time bin is related to the number of X-rays \((X)\) detected during the same time bin by the relation

\[ X = X_0 (N_0 + N_{III}), \]

where \(X_0\) and \(N_0\) are constants determined from the correlation analysis. Table I gives the values of \(X_0\), \(N_0\), and the correlation coefficient for type III's > 25 s.f.u. and 2 s time bins.

This corresponds to a count rate of roughly \( \Phi(\varepsilon = 20 \text{ keV}) \approx 0.4 \text{ cm}^{-2} \text{ keV}^{-1} \) per type III, or a photon rate of \( \approx 7.6 \times 10^{27} \text{ photons keV}^{-1} \) per type III burst at 20 keV for the average spectrum, which remains nearly constant.

We investigated also the delays between the maxima of the type III rate and HXR peaks. The cross-correlation was performed for each energy channel separately and for 13 time intervals each covering a peak in HXR and type III rate, with a time resolution of 1 s. The type III rate maxima are delayed in 11 cases by up to 2.7 s, and precede the HXR peaks only in 2 cases, less than 0.5 s. The cross-correlation times for the 33–60 keV channel are listed in Table II, where \( t_{\text{radio}} - t_{HX} \) is the time delay of the
### TABLE II

Delays between peaks of the type III rate and HXR fluence

<table>
<thead>
<tr>
<th>Time interval (UT)</th>
<th>Delay $t_{\text{radio}} - t_{\text{HXR}}$ (s)</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:14:10–14:35</td>
<td>0.3</td>
<td>0.39</td>
</tr>
<tr>
<td>16:14:35–15:15</td>
<td>0.4</td>
<td>0.48</td>
</tr>
<tr>
<td>16:15:15–15:32</td>
<td>2.7</td>
<td>0.95</td>
</tr>
<tr>
<td>16:15:32–15:40</td>
<td>1.2</td>
<td>0.60</td>
</tr>
<tr>
<td>16:15:40–15:46</td>
<td>0.2</td>
<td>0.43</td>
</tr>
<tr>
<td>16:15:46–15:55</td>
<td>1.5</td>
<td>0.73</td>
</tr>
<tr>
<td>16:15:55–16:02</td>
<td>$-0.4$</td>
<td>0.51</td>
</tr>
<tr>
<td>16:16:02–16:14</td>
<td>1.0</td>
<td>0.65</td>
</tr>
<tr>
<td>16:16:20–16:29</td>
<td>0.1</td>
<td>0.71</td>
</tr>
<tr>
<td>16:16:29–16:39</td>
<td>1.2</td>
<td>0.40</td>
</tr>
<tr>
<td>16:16:39–16:47</td>
<td>$-0.5$</td>
<td>0.57</td>
</tr>
<tr>
<td>16:16:47–16:53</td>
<td>0.1</td>
<td>0.83</td>
</tr>
<tr>
<td>16:16:53–17:12</td>
<td>0.1</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Type III rate as determined by a cross-correlation analysis of the two time profiles in the given time interval.

The delay between HXR emission and the type III rate varies between $-0.5$ and 2.7 s, with an average of 0.6 s. These delays have little effect on the correlation of the main flare phase (Figure 3) which was performed with a time resolution of 2 s. The delays for the three lowest energy channels are found to be identical within an accuracy of $\pm 0.2$ s, but the delay for high energy channels (>120 keV) are 1–2 s smaller, in agreement with studies of HXR delays as a function of energy (Schwartz, 1984; Bai et al., 1983). We emphasize that there are type III bursts with smaller delays with respect to HXR emission than those found by correlating the type III rate.

### 3.4. Type III Drift Rate

The frequency–time drift rate of type III bursts basically provides information on the source motion, but atmospheric properties can also be obtained from statistical drift rate distributions (Aschwanden and Benz, 1986). Figure 4 shows the drift rate distribution of the 754 type III bursts, determined by linear regression fits in the 229–397 MHz range. The drift rate distribution is consistent with earlier observations (e.g., Benz and Zlobec, 1978), yielding a similar ratio of the normalized drift rate $(d\nu/dt)/\nu$. A total of 79% of the type III bursts are normal, i.e., the negative drift rate corresponds to upward moving beams. Other drift effects such as light path differences of an extended source or group delay effects in a non-barometric atmosphere do not change the sign of the drift rate for such low values as $|d\nu/dt| \approx 100$ MHz s$^{-1}$ (Aschwanden and Benz, 1986). The typical range of the drift rate is found to be $d\nu/dt \approx 100–500$ MHz s$^{-1}$ at an average frequency of 300 MHz for this flare. The drift rate relation for a moving electron beam exciting fundamental plasma emission in a barometric atmosphere is

$$
\frac{d\nu}{dt} = -\frac{\nu v_B \cos \vartheta}{2\lambda},
$$

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where $v_B$ represents the source velocity and $\lambda$ the atmospheric scale height. For vertically upward moving beams ($\theta = 69^\circ$ from Hz position S 25 W 67) and an isothermal atmosphere of $2 \times 10^6$ K ($\lambda \approx 0.9 \times 10^5$ km), we get a beam velocity of $v_b/c \approx 0.6$ for a drift rate of $d\psi/dt = 100$ MHz s$^{-1}$. Hence, a shorter scale height of $\lambda \approx 10^4$ km is required to explain the higher drift rates of $d\psi/dt \approx 500$ MHz s$^{-1}$ with reasonable beam velocities of $v_b/c \approx 0.3$ (corresponding to $\approx 20$ keV).

Because the sign of the type III drift rate is key to understanding the directivity of electron beams in the solar corona, we study the ratio of positive to negative drift rates during the flare. Figure 4 shows no essential change of this ratio during the main flare phase of 16:15:20–16:17:10 UT. There are about 80% upward moving and 20% downward moving type III bursts present through the entire flare. For downward moving beams, however, it may be more difficult to produce type III emission for two reasons: (i) the propagation may simply be too short to develop a positive slope in velocity space, (ii) a beam propagating in a converging magnetic field loses parallel
momentum. Thus, most of the downgoing beams, which may be responsible for the hard X-ray emission by thick-target bremsstrahlung, may not be visible in our observations. However, the acceleration mechanism must produce a proportional number of upward and downward moving electron beams in order to explain the measured correlation between the rate of mostly upward directed type III beams and HXR emission.

3.5. Correlation of hard X-ray fluence with type III starting frequency

The starting frequency of normal drift type III bursts is a measure of the local plasma frequency in the source and provides a lower limit on the electron density in the acceleration region. Earlier studies demonstrated an occasional correlation of the type III starting frequency with the associated hard X-ray fluence (Rust et al., 1981; Kane and Raoult, 1981; Benz et al., 1983; Raoult et al., 1985). This correlation was interpreted either as a variation of the electron density in the acceleration source or as an increase of the time of flight for the development of an unstable velocity distribution.

We investigated the behavior of the starting frequency of the 754 type III bursts during the 1980 June 27 flare. Figure 5 shows the variation of the maximum starting frequency in 2 s time bins and for various flux thresholds (1, 25, 100, 250 s.f.u.). Weak type III bursts have starting frequencies over the entire frequency range of 229–397 MHz. Bursts with > 25 s.f.u. reach up to the maximum starting frequency near 400 MHz, but occur mainly during the time of impulsive HXR peaks. However, selecting only strong type III burst with fluxes of > 100 s.f.u. or > 250 s.f.u. reveals a striking correlation between the starting frequency of these intense type III bursts and the HXR fluence.

Because an electron beam has to travel a minimum distance from the injection point until it becomes unstable toward growing Langmuir waves, the starting frequency of type III bursts is related to this minimum distance. This minimum distance was estimated to be $x_{\text{min}} \approx 4 \alpha \tau v_e$ by Kane, Benz, and Treumann (1982), where $\alpha$ is the power-law index of the electron spectrum in the acceleration source, $\tau$ is the characteristic acceleration time, and $v_e$ is the thermal velocity of the bulk electrons. Figure 5 confirms that the starting frequency is roughly correlated with the spectral index $\alpha$ (here the spectral ratio $R(33-60 \text{ keV})/R(22-33 \text{ keV})$. However, this flare is typical in that it exhibits a spectral soft-hard-soft evolution for every HXR peak (on time-scales of 5–10 s), i.e., the HXR fluence and spectral index depend on each other. Thus, since the starting frequency of type III bursts correlates with the HXR fluence it automatically correlates with $\alpha$.

3.6 Temperature evolution

The evolution of non-thermal and thermal components during the flare is described in Section 3.1. A superhot isothermal component of $34 \times 10^6$ K, the only thermal component visible in the HXR spectra, begins to appear after 16:16 UT and dominates the HXR fluence after 16:17:20 UT (Figure 6, bottom). The GOES soft X-ray spectra show a slow rise in temperature from 14 to $19 \times 10^6$ K (Lin et al., 1981) with a maximum at 16:18 UT, about 4 min after the onset of the flare, indicating a gradual heating of the...
flare plasma. The first 3 min, 16:14–16:17 UT, are completely dominated by a non-thermal double power-law spectrum in hard X-rays. This is interpreted as thick-target emission from injected electron beams with the injected power plotted vs. time in Figure 6 (middle). The production of type III bursts is plotted in Figure 6 (top). It starts somewhat earlier than the HXR flare emission but stops abruptly at 16:17:10 UT. This is coincident with the peak in the fluence of the superhot component determined by examining the spectra shown in Figure 3 of Lin et al., 1981).

The disappearance of the type III bursts as the hot component becomes the dominant feature of the flare may be interpreted as discontinuation of the acceleration of electron beams, as the dropping hard X-ray flux indicates.

However, this coincidence between temperature rise and the disappearance of type III bursts may not be accidental, because the development of the bump-in-tail instability,
Fig. 6. The relation among the flare plasma temperature, injected power, and the occurrence of type III bursts. The evolution of temperature is shown for the superhot isothermal component (solid line, from the Phoswich Hard X-ray spectra) and for the flare plasma (dashed line, from GOES soft X-ray data) in the lower frame; the non-thermal component is shown in the middle frame as injected power calculated from the thick-target model (Lin et al., 1981). In the upper frame we show the type III burst rate in 10 s bins. Note that the occurrence of type III bursts covers roughly the non-thermal flare phase, and terminates with the rise of the superhot isothermal component. It is conjectured that the fade-out of type III generation is caused by the heating of the flare plasma.

The generally accepted driver for type III bursts, is sensitive to the temperature of the bulk electrons. The suppression of the bump-in-tail instability by a heating process of the cold electrons is illustrated in Figure 7. The criterion for the beam instability, a positive slope of the beam velocity distribution in the thermal tail, is violated for low density beams or high bulk plasma temperatures. The example depicted in Figure 6 shows suppression of a positive slope for beams with \( v_b = 4v_{\text{thermal}} \), and for a density ratio \( n_b/n_{\text{th}} = 0.2 \), at a temperature of \( 10^7 \) K. For beams with weaker intensity, an even lower temperature may impede type III bursts.

4. Conclusions

The 1980 June 27 flare was observed by hard X-ray detectors of unprecedented high energy and time resolution, and simultaneously by broadband radio observations with 0.1 s time resolution.
There was an extremely high type III productivity during the main flare from 16:14–16:17 UT, amounting to 754 type III bursts in the 200–400 MHz frequency range, and > 165 bursts in the 100–200 MHz frequency range. The type III bursts have typical fluxes of 10–100 s.f.u., and 80% of them have frequency bandwidths of < 50 MHz at 200–400 MHz, i.e., they are mainly narrowband type III bursts referred to as ‘blips’ by Benz, Bernold, and Dennis (1983). At the beginning of the impulsive flare phase at 16:14:40–16:15:30, there was also a cluster of > 700 decimetric millisecond spikes in the band of 580–900 MHz (Benz, 1987).

The hard X-ray flare is very intense and shows about 13 significant fluctuations with rise times of 3–15 s. Besides these fluctuations, no significant structures of the HXR time profile exceeding the 3σ significance level have been found, down to a time resolution of 32 ms and 8 ms.

By comparing the temporal evolution of the radio and HXR emission we obtained the following results:

1) A correlation is found between the rate of type III bursts and the hard X-ray fluence in all five energy ranges from 22 to > 235 keV. The linear regression yields 1400 HXR counts per type III burst in the 22–33 keV range, or 4000 HXR counts/type III burst in the total range from 22 to > 235 keV. This corresponds to a photon
flux of \( \approx 7.6 \times 10^{27} \) photons keV\(^{-1} \) per type III burst at 20 keV for the average spectrum. In contrast, the radio flux does not correlate with the hard X-ray fluence at any frequency.

(2) The maxima of the type III burst rate are generally delayed with respect to the peaks of the hard X-ray fluence at \(< 120 \text{ keV} \). This delay varies from \(-0.5\) to \(2.7 \text{ s} \), with an average of \(0.6 \text{ s} \).

(3) Most (\( \approx 80\% \)) of the bursts are normal type III bursts in that they drift to lower frequencies with advancing time (\( {d} f / {d} t < 0 \)) indicating that they are produced primarily by upward drifting beams.

(4) The starting frequency of type III bursts (>100 s.f.u.) correlates well with the hard X-ray fluence and the HXR spectral index, supporting the relationship between the injected electron spectrum and the minimal distance for type III evolution.

(5) The generation of type III bursts fades out shortly after the rise of a superhot isothermal component in hard X-rays of \(34 \times 10^6 \text{ K} \) after 16:17 UT.

The deficiency of temporal fine structures in hard X-rays as well as the lack of a detailed correlation between radio and HXR fluence suggests no direct coupling between the two emission processes; a spatial separation of the sources is likely. However, the good correlation between the type III rate (and starting frequency) with the HXR fluence strongly supports a casual relationship most likely associated with a common acceleration mechanism. The fluctuating rate of type III burst production, varying between 1 and 8 bursts per second during the main flare phase, reflects either the quantized operation of the accelerator or a subsequent fragmentation by injection into diverging magnetic field lines. A similar argument has been put forward for the numerous occurrences of decimetric millisecond spikes, with up to 100 single spikes per second (Benz, 1986).

In addition, a rough correlation of the type III starting frequency with the HXR spectral index has been found. This is most likely explained by the relation between the injected electron spectrum and the minimum distance for type III initiation. The minimum distance between the accelerator and the type III source is typically \(10^4 \text{ km} \) to \(10^5 \text{ km} \) (Kane, Benz, and Treumann, 1982). This is a second independent argument that the type III burst occurrence is modulated by characteristics of the acceleration mechanism itself rather than by coronal topology near the type III source. Thus, we conclude that the cause of the observed fragmentation is most likely to be in the acceleration mechanism itself, rather than in subsequent bifurcations of the magnetic field. The elementary quantization time-scale of the accelerator, derived from the number rate of type III bursts, is about \(0.1 \text{ s} \).

The ratio of upward to downward moving beams cannot be derived from these observations. The sign of the drift rate yields a ratio of \(4:1 \). However, previous observations always counted a much larger fraction of normal drift than reverse drift type III's, because the bump-in-tail instability is more likely to be suppressed for downward moving beams that commonly meet higher densities and higher temperatures near the transition layer. Thus, we cannot exclude a symmetric acceleration mechanism, producing an equal number of downward and upward accelerated beams.
For the most likely interpretation of the hard X-ray emission, in terms of thick-target bremsstrahlung, the injection rate amounts to $\approx 10$ electron beams per second. Each electron beam carries an energy of $\approx 10^{28}$ ergs, according to the computed injected power from the non-thermal HXR spectra. The individual injections cannot be resolved in the hard X-ray time profile, because the (energy-dependent) spatial dispersion of downgoing electron beams and the energy loss times smear out the time structure of the injection mechanism. This explains the lack of fine structures in hard X-rays.

Another result emerges from the temperature evolution during the flare. The generation of type III bursts, driven by the bump-in-tail instability, is suppressed after the rise of a superhot thermal component.

The present work shows evidence for a much higher fragmentation of the acceleration mechanism and the flare energy release than has been believed before. This high degree of quantization of the acceleration mechanism was not recognized before because of the convolution of the hard X-ray time profile, and was ignored in the dynamic radio spectra due to a lack of sensitivity and numeric structure recognition. It is desirable to confirm this high degree of fragmentation for a larger number of flares.

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