THE TIMING OF ELECTRON BEAM SIGNATURES IN HARD X-RAY AND RADIO: SOLAR FLARE OBSERVATIONS BY BATSE/COMPTON GAMMA-RAY OBSERVATORY AND PHOENIX

MARKUS J. ASCHWANDEL
University of Maryland, Astronomy Department, College Park MD 20742

ARNOLD O. BENZ
Institute of Astronomy, Federal Institute of Technology (ETH), CH-8092 Zurich, Switzerland

AND

RICHARD A. SCHWARTZ
Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, Code 682, Greenbelt, MD 20771

Received 1993 March 26; accepted 1993 May 11

ABSTRACT

We analyzed two solar flares of 1992 September 5 and 6, using the high time resolution (64 ms) hard X-ray data from BATSE/CGRO, and 100–3000 MHz radio (100 ms) dynamic spectra from PHOENIX. The broadband radio data reveal a separatrix frequency (at 620 and 750 MHz in the two flares) between normal- and reverse-drifting radio bursts, indicating a compact acceleration source where electron beams are injected in both the upward and downward direction. We find a mean injection rate of 1.2 bursts s⁻¹ in one flare and more than 0.7 bursts s⁻¹ in the other. From 12 broad-band, reverse-drifting radio bursts we find in five cases an unambiguous one-to-one correlation between the reverse-drifting radio bursts and hard X-ray (HXR) pulses of similar duration (400 ± 220 ms). The high significance (15 ± 6 σ) of the HXR pulses and the small scatter (± 150 ms) in the relative timing strongly supports a close causal connection. The cross-correlation between HXR and radio pulses shows that the HXR pulses are coincident (within the instrumental time resolution) with the reverse-drifting bursts at the injection frequency (880 ± 50 MHz), and lead the radio bursts by 270 ± 150 ms at the highest observable frequency (1240 ± 100 MHz). The average drift time of the downward propagating radio bursts is measured to 150 ms, corresponding to a drift rate of 2350 MHz s⁻¹.

We examined various effects to model the observed timing of radio and HXR pulses (propagation delays, radio wave growth and damping, group velocity delays, radio wave scattering, radio wave ducting, light path differences, etc.). Assuming an exciter velocity of vₑ/c = 0.2 ± 0.1 for the reverse-drifting radio bursts, we infer an altitude difference of H = 8000 ± 3000 km between the injection site and the HXR source. The most likely explanation for the retarded radio emission seems to be a combination of the following two effects: (1) HXR-emitting (>25 keV) and radio-emitting electrons have different energies (the exciter velocity of the reverse-drifting radio bursts is associated with <5 keV electrons), and (2) a low (marginal) growth rate for plasma emission at the second harmonics. Delay effects caused by group velocity, collisional damping, wave scattering, and wave ducting are found to be minor (<30 ms each).

Subject headings: Sun: corona — Sun: flares — Sun: particle emission — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

For several decades the dynamics of rapid energetic processes in solar flares has been explored by analyzing the various radiative signatures of accelerated particles, such as nonthermal hard X-rays (HXR), gamma rays, and coherent radio emission. A simple technique to investigate the nature of particle accelerators operating in solar flares is to count and measure radio type III bursts, the most unambiguous tracers of propagating electron beams in the solar corona. However, in order to ensure that the radio bursts and their evolution is related to the primary energization process and not to secondary effects, it is highly desirable to establish a correlation of electron beam signatures in different physical processes, e.g., HXR bremsstrahlung and coherent radio emission. One of the most crucial tests is a correspondence of fine structures in widely separated wavelength regimes, and the relative timing of correlated fine structures.

First correlative studies were concentrated on groups of metric/decimetric type III bursts and multiple X-ray spikes (Kundu 1961; Kane 1972; Kane, Pick, & Raoul 1980; Kane & Raoul 1981; Kane 1981; Kane, Benz, & Treumann 1982a; Benz, Bernold, & Dennis 1983a). Kane et al. (1982a) claimed a one-to-one correspondence between three HXR peaks and single type III bursts. The radio bursts were found to be delayed by 0.1–0.8 s at less than 273 MHz. A flare with seven HXR subsecond spikes has been compared with simultaneous reverse-drifting radio bursts with a time resolution of 0.1 s (Dennis et al. 1984), but no systematic trend has been found for the relative time delays, although one single case was coincident within 0.1 s. Statistical correlations of HXR spikes with the next following type III burst revealed radio delays of 0.5–1.5 s in the 163–391 MHz range (Benz et al. 1983b), with the shorter delays for the bursts with the higher start frequency.

One of the major obstacles in determining the timing of radio bursts is their frequency-time drift, which makes their timing frequency-dependent. At a decimetric frequency of 1.6 GHz, where the frequency-depending time delay is expected to be much smaller than at metric frequencies, the unexpected
result was found that the HXR peaks were delayed from the peak of the reverse-drifting bursts, by an average delay of 400 ms in 13 cases (Sawant et al. 1990). This result seems to be controversial for several reasons: (1) the 1.6 GHz peaks tend to occur delayed to the decimetric reverse-drifting bursts (with a mean delay of 0.2 ± 0.3 s according to Table 1 in Sawant et al. 1990), leading to an even larger time lag of ≈600 ms for the HXR pulses with respect to the reverse-drifting bursts; (2) the 1.6 GHz microwave emission may be dominated by gyrosynchrotron emission, which is known generally to peak later than the HXRs; and (3) both the microwave and correlated HXR time structures in the study of Sawant et al. (1990) seem to consist of two-to-three unresolved substructures, that makes a one-to-one correspondence ambiguous. Another timing study (Raoul et al. 1989) between metric type III bursts and 22 GHz microwave bursts showed delays of arbitrary signs (−1 · · · +2 s), possibly indicating competing delay processes of different origins.

Two kinds of improvements are required to make a one-to-one correlation between HXR and radio time structures more promising: (1) broader frequency coverage in radio and (2) higher sensitivity in X-rays. First, only broad-band radio data should be used, where the earliest start of normal- or reverse-drifting radio bursts can clearly be identified. In the optimal case one should concentrate on oppositely drifting burst pairs with a common injection point only. Such bursts with opposite drifts at the low and high frequencies were already noticed in 1960 (Kundu et al. 1961), and have since been found in sufficiently broad-band radio dynamic spectra. The broad-band coverage allows us then to correlate the radio signature at the injection frequency and to quantify the frequency-dependent time delay. In this study we analyze the 0.1–3.0 GHz dynamic spectra of a flare, where 10 pairs of oppositely drifting radio bursts have been identified by using contrast enhancing techniques.

The second improvement required is higher sensitivity in HXRs to resolve fine structures. The average rate of precipitating electron beams in a typical flare may be of the order of ≈1 burst s−1; the shortest periods of metric type III bursts and type U-bursts was found to be 1–2 s (Zhao, Mengeney, & Pick 1991; Aschwanden et al. 1993b, 1993c; Aschwanden, Benz, & Montello 1994). If we believe that the nonthermal HXR flux is made of a superposition of type III-correlated pulses, with a typical duration of ≈0.5 s and a mean rate of ≈1 s−1, there is a good chance to find some of these quasi-periodic pulses isolated, if the HXRs are recorded with sufficient count statistics.

In this study we analyzed two flares with HXR data from the Compton Gamma Ray Observatory (CGRO), which contains the most sensitive space-borne HXR detectors ever flown, and provides unprecedented information on fast time structures in solar flares (see first results in Machado et al. 1993a, 1993b). Here we found several subsecond structures in the HXR data which are highly correlated with reverse-drifting radio bursts, regarding the relative timing as well as the pulse duration. We performed a detailed timing study for all reverse-drifting bursts and find systematic trends in the time delays: the HXR pulses are fairly coincident within the instrumental time resolution of 64 ms with the reverse-drifting bursts at the injection frequency, but lead the drifting radio bursts at other frequencies. We find that the frequency-dependent time delay of the reverse-drifting radio bursts is at the limit of expected propagation delays. We discuss various physical effects which might account for the retarded radio emission. This study demonstrates that broad-band spectral coverage is extremely important in understanding the detailed timing between electron beam signatures in radio and HXRs.

2. Observations

We present solar flare observations obtained by the Burst and Transient Source Experiment (BATSE) HXR detector on the CGRO and the radio spectrometer PHOENIX from ETH Zurich, Switzerland. The quality of the data is unprecedented because BATSE has a substantially higher sensitivity than any previous space-borne HXR detector, while the PHOENIX spectrometer was upgraded with a number of improvements (broader frequency coverage, continuous antenna tracking). While BATSE data are available since 1991 April, the upgraded PHOENIX instrument resumed routine observations in 1992 September. From the 341 solar flares registered by BATSE, from 1992 September to December, we identified nine flares with coincident PHOENIX data. For this study we selected the two most intense, type III-emitting flares, observed on 1992 September 5, 1127 UT and on 1992 September 6, 1154 UT.

2.1. History of Active Region

The observations of these two flares are summarized in Table 1. Flare observations have been reported in Hz, soft X-rays, HXRs, microwaves, and in the metric/decimetric frequency range. The flare location was identified from Hz in active region no. 7270 for both flares. The longitude difference of both flare locations, however, indicates a spatial separation of ≈100,000 km inside the active region. The active region no. 7270 produced two “major event” X-class flares on the same day, and 22 M-class flares between September 4 and 9. “It is interesting to note that all of the major events and ten of the minor M-class events observed in September occurred in a single 25 hour period (on September 6) while region no. 7270 was undergoing rapid growth and frequent outbursts” (Solar News Letter). Region no. 7270 spawned 70 optical and X-ray flares. Monitoring the flare activity in the BATSE flare catalog we find that September 6 was one of the most active days in 1992. Both flares were also observed by SXT and HXT on the YOHKOH satellite.

The two events may be considered as “homologous flares,” because they share many common characteristics. The two “twin flares” have their origin in the same parental active region, born 24 hr apart, and they exhibit a similar magnitude in HXR flux, soft X-ray flux, Hz brightness, and radio flux, and a similar time evolution. Although the coherent radio emission shows very similar features in both flares, we notice that the flare of September 6 is more “transparent” at decimetric wavelengths, revealing crucial information on the acceleration source, which is obscured in the September 5 flare.

2.2. BATSE Observations

BATSE consists of eight large-area, wide-field detector modules arranged on the corners of the CGRO spacecraft. Each detector module consists of an uncollimated, shielded NaI scintillation crystal with an area of 2025 cm2 and a thickness of 1.27 cm, sensitive in the energy range of 25 keV–1.9 MeV. Technical characteristics and performance of BATSE are described in Fishman et al. (1989, 1992). We use BATSE background data (DISCLA data type) from the eight large area
TABLE 1
PARAMETERS OF TWO SOLAR FLARES

<table>
<thead>
<tr>
<th>Flare</th>
<th>1992 September 5, 1127 UT</th>
<th>1992 September 6, 1154 UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ha (Penticton)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical importance</td>
<td>1N</td>
<td>1N</td>
</tr>
<tr>
<td>Active region</td>
<td>7270</td>
<td>7270</td>
</tr>
<tr>
<td>Flare location</td>
<td>S08 W21</td>
<td>S11 W42</td>
</tr>
<tr>
<td>Magnetic type</td>
<td>Beta</td>
<td>Beta-gamma-delta</td>
</tr>
<tr>
<td>Soft X-rays (GOES)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Begin, end</td>
<td>1120, 1132, 1200 UT</td>
<td>1145, 1158, 1245 UT</td>
</tr>
<tr>
<td>GOES class</td>
<td>M4.0</td>
<td>M4.0</td>
</tr>
<tr>
<td>Hard X-rays (BATSE/CGRO)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BATSE event</td>
<td>No. 3225</td>
<td>No. 3239</td>
</tr>
<tr>
<td>Begin, peak, end</td>
<td>1122:03, 1127:16, 1131:58</td>
<td>1151:15, 1151:23, 1210:58 UT</td>
</tr>
<tr>
<td>Duration</td>
<td>595 s</td>
<td>1183 s</td>
</tr>
<tr>
<td>Peak counts s⁻¹ cm⁻²</td>
<td>9.5 × 10⁴ c s⁻¹</td>
<td>3.9 × 10⁴ c s⁻¹</td>
</tr>
<tr>
<td>Total counts 2000 cm²</td>
<td>8.3 × 10⁶ c</td>
<td>1.9 × 10⁶ c</td>
</tr>
<tr>
<td>Energy range</td>
<td>25–300 keV</td>
<td>25–300 keV</td>
</tr>
<tr>
<td>Microwaves (Penticton)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio flux 2.695 MHz</td>
<td>140 SFU</td>
<td>84 SFU</td>
</tr>
<tr>
<td>Radio flux 8.8 MHz</td>
<td>220 SFU</td>
<td>230 SFU</td>
</tr>
<tr>
<td>Radio flux 15.4 GHz</td>
<td>140 SFU</td>
<td>170 SFU</td>
</tr>
<tr>
<td>Radio (PHOENIX)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analyzed time interval</td>
<td>1126:30–1127:40 UT</td>
<td>1153:30–1154:15 UT</td>
</tr>
<tr>
<td>Duration</td>
<td>70 s</td>
<td>45 s</td>
</tr>
<tr>
<td>Radio structures</td>
<td>&gt;48</td>
<td>52</td>
</tr>
<tr>
<td>Average burst rate</td>
<td>&gt;0.7 s⁻¹</td>
<td>1.2 s⁻¹</td>
</tr>
<tr>
<td>Maximum burst rate</td>
<td>...</td>
<td>4 s⁻¹</td>
</tr>
<tr>
<td>Normal-drifting bursts</td>
<td>&gt;16</td>
<td>12</td>
</tr>
<tr>
<td>Reverse-drifting bursts</td>
<td>&gt;32</td>
<td>20</td>
</tr>
<tr>
<td>Reverse/normal-drifting pairs</td>
<td>...</td>
<td>10</td>
</tr>
<tr>
<td>Start frequency</td>
<td>750 ± 50 MHz</td>
<td>610 ± 20 MHz</td>
</tr>
</tbody>
</table>

detectors (LADs) in the four energy channels 25–50 keV, 50–100 keV, 100–300 keV, and greater than 300 keV, sampled with a time resolution of 1.024 s. These data are routinely archived in the Solar Data Analysis Center (SDAC) at NASA/ Goddard Space Flight Center (GSFC) for all identified solar flare events (Schwartz et al. 1992). We use also high time resolution data from BATSE, recorded with a time resolution of 64 ms, accumulated in each of the four energy channels and summed from each of the LADs after a burst trigger (data type DISCSC; Discriminator Science Data), made available through the BATSE team at Marshall Space Flight Center (MSFC) (courtesy of G. Pendleton). The accuracy of the BATSE clock on board CGRO, which is crucial for the purpose of this correlative study here, is confirmed to be accurate to within a few ms, after an initial offset of 2.042 s was corrected on 1992 June 25. We do not correct for the time difference between the spacecraft position in orbit and radio observing site, which corresponds to a light travel time difference of less than 30 ms in the worst case and is found to be less than 2 ms in the analyzed flare of September 6, 1154 UT.

2.3. PHOENIX Observations
The spectrometer PHOENIX (Benz et al. 1991) with the extended frequency range of 0.1–3.0 GHz was put into operation on 1989 June, but broad-band routine observations started only in 1992 September, after major instrumental upgrades have been completed, such as new computer controls and continuous antenna tracking. The broad-band observing mode covers the frequency range of 100 MHz–3 GHz with 200 spectral channels, with a frequency resolution of 14 MHz, and a time resolution of 100 ms. The absolute timing is estimated to be accurate within a few ms, controlled by the time signal of the atomic clock of the public long wavelength sender of Prangin, Switzerland. The rms noise of the quiet Sun background in the raw data amounts to ≈1 SFU (= 1 × 10⁻²² W m⁻² Hz⁻¹). The stability of the background flux is found to be better than 1 SFU, now that the new continuous antenna tracking system has been implemented.

The radio data have been calibrated based on instrumental reference sources and published values of the quiet Sun background. Terrestrial interferences have been largely removed in the displayed images by substituting the fluxes from adjacent frequency channels. A preflare background has also been subtracted to enhance the contrast of weak burst structures (≈1 SFU), which are substantially below spectral variations of the quiet Sun background (≈20 SFU). Additional contrast enhancing has been applied in Figures 3–7 (described in next section).

2.4. Analysis of Radio Bursts
The representation of dynamic spectra on a logarithmic flux scale in Figures 1–2 shows clusters of metric/decimetric radio bursts during the impulsive (HXR) flare phases, that can be
Fig. 1.—Overview on the central portion of the flare of 1992 September 5, 1125–1130 UT in radio (top: PHOENIX, 250–3000 MHz spectrogram) and hard X-rays (bottom: DISCLA count rates of BATSE/CGRO, from the most sunlit detector, time resolution 1.024 s). A preflare background has been subtracted from the radio data. The microwave flux integrated from 2 to 3 GHz is overlaid in the top panel. The flare started at 1120 UT in soft X-rays, and ended at 1132 UT in hard X-rays.

Fig. 2.—Central portion of the flare of 1992 September 6, 1152–1157 UT in radio and hard X-rays (same representation as in Fig. 1). The flare started at 1145 UT in soft X-rays, and ended at 1210 UT in hard X-rays.

© American Astronomical Society • Provided by the NASA Astrophysics Data System
fully resolved only by enhancing the dynamic range. This was performed (in Figs. 3–7) by subtracting a lower envelope that filters out time structures \( \geq 1 \) s (The applied “iterative erosion” algorithm is described in Aschwanden et al. 1993b). The so processed grayscale representations show radio fine structures down to the rms level of \( \approx 1 \) SFU.

The fine structures of the radio dynamic spectra of the September 5 flare are enlarged in Figure 3. The frequency of \( \approx 750 \) MHz represents a separatrix between normal- and reverse-drifting radio bursts, providing some interesting information on the location of the injection. The radio bursts appear to be clustered around the times of the HXR peaks, which do not exhibit much significant fine structures in this flare. However, fine structures in radio and HXR are much more conspicuous in the flare of September 6. The time interval of 1153:30–1154:15 UT (Fig. 4) is found to be most suitable to perform quantitative analysis on the relative timing between radio and HXR structures that is described in the following.

In Figure 4 we perform a count of all detectable radio bursts in the frequency range of 350–1500 MHz and find a total of 52 burst structures, whereof 22 structures are broad-banded and reveal drifting features, while 30 bursts are narrow-banded (\( \leq 50 \) MHz), for which the drift rate could not be measured. From the 22 drifting structures we find that 12 bursts have a normal-drifting branch, while 20 bursts contain a reverse-drifting branch. The most interesting finding is that 10 structures consist of a pair of two oppositely drifting bursts, starting practically simultaneous at the same start frequency in the upward and downward direction, suggesting a symmetric injection from a common source. The start frequencies of all 52 radio bursts (defined by the earliest time when the burst becomes detectable, regardless whether it drifts upward or downward, marked by circles in Fig. 4) are scattered over the range of 400–1200 MHz. However, 50\% of the start frequencies are confined in a narrow range of 610 ± 20 MHz. This narrow band of injection points is clearly visible during the time interval of 1153:38–1154:12 UT in Figure 4, where 80\% of the bursts start in this narrow band.

In the following we focus on broad-band reverse-drifting bursts, which are commonly interpreted in terms of electron beams propagating downward in the solar corona, and may have a correlation with the nonthermal HXR flux, if the HXRs are produced by thick-target bremsstrahlung from precipitating electrons. From the 20 reverse-drifting bursts we find 12 with a broad bandwidth, extending to the higher frequency range of 800–1500 MHz. All 12 of these analyzed reverse-drifting bursts are shown in detail in Figures 5–6, and the timing parameters are listed in Table 2. We measure the start time \( t_{L1} \), which is defined by the earliest detection time or leading edge (L1) of the burst at the injection frequency \( \nu_1 \) (with a mean of \( \nu_1 = 730 \pm 160 \) MHz). The highest frequency at which the reverse drifts are detected is found at \( \nu_2 \leq 1500 \) MHz, and the time of the leading edge (L2) at the highest frequency \( \nu_2 \) is called \( t_{L2} \). The reverse-drifting bursts have a positive delay toward higher frequencies by definition, which was found to vary between 200 ms and 900 ms, with a mean of 510 ± 240 ms. The rise time of the radio bursts is measured between the leading edge \( (t_{L2}) \) and the peak flux time \( (t_{R2}) \) and is found to range from 400 to 900 ms, with a mean of \( t_{R2} - t_{L2} = 490 \pm 150 \) ms.

![Figure 3](https://example.com/fig3.png)

**Fig. 3.—** Enlargement of a 70 s time interval during the main impulsive phase of the 1992 September 5, flare (see Fig. 1). A lower flux envelope is subtracted from the radio data to enhance fine structures \( \leq 2 \) s. Black is enhanced flux. High time resolution HXR data with 64 ms (data type DISCSC, summed count rate of the two most sunlit detectors) are shown in the bottom panel.
2.5. One-to-One Correlation of HXR and Radio

Of special interest in this study is the timing between reverse-drifting radio bursts and correlated time structures in HXRs. Figures 5–6 show the coregistered HXR flux with a time resolution of 64 ms. The time structures in both radio and HXR are rather complex. Since we do not have direct information on propagation delays and growth times of the plasma instability producing the radio bursts, there is considerable uncertainty about the relevant time windows where possibly correlated HXR enhancements are expected to start. For simplicity we assume that HXR emission is not expected to rise before the earliest radio detection time \( t_{r1} \), and no later than the latest radio peak time \( t_{r2} \). The corresponding time windows are marked in HXR in Figures 5–6 (hatched areas).

| Radio Start Freq. (MHz) | Radio Start Time (UT) 1153:30 | Radio Lead Delay (s) | Radio Rise Time (s) | Radio FWHM 1 (s) | HXR FWHM 2 (s) | Radio HXR Delay 1 (s) | Radio HXR Delay 2 (s) | HXR Sign. |
|------------------------|--------------------------------|---------------------|---------------------|----------------|----------------|----------------------|----------------------|----------------|}
| 5a                     | 930                            | 1153:30.7           | 0.2                 | 0.4            | 0.4            | 0.32                 | +0.16                | +0.32        | 16.7          |
| 5b                     | 900                            | 1153:38.1           | 0.7                 | 0.6            | …              | …                   | …                   | …             | …             |
| 5c                     | 850                            | 1153:40.8           | 0.4                 | 0.4            | …              | …                   | …                   | …             | …             |
| 5d                     | 850                            | 1153:42.8           | 0.3                 | 0.9            | …              | …                   | …                   | …             | …             |
| 5e                     | 850                            | 1153:46.9           | 0.3                 | 0.4            | 0.7            | 0.5                 | 0.13                 | +0.27         | +0.26         | 5.4           |
| 5f                     | 830                            | 1153:49.2           | 0.5                 | 0.5            | …              | …                   | …                   | …             | …             |
| 5g                     | 830                            | 1153:50.3           | 0.9                 | 0.6            | …              | …                   | …                   | …             | …             |
| 5h                     | 930                            | 1153:54.4           | 0.4                 | 0.5            | 0.4            | 0.4                 | 0.32                 | +0.04         | +0.49         | 12.3          |
| 5i                     | 850                            | 1153:56.2           | 0.5                 | 0.4            | 0.3            | 0.3                 | 0.70                 | -0.05         | +0.16         | 20.6          |
| 5j                     | 820                            | 1153:58.7           | 0.3                 | 0.4            | 0.4            | 0.3                 | 0.51                 | +0.10         | +0.11         | 18.2          |
| 5k                     | 620                            | 1154:01.4           | 0.7                 | 0.4            | …              | …                   | …                   | …             | …             |
| 5l                     | 450                            | 1154:02.1           | 0.9                 | 0.4            | …              | …                   | …                   | …             | …             |
| 730                    | 0.51                           | 0.49                | 0.44                | 0.38           | 0.40           | 0.10                 | 0.27                 | ±160         | ±6.0          |
The time structures of the HXR emission during these 12-sdefined time windows can be described as Gaussian-like, single peak structures in five cases (Figs. 5a, 5e, 6b, 6c, 6d), while the other cases are more complicated, possibly consisting of a superposition of multiple HXR peaks. Many of the HXR time structures show a prompt rise of the HXR flux immediately after the injection time \( t_{i1} \), within \( \pm 200 \) ms (e.g., Figs. 5a, 5b, 6b, 6c, 6d).

In the following we focus on the five best correlated cases (see Table 1). The FWHM duration of the five reverse-drifting radio bursts in \( 440 \pm 150 \) ms at the injection frequency, and \( 380 \pm 80 \) ms at the highest frequency. The FWHM duration of the correlated HXR pulses is surprisingly similar, with \( 400 \pm 220 \) ms. The average significance of the five single-peaked HXR structures is \( 15 \sigma \), according to Poisson statistics of HXR counts above the \( \pm 1 \) s flux envelope within the time intervals \( [t_{i1}, t_{f2}] \). We cross-correlate HXR and radio structures in Figure 7. The definitions of the relevant peak times \( (t_{f1}, t_{r2}, t_{x}) \) is given in Figure 9. The cross-correlation of the HXR peaks (at \( t_x \)) with the correlated radio pulses at the injection frequency \( v_1 \), at \( t_{f1} \), shows a close coincidence; the relative delay \( t_{f1} - t_x \) is \( 100 \pm 120 \) ms is not significant and is of the order of the instrumental time resolutions. However, correlating the HXR peak times \( t_x \) with the radio bursts at the highest frequency \( v_2 \) (at the peak times \( t_{r2} \)), which are expected to be coincident in a simple-minded precipitation model, we find an average delay of \( t_{f2} - t_x = 270 \) ms. The individual delays are significant, but are scattered over a range of \( \pm 150 \) ms (see Table 2). The relative time lag of radio peak time increases continuously from the injection frequency toward higher frequencies. The cross-correlation delay is shown as a continuous function of the frequency in Figure 8, in steps of 50 MHz. The measured radio delay is fitted by linear regression, and an average drift rate of \( 2350 \) MHz s\(^{-1}\) is found in the range of 800--1500 MHz (Fig. 8). The HXR/radio delay is found to be minimal at 800--900 MHz and increases also toward lower frequencies.

Since the HXR time profile shows a number of rapid fluctuations we may ask how high is the chance coincidence between radio and HXR structures. In radio we found 12 well-defined reverse-drifting bursts within a time window of \( dt_{f2} = 45 \) s, where five were unambiguously correlated with HXR time structures with \( t_{r2} - t_x = 270 \pm 150 \) ms, or an uncertainty of \( dt_x = 300 \) ms. There is no unique definition of time structures.
in HXRs, but since we are interested on timescales similar to the radio bursts, we subtract a lower envelope from the HXR flux to enhance fast time structures on timescales \( \lesssim 1 \) s (see hatched structures in Fig. 4 bottom). From the envelope-subtracted HXR flux (Fig. 4) one can count \( \approx 15-25 \) significant time structures in HXR. If we adopt 20 as the best estimate of the number of HXR time structures, the probability for a single correlation \( p \) (of a single radio reverse-drifting burst with a comparable HXR time structure) can be evaluated by

\[
p = \frac{N_x \times d t_x}{d t_{\text{flare}}},
\]

which is \( p = 20 \times 0.3/45 = 0.13 \). The probability \( P_{m,n} \) for \( m \) (radio/HXR) correlations out of \( n \) (radio) events, with \( p \) the probability for a single correlation, is given by binomial statistics:

\[
P_{m,n} = C_n^m \times p^m (1 - p)^{n-m},
\]

\[
C_n^m = \frac{n!}{m!(n-m)!}.
\]

The binomial probability for such a coincidence, with \( m = 12 \), \( n = 5 \), and \( c = 0.1 \) is \( P_{12,5} = 1 \times 10^{-2} \), and thus is unlikely to be due to chance coincidence.

We emphasize that there is no unique definition of time structures in a time profile. If the time structures would be well-separated, in the sense that the flux drops down to the background between structures, a time structure could be easily defined (such as in the case of different flares). However, if a time profile is composed of a superposition of overlapping time structures, no unambiguous deconvolution can be made without a priori knowledge of the shape of structures. The subtraction of a lower envelope merely represents a high-pass filter that enhances fast structures and peaks of longer structures, but it does not allow to measure the true duration of the convolved time structures. In the case of a superposition of triangle-like structures, the FWHM of the triangles may be arbitrarily longer than the timescales suggested by subtracting a closely fitting envelope. Thus, the duration of fast HXR structures measured here (400 ms) does not necessarily prove their existence. However, we justify the application of an envelope-subtraction (that enhances timescales of \( \lesssim 1 \) s) by the nature of the correlated radio data, where unambiguous bursts with
timescales of \( \leq 1 \) s have been identified in a broad frequency range and are found to be well-correlated in unconfused cases. Thus, we may use the high correlation coefficient between HXR and radio structures to justify a posteriori the correct timescale of the envelope filter.

3. DISCUSSION

The unprecedented sensitivity of the \textit{CGRO} HXR data combined with high time resolution and broad-band spectral coverage in radio allow us to probe the density structure of the particle acceleration source and the dynamics of injected electron beams in far more detail. In particular, we are able to establish an unambiguous correlation between signatures of electron beams in radio and HXRs, and to determine the timing between injected electron beams and their correlated HXR response with high precision. In the following we discuss different timescales of the particle acceleration process (§3.1), the inferred spatial structure of the acceleration source (§3.2), and physical effects which determine the observed timing between signatures of electron beams in radio and HXRs, such as propagation effects (§3.3), damping and growth rate effects of radio waves (§3.4), group velocity effects (§3.5), radio wave scattering (§3.6), radio wave ducting (§3.7), or secondary acceleration by radio-frequency heating (§3.8).

3.1. Timescales of Particle Acceleration

We find a hierarchy of timescales in the two observed solar flares, which are perhaps related to different macroscopic structures in the flaring active region. Although enhanced \( \geq 25 \) keV HXR emission is detected over a period of 10–20 minutes in both flares, particle acceleration seems to operate in a coherent fashion not longer than \( \approx 1 \) minute at a time considering the uninterrupted length of an impulsive phase where rapid fluctuations in HXR and a clustering of type III radio bursts occur. The corresponding intervals are 60 s and 70 s in the analyzed cases. Subsequent impulsive flare phases are found to be separated by several minutes.

During the 1 minute periods of continuous particle acceleration we find modulations with typical timescales of 5–10 s,
where the (nonthermal) $\geq 25$ keV HXR flux varies by a notable factor. These omnipresent HXR time structures were coined "elementary flare bursts" (de Jager & de Jonge 1978). Both of the flares studied here contain about six such time structures, which correlate to some extent with a clustering of type III bursts (e.g., Fig. 3). A similar clustering was also found in the 1980 June 27 flare, where the type III rate revealed a linear correlation with the modulated HXR flux (Aschwanden et al. 1990).

Proceeding to smaller time structures, we found 52 discrete radio bursts during an interval of 45 s (Fig. 2), with a maximum rate of four bursts per second (at 1153:55 UT). The average burst rate was $1.2 \pm 1$ s$^{-1}$ and greater than $0.7 \pm 1$ s$^{-1}$ for the two studied flares, respectively. Counting the type III bursts at a fixed frequency, we do not find a rate higher than $\approx 1$ s$^{-1}$. In studies on the quasi-periodicity of type III radio bursts, the observed period of a few seconds (Mangeney & Pick 1989; Zhao et al. 1991) has been attributed to the timescale on which an Alfvénic disturbance traverses the accelerator source. In a recent study, type III burst rates of $0.5-1$ s$^{-1}$ have been found to be persistent as quasi-periodic structures over the entire duration of flares, indicating the presence of a coherent cycle in the acceleration source (Aschwanden et al. 1993b, 1993c, 1994), opposed to a stochastic source, highly fragmented in space. The rate of type III bursts may reflect the basic non-linear cycle of an individual particle accelerator. A quasi-periodic cycle is expected in every dissipative nonlinear system that is driven in marginal stability. The so-called "limit cycle" is determined by the oscillatory feedback mechanism between driving and dissipative forces. Considering the time profiles of the five HXR peaks which have been found unambiguously correlated with a reverse-drifting radio burst, enhanced electron injection seems to be operated in pulses with a typical duration of $400 \pm 220$ ms at an average rate of $1.2 \pm 1$ s$^{-1}$ at the busiest frequency; that constitutes a reasonable duty cycle of $\approx 50\%$ for the main accelerator.

The actual timescale of particle acceleration itself, the time required to accelerate a particle from a bulk-energized superthermal tail up to nonthermal energies, say $\geq 25$ keV, may be shorter than $\approx 200$ ms, considering the shortest rise times of rapid HXR structures (e.g., Figs. 5a, 5b, 6b). We investigated delays between the 25–50 keV channels, but did not find significant time delays beyond the time resolution of 64 ms.

Thus, we find a hierarchy of four timescales relevant to particle acceleration in solar flares: (1) duration of recurrent activation (total flare duration; here 10 minutes), (2) duration of continuous operation (impulsive phases; $\approx 1$ minute), (3) modulation of acceleration efficiency (HXR "elementary bursts"; typically 5 s), (4) nonlinear cycle of individual accelerator (fastest period of type III bursts at a fixed frequency; $\approx 1$ s). These four timescales have also been discussed in the context of the energy release process in Sturrock et al. (1984).

### 3.2. Density Structure of Acceleration Source

The signatures of electron beams can be perceived as drifting structures in radio dynamic spectra. Normal-drifting (frequency-time drift rate negative) are generally interpreted as plasma emission of electron beams propagating upward in the solar corona (e.g., metric type IIIIs), while reverse-drifting bursts (positive drift rate) indicate downward motion, if the electron density decreases with altitude. Broad-band spectra provide a higher chance to detect both normal and reverse-drifting bursts in the same flare phase (e.g., see Fig. 1 in Benz 1987). If the underlying acceleration source is located in a well-defined altitude, we expect the corresponding plasma frequency to separate between upward and downward accelerated electron beams. The flare of 1992 September 6 indeed shows such a separatrix at $610 \pm 20$ MHz, while the 1992 September 5 flare shows a more diffuse separatrix in the range of 700–800 MHz. The two flares analyzed here show a comparable amount of upward and downward drifting bursts, while some bursts start simultaneously in both directions, suggesting a symmetric injection. Such "oppositely drifting pairs" of type III bursts provide an excellent mean to localize the electron density of the acceleration region. In addition, the spectral distribution of such "injection points" contain essential information on the spatial fragmentation of the acceleration source; provided the electron density is a monotonous function of the height in the flaring volume.

The distribution of start frequencies is concentrated in a small range in both flares analyzed here. In the September 6 flare, 50% of the bursts start between $610 \pm 20$ MHz; that is a variation of $\pm 3\%$ in plasma frequency. If we interpret the start frequency of these drifting radio bursts as injection points of accelerated electron beams, we can conclude that the majority of electron beams are accelerated in a region which has less than $\approx \pm 6\%$ variation in electron density. It is therefore likely that the acceleration source is confined to a small volume. A variation of 6% in electron density corresponds roughly to 6% of the density scale height; i.e., $\approx 6000$ km in standard coronal models. Thus, using the plasma frequency as diagnostic of the density structure in the acceleration region, we find that during the main flare phase the majority of electron beams are accelerated in a relatively compact region with a radius of a few 1000 km, while a smaller number of beams originates in a larger flare volume dispersed over a few 10$^4$ km. The important asset of the "oppositely drifting pair bursts" detected here is that their start frequency is identical with the injection point, and thus reveal the fragmentation or clustering of individual acceleration sources as function of the electron density scale height.
3.3. Kinematics and Propagation Delays of Precipitating Electron Beams

We now investigate whether the reverse-drifting radio bursts can be interpreted in terms of plasma emission produced by the downward injected electron beams. From the cross-correlation of the HXR pulses with the radio bursts as function of the frequency we found an average drift rate of 2350 MHz s$^{-1}$ (Fig. 8). This corresponds to an average drift time of $\tau_{drift} = 150$ ms for the five analyzed reverse-drifting bursts, between the average injection frequency $v_1 = 880 \pm 50$ MHz and the average maximum frequency $v_2 = 1240 \pm 100$ MHz. If we interpret this drift time as propagation time between the injection point and the arrival point at high-density regions near the chromosphere (Fig. 9), we can estimate the difference in altitudes. The difference in plasma frequency is about $\Delta f_{\phi}/f_{\phi} \approx 1.4$; that corresponds to a factor of 2 in electron density, or 0.7 electron density scale heights. Instead of using a standard coronal density model for the density scale height, which bears large uncertainties due to the unknown temperature and the questionable applicability of hydrostatic conditions, we use the observed values of type III exciter speeds, which are found in a typical range of $v_{\phi}/c = 0.2 \pm 0.1$ ($v_{\phi}/c = 0.3$, Stewart 1965; $v_{\phi}/c = 0.07-0.25$, Dulk et al. 1987; $v_{\phi}/c = 0.14-0.21$, Aschwanden et al. 1992). The kinetic energy of electrons associated with the radio burst exciter speed of $v_{\phi}/c = 0.2 \pm 0.1$ corresponds to 10 keV, with an uncertainty range of 2-25 keV.

The lower limit of possible exciter speeds for the downward injected electron beams can be estimated from the collisional deflection time of the beam electrons, which is

$$\tau_d = 3.1 \times 10^{-20} \left( \frac{v_{\phi}}{c} \right)^3 \left( \frac{n_{10}}{n_0} \right) s,$$

with $\beta = v_{\phi}/c$ and $n_{10} = n_0/(10^{10}$ cm$^{-3})$. The electron density at the maximum frequency of 1240 MHz is $n_0 = 1.9 \times 10^{10}$ cm$^{-3}$ for fundamental plasma emission, or $n_0 = 0.5 \times 10^{10}$ cm$^{-3}$ for harmonic plasma emission. Requiring a deflection time of $\tau_d > 150$ ms for the downward propagating electron beams, as constrained by the observed average drift time $\tau_{drift} = 150$ ms, we obtain a lower limit for the beam velocity, i.e., $v_{\phi}/c > 0.15$ (>6 keV) for fundamental plasma emission, and $v_{\phi}/c > 0.10$ (>2 keV) for harmonic plasma emission, respectively. Since we have no firm information whether the fundamental or harmonic emission prevails, we adopt a lower limit of $v_{\phi}/c > 0.1$ in the following calculations.

In first order, the observed drift time $t_{s2} - t_{s1}$ is the sum of the beam propagation time and the light path difference of the radio signal (Stewart 1965)

$$t_{s2} - t_{s1} = \frac{H}{v} + \frac{H \cos \vartheta}{c},$$

(4)

with $H$ the altitude difference, $v$ the velocity of the electrons ($v = v_{\phi}$ for radio-emitting electrons, and $v = v_{\phi}$ in the case of HXR-emitting electrons), and $\vartheta$ the angle between the propagation direction and the line of sight. Applying an exciter velocity of $v_{\phi}/c = 0.2 \pm 0.1$ and the observed drift time $t_{s2} - t_{s1} = 150$ ms, we find for the altitude difference $H$ between the injection site and the maximum frequency source (from eq. [4]),

$$H = \frac{c (t_{s2} - t_{s1})}{(1/\beta_R + \cos \vartheta)}$$

(5)

(at flare location S11W42, $\vartheta = 42^\circ$), the following values: $H \approx 8000 \pm 3000$ km, where the uncertainty refers to the assumed error of $\pm 50\%$ in the exciter velocity $v_{\phi}$. The absolute altitude of the injection site may be located in a height range of 0,000–15,000 km, depending on the true height of the $\geq 25$ keV HXR source (<2500 km, Kane et al. 1982b; $\approx 8700 \pm 2000$ km, Matsushita et al. 1992).

Similarly we can derive the kinematics of the $\geq 25$ keV HXR-emitting electrons. If the injection takes place at time $t_1$ at height $H$, the elapsed time between injection and detection of the HXR pulse is in first order the sum of the beam propagation time and the light path difference of the HXR signal (eq. [4]). The velocity of the HXR-emitting electrons is $v_{\phi}/c \approx 0.3$, according to the lower energy cutoff of 25 keV, because the electron spectrum is steeply dropping toward higher energies. Using the height $H$ derived above we find $t_{s2} - t_1 = 110 \pm 40$ ms.

In a simple-minded precipitation model, the thick-target HXR emission is expected to coincide with the arrival time of electron beams near the chromosphere, at the supposed thick-target HXR emission site. However, we find that the radio bursts at the highest observable frequency $v_2$ are delayed to the HXRs by an amount of $t_{s2} - t_1 = 270 \pm 150$ ms. A part of the HXR/radio delay can be explained by different propagation speeds, in our estimate by an amount of

$$dt_{s2} = \frac{H}{c} \left( \frac{1}{\beta_R} - \frac{1}{\beta_X} \right) = (t_{s2} - t_{s1}) \left( \frac{1 - \beta_{\phi}/\beta_X}{1 + \beta_R \cos \vartheta} \right),$$

(6)

which is $dt_{s2} < 70$ ms for $\beta_R > 0.15$ (fundamental emission), or $dt_{s2} < 90$ ms for $\beta_R > 0.10$ (harmonic emission), with $\beta_X = 0.3$ (25 keV) and $(t_{s2} - t_{s1}) = 150$ ms. Thus, the difference in propagation speeds can account for some fraction of the observed radio delay $(t_{s2} - t_1 = 270 \pm 150$ ms), if the radio-emitting electrons have a lower energy than the HXR-emitting electrons. However, there has to be an additional HXR delay effect for

---

© American Astronomical Society • Provided by the NASA Astrophysics Data System
the radio emission, because the HXR pulse precedes the peak of the radio emission at the injection frequency \((t_{RI} - t_x = 110 \pm 120 \text{ ms}; \text{ cf. Table 2})\), although the HXR pulse is detected only at \(t_x - t_I = 110 \text{ ms}\) after the injection time \(t_I\).

3.4. Damping and Growth Rate Effects

Now we investigate whether the timing inferred from the cross-correlation of HXR and radio pulses, which is sensitive to the center of gravity of the pulse shapes, could be biased against unequal pulse shapes or convolution effects. The time dependence of radio type III bursts \(I(t)\) has often been modeled by a convolution of an exciter function \(E(t)\) with a damping function (e.g., Hughes & Harkness 1963),

\[
I(t) = \int_0^t E(t')e^{-\alpha(t-t')/\tau} dt'.
\] (7)

For the case of plasma emission, the exciter function \(E(t)\) is a function of the electron injection rate, while the damping function is commonly attributed to collisions or nonlinear Langand damping (e.g., Dulk 1985). The pulse shape of thick-target HXR emission can similarly be characterized by the energy loss time due to collisional bremsstrahlung. Because the FWHM of the HXR pulses was measured to be 400 ± 220 ms for the five analyzed bursts here, which is considerably longer than the collisional loss time in typical chromospheric densities \((N_e \gtrsim 10^{15} \text{ cm}^{-3})\) where thick-target HXR emission is believed to occur, we can conclude that the duration of the observed HXR pulses mimics the time profile of electron injection rather than the collisional energy loss time. If we use the HXR time profile as proxy for the electron injection rate, we can characterize the exciter function \(E(t)\) of the radio bursts by the time profile of the HXR pulses, i.e., with a mean duration of 400 ± 220 ms. On the other side, we found the FWHM duration of the radio bursts (with 440 ± 150 ms at the injection frequency, and 380 ± 80 ms at the highest observed frequency) very similar to the FWHM duration of the HXR pulses. From the similar durations of the observed radio signals \(I(t)\) and the exciter profile \(E(t)\) we can conclude that the damping time \(\tau\) (eq. [7]) is negligibly small compared with the FWHM duration of \(E(t)\), i.e., \(\tau \lesssim 400\) ms. This is also consistent with the collision time of thermal electrons, \(t_{coll} \approx [50n_e T^{-3/2}]^{-1} \text{ Hz},\) amounting to \(\lesssim 5\) ms (at the maximum frequency of 1240 MHz) for fundamental plasma emission, or \(\lesssim 20\) ms in the case of harmonic plasma emission, assuming a coronal temperature \(T < 3\) MK.

Radio emission of type III bursts is governed by coherent growth of Langmuir waves which saturate at a typical brightness temperature level of \(T_B = 10^8 - 10^{12} \text{ K}\) (Dulk 1985). The growth time of any coherent emission mechanism has to be shorter than the collisional deflection time. The effective growth rate \(\gamma_{eff}\) of Langmuir waves

\[
\gamma_{eff} = \gamma_{in} - v_{Coll} > 0
\] (8)

has to be positive. To reach a detectable flux (which is assumed to correspond to a brightness temperature of \(< 10^9 \text{ K}\)) we estimate that \((\ln [W_{min}/W_{thermal}] \lesssim 10^9 \text{ K}/10^6 \text{ K}) \approx 7\) e-folding growth times are required, i.e., \(t_{growth} \lesssim 7t_{coll} \approx 40\) ms for fundamental plasma emission, or \(t_{growth} \lesssim 150\) ms for harmonic plasma emission. Thus, up to 50% of the observed HXR/radio delay of 270 ms could be caused by the marginal growth rate of Langmuir waves, in the case of harmonic plasma emission.

3.5. Group Velocity Delay Effects

The radio emission of the analyzed reverse-drifting bursts is interpreted in terms of plasma emission, but it is not clear a priori whether it is at the fundamental or harmonic plasma frequency. We have not observed fundamental/harmonic pairs that could lead to a clear identification. Plasma emission in the frequency range of 750–1500 MHz is assumed to be at the harmonic level, because free-free absorption strongly suppresses fundamental plasma emission at these frequencies, assuming standard coronal density models. The free-free opacity at 1 GHz is less than unity only if the density scale height is \(\lesssim 700\) km for fundamental, or \(\lesssim 10^4\) km for harmonic plasma emission (Dulk 1985). If electron beams are injected in overdense fiber structures with such small diameters, plasma radiation can escape from these overdense fiber structures across the steepest transverse density gradient and propagate in the ambient low-density corona at microwave frequencies of 6–8 GHz (Benz et al. 1992). Thus we cannot rule out fundamental plasma emission for the reverse-drifting bursts observed here at 750–1500 MHz.

For fundamental plasma emission, time delays in the order of \(\lesssim 1\) s can occur due to the low group velocity near the plasma frequency. The total time delay integrated along the path to the observer is

\[
t_{\text{group}} = \int \frac{1}{v_{gr} - c} ds.
\] (9)

Using the simplified dispersion relation for plasma emission, i.e., \(v_{gr} = \omega / k \approx nc \approx c(1 - \omega_p^2)^{1/2}\), and integrating from \(n = 0\) to \(n = 1\) in an exponentially decreasing atmosphere (with scale height \(\lambda\)), the total group delay amounts to

\[
t_{\text{group}} \approx 1.4 \frac{\lambda}{c \cos \alpha} \text{ s},
\] (10)

with \(\alpha\) being the angle between propagation direction and line of sight. Thus, for fundamental emission with \(\alpha = 0\) in the standard corona (\(T = 1.5 \text{ MK}; \lambda = 70,000\) km), the expected group delay is \(\approx 300\) ms. However, fundamental emission at 1 GHz can only escape, when the density scale height along the escape path (e.g., perpendicular to an overdense fiber structure) does not exceed \(\lambda = 700\) km. The resulting group delay is then reduced to 3 ms, according to equation (10). Even if we assume strong attenuation by a factor of 1000 for the detected plasma emissions, the free-free opacity can only be enhanced by a factor of \(\tau_{eff} = \ln(1000) \approx 7\); that increases the maximum density scale height and the resulting group delay by the same factor, i.e., \(t_{\text{group}} \lesssim 20\) ms. For harmonic plasma emission, the group delay is negligible, because \(v_{gr} \approx c\). Thus, we conclude that the observed radio delay of 270 ms between HXR and radio cannot be explained by group delay effects, neither at the fundamental nor harmonic plasma level.

3.6. Time Delay Induced by Scattering of Radio Waves

Scattering of radio waves on density inhomogeneities has been proposed long ago (Riddle 1972a, b; Stewart 1972), including ducting and scattering of radio waves in coronal fiber structures (Bougeret & Steinberg 1977; Duncan 1979). The problem was addressed in recent studies (Roelof & Pick 1989; Lecacheux et al. 1989; Bastian 1993), but quantitative results depend on a detailed knowledge of the structure of the coronal inhomogeneities and the spectrum of density fluctua-
tions in the lower corona. However, we want to investigate possible time delay effects induced by scattering of radio waves. Since the spatial size of type III radio sources can subtend considerable angles, presumably caused by wave scattering of electromagnetic waves off coronal inhomogeneities, we evaluate time delays induced by the extra light travel path of scattered radio waves. The apparent spatial size of type III sources is strongly frequency dependent: \( \approx 15' - 30' \) at 43 MHz (Dulk & Suzuki 1980; Dulk et al. 1980), \( \approx 5' - 20' \) at 80 MHz (Stewart 1974; Dulk & Suzuki 1980; Dulk et al. 1980) \( \approx 3' - 7' \) at 169 MHz (Bougeret et al. 1970), \( \approx 2' - 3' \) at 333 MHz (Aschwanden, Bastian & Benz 1993a); \( \approx 1.5' \) at 333 MHz (Willson, Aschwanden, & Benz 1991); \( \approx 40' \) at 1446 MHz (Aschwanden et al. 1992); \( \approx 25' - 30' \) at 1446 MHz (Willson & Benz 1990), \( 17' - 34' \) at 1496 MHz (Bastian 1991). The latter source diameter measurements at decimeter wavelengths are taken from recent VLA observations, which are referred to as type III bursts, narrowband decimeter bursts, type U-bursts, and are likely to be attributed to plasma emission. In Figure 10 we plot the measured source sizes \( D \) as function of the observed frequency \( \nu \), and find that all the measurements can be fitted by the power-law relation

\[
D(\nu) = 30,000 \nu^{1.08} \text{ km}.
\]

(11)

Since type III sources appear as an amorphous brightness distribution with diameter \( D(\nu) \), while the sources of beam-driven plasma emission are likely to be smaller based on the diameters of magnetic loops measured in X-rays, the apparent size of type III sources may be considerably enlarged due to wave scattering. If we assume that the observed electromagnetic wave is emitted at an angle of \( \theta \) to the line of sight and is subject to a single scattering in direction to the observer after a mean free path in the order of the source radius \( D/2 \), the delay due to the extra light path of the scattered wave is

\[
\tau_{\text{scatter}}(\nu, \theta) = \frac{D(\nu)}{c} \left( 1 - \cos \theta \right) \approx 0.10 \nu^{-1.08} \frac{(1 - \cos \theta)}{2} \text{ s}.
\]

(12)

Even for large-angle scattering, in the order of \( \theta = 90' \), where the scatter delay amounts to \( \tau_{\text{scatter}} = D/2c \), which is 60 ms

At 800 MHz, or 30 ms at 1.5 GHz, the resulting light path difference is nearly an order of magnitude too small to explain the observed HXR/radio delay of (270 ms).

3.7. Time Delay by Ducting of Radio Waves

Refraction guides the radio waves along low-density flux tubes (called ducts) similar to light waves in an optical fiber. When the radiation reaches the higher corona, the plasma frequency of even the high-density ducts falls below the frequency of the radiation, and the radiation escapes from the duct. Ducting has been proposed to account for the coincidence of apparent source position of fundamental and harmonic type III bursts. The observed position of fundamental/harmonic pairs—observed at the same frequency—nearly coincide (e.g., Suzuki & Dulk, 1985). Therefore, the fundamental emission must be ducted at least to the true source position of the harmonic, i.e., a distance of \( H_{\text{duct}} = 4 \ln(4) \approx 25,000 \) km for the reverse-drifting bursts. Although this estimate of the local density scale height, we expect a ducting delay

\[
t_{\text{duct}} \approx \frac{H_{\text{duct}}}{c} (1 - \cos \theta),
\]

(13)

of \( t_{\text{duct}} \approx 20 \) ms, with \( H_{\text{duct}} = 4 \ln(4) \approx 25,000 \) km. This value is also in close agreement with the height of 1.5 GHz radio sources statistically determined from stereoscopic VLA measurements (25,000 \( \pm \) 15,000 km; Aschwanden & Bastian 1993). Although the latter measurements were made from 20 cm emission of active regions, which is believed to be dominated by free-free emission, the observed electromagnetic radiation may be subject to the same ducting effects as the plasma emission from type III sources.

3.8. Secondary Acceleration by Radio-Frequency Heating

So far we considered the model where HXR emission and radio emission is caused by electron beams in the same loop system. Alternatively, the two emissions may originate from different electron populations in different loops, possibly triggered by a common signal. A scenario of this type has been proposed by Sprague & Vlahos (1983), and was also discussed by Melrose & Dulk (1984), and Reames (1990). Sprague & Vlahos (1983) suggested that a considerable fraction in the thick-target beam producing HXRs is converted into electroncyclotron maser emission, driven by the loss-cone distribution of particles reflected in the converging magnetic field. The waves are emitted at the electron gyrofrequency or some low harmonic of it and initially propagate at a large angle to the magnetic field. They are absorbed when their frequency matches a higher harmonic of the gyrofrequency and transfer their energy to resonant electrons in an adjacent loop. The accelerated particles may then form up- and down-going beams causing the radio bursts. In this scenario one would expect a delay of the radio emission in the secondary loop with respect to the precipitation-induced HXR emission in the primary loop, due to (1) the light travel of the maser waves from the primary loop to the absorption region in the secondary loop, (2) the beam formation time, (3) the Langmuir growth time, and (4) radio propagation effects. The observed simulta-
neity of emission from the injection site and HXR peaks does not support this scenario.

4. CONCLUSIONS

In this study we present the first results of a detailed correlation between high time resolution data from BATSE/CGRO and the upgraded radio spectrometer PHOENIX. We analyzed the time structures of the two solar flares from 1992 September 5 (1127 UT) and 1992 September 6 (1154 UT) in HXRs and metric/decimetric radio under special consideration of the relative timing of electron beam signatures in both wavelength domains. The high sensitivity and time resolution of BATSE/CGRO as well as the uniform broad-band coverage of the PHOENIX radio data have proved to be extremely important for this task. The results can be summarized as follows.

1. The two flares exhibit in HXR and radio a hierarchy of four different time scales related to the (macroscopic) organization of particle acceleration: (1) duration of recurrent activation (total flare duration; here 10 minutes), (2) episodes of contiguous acceleration (impulsive phases, characterized by rapid fluctuations in HXR and temporal clusters of radio type III bursts; here 1 minute), (3) modulation of particle acceleration efficiency (so-called HXR “elementary bursts”; here 5–10 s each), (4) nonlinear cycle of a spatially coherent acceleration source (mean period of coherent type III train at a fixed frequency; here ≈ 1 s).

2. The spatial organization of the particle acceleration source in a flare can be inferred from the spectral distribution of injection frequencies in the radio spectra. The most reliable tracer of injection points is the start frequency of upward/downward-drifting burst pairs. We find that the distribution of injection points forms a separatrix between upward and downward drifting bursts in the two analyzed flares (at 750 ± 50 and 610 ± 20 MHz). During the main impulsive flare phase, up to 80% of the injection points were found to be concentrated in a small frequency band of ±20 MHz, corresponding to a variation of ±6% in electron density, probably confined to a compact region with a radius of a few 1000 km.

3. The one-to-one correspondence of precipitating electron beams and thick-target HXR emission can be inferred from the relative timing of reverse-drifting radio bursts and correlated fine structures in HXR. We analyzed all (12) reverse-drifting radio bursts in the 1992 September 6 flare and found that the five most unambiguously correlated bursts coincided with the HXR pulses within a relative scatter of ±150 ms. An accidental coincidence is largely ruled out by statistical tests. The correlated HXR and radio pulses have a similar duration of ≈400 ms. The average significance of the five correlated HXR time structures is 15σ.

4. The following relative timing between HXR and radio time structures has been found from cross-correlations: The HXR pulses are nearly coincident (100 ± 120 ms) with the radio bursts at the injection frequency of ≥800 MHz, but lead the radio bursts at all other frequencies. The downward drifting radio bursts are significantly delayed with respect to the HXR pulses, with a mean delay of 270 ± 150 ms at the average maximum frequency of 1240 MHz, where the relative delay is expected to be smallest in a standard thick-target model. The mean drift rate of the five analyzed reverse-drifting bursts is 2350 MHz s⁻¹.

5. We examined various effects which could be responsible for the retarded radio emission (particle propagation effects, different energies for the HXR-emitting and radio-emitting electrons, group velocity delays, collisional damping and wave growth times, radio waves scattering, radio wave ducting, light path differences, time difference between spacecraft orbit and ground-based radio station, clock errors). From all investigated effects (see Table 3), we find the following accumulative upper limit for the expected HXR/radio delay: less than 190 ms for fundamental plasma emission, and less than 310 ms for harmonic plasma emission, opposed to the observed HXR/radio delay of (t_{HXR} – t_{X}) = 270 ± 150 ms. The values found for the upper limits favor harmonic emission, as expected from the argument of lesser free-free absorption. The calculations show that the HXR/radio delay is mainly caused by the two following effects: (1) radio-emitting electrons have a lower energy
than the HXR-emitting electrons (> 25 keV), and (2) the radio wave growth time can be as long as <150 ms in marginal stability.

These results have two major implications: On one hand they give more confidence to the flare model with precipitation-induced thick-target emission in HXR, because unambiguously correlated signatures of electron beams in both radio and HXR wavelengths now become detectable, and are found to mutually coincide within the instrumental time resolution at the injection frequency. The data analyzed here can be considered as the most unambiguous detection of electron beams at HXR wavelengths in solar flares so far. On the other hand, we encountered the complication that the relative timing of beam-driven HXR and radio emission is strongly dependent on the radio frequency and particle energy. This complication requires more modeling effort to understand the accurate timing, but provides new constraints on physical parameters, on the other hand.

We are pleased to thank the individuals who made BATSE/CGR data available, notably G. Fishman for the open policy of handling solar CGRO data, the BATSE team at MSFC, G. Pendleton for providing the high time resolution DISCOSS Aeta, B. M. mis & A. A. 224, 242.

REFERENCES

Fishman, G. J., et al. 1989, The Burst and Transient Source Experiment (BATSE)—Scientific Objectives and Capabilities, GRO Science Workshop (Greenbelt: GSFC), 3
Matsushita, K., Masuda, S., Kosugi, T., India, M., & Yaji, K. 1992, PASJ, 44, L89
———. 1974, in IAU Symp. 57, Coronal Disturbances, ed. G. Newkirk, Jr. (Dordrecht: Reidel), 161

© American Astronomical Society • Provided by the NASA Astrophysics Data System