Microwave and Hard X-ray Emission Bursts during Solar Flares

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Analysis of time intervals and peak fluxes between hard X-ray (HXR) of energies 17-40 keV and solar microwave (MW) bursts observed at 3.75, 9.4 and 17 GHz during impulsive and extended solar flares shows both simultaneous emission between MW and HXR emissions and delay at onset and peak. The flares showing simultaneous emission between MW and HXR emissions may be simple loop flares. The time delay may be due to differences in source location, mechanism and kinetic energies of electrons required to produce MW and HXR emission bursts. The peak fluxes of the MW and the HXR emissions are well correlated during impulsive flares, and radio flux and photon counts $S^{-1}$ increase linearly, suggesting that they may be produced by the same species of accelerated solar particles.

1 Introduction

Microwave (MW) and hard X-ray (HXR) emissions observed during flares are intimately related to each other, although their wavelengths are quite apart; the reason is that both the radiations are caused by energetic electrons in the flares of thermal or non-thermal nature. Dulk and Dennis concluded that both the radiations emanate from a common source. The studies by McKenzie, Kane, Cranell et al., Takakura et al. and Cornell et al. show delays up to 10 s at peak. These investigations led to a controversy about the time delay between MW and HXR radiations during flares. Takakura and Cranell et al. pointed out that the delay is lesser at higher frequencies.

The close similarity of time profiles led various investigators to examine the correlation of fluxes of HXR and MW emissions. Different radiations observed during solar flares originate at different heights. The time delay study between MW and HXR radiations will tell us about the mechanism and the height at which the flare triggers first and also about the evolution of energetic electrons. From the onset time delay we can infer about the height at which the flares get triggered initially. From the peak time delay we can study the evolution of energetic electrons and also other particles produced during solar flares.

In this paper we have studied time interval between HXR (17-40 keV) and MW (at 3.75, 9.4 and 17 GHz) to see how the time delay varies with change of frequency of MW emissions and the correlation between peak flux of HXR and MW at various frequencies. These studies throw light on the mechanism of acceleration of electrons (and also acceleration rates) involved in the production of HXR and MW emissions. Further, we have also studied the relation between peak fluxes of HXR and MW emissions at various frequencies separately during impulsive and extended solar flares.

2 Observational Data and Analysis

In studying the relation between MW and HXR emission bursts, we have used time correlation method used earlier by Swarup et al., Zirin, Verma and Pande, and others.

The HXR emission data used in this study were supplied by Prof. K Tanaka of Tokyo Astronomical Observatory, Japan. The Hinotori Satellite recorded HXR data during 26 Feb. 1981-15 Sep. 1982. The data book published by the above team contains 609 flare time profiles (FTPs). Each FTP consists of four frames. The first frame counts 17-40, the second 40-67, the third 67-152, and the fourth 152-359 keV photons. Details about the photon counting for various energy levels are given in Hinotori Satellite Preliminary Solar Hard X-ray Data, Parts I and II (Ref. 18).

The MW (17 GHz) data used in the present study were supplied by Kosugi and Shiomi of Tokyo Astronomical Observatory, Japan. The 17 GHz data recorded at Nobeyama Solar Radio Observatory during 1978-82 were published under the title Solar Radio Activities. In the present study, we have used the data given in Section 5 of this data book, where a list of outstanding events at 17 GHz is given with a time resolution of 0.1 min or 6s. The 3.75 and 9.4 GHz MW emissions data were originally recorded at Towakawa Observatory, Japan, and included in the Chapter "Solar radio emission out-
standing occurrences" which appeared in Solar Geophysical Data (SGD)\textsuperscript{20}. The resolution of reported MW events in SGD is 0.1 min or 6s, although the MW emission data at 3.75, 9.4 and 17 GHz are recorded with temporal resolution better than a second.

The present study is limited to the period of observation embraced by Hinotori Satellite for HXR data. In the present study, we have used the first frame (17-40 keV) for HXR data, basically because the frequency of events is maximum in this frame. We have read the onset and peak times for each flare within 1s from FTPs by using Bausch and Lomb magnifying eye piece (magnification = 7) and its millimetre scale having a least count of 0.1 mm but noted with resolution of 6s to match time resolution MW data. As mentioned above, Hinotori recorded 609 FTPs during 1981-82. As many as 65 FTPs were excluded from our analysis, because there is uncertainty in either onset or peak intensity times or in both in the HXR data. Finally, we were left with 544 HXR FTPs and out of them we could get only 75 MW events at 17 GHz, 164 events at 9.4 GHz, and 118 events at 3.75 GHz, as shown in Table 1. Only simple or complex type MW (at 3.75, 9.4 and 17 GHz) emission bursts recorded during flare duration were considered in this study. Out of 75 MW bursts at 17 GHz, 69 and 6 bursts are recorded during impulsive and extended solar flares respectively (Table 1). Here, we call those flares as impulsive solar flares whose HXR bursts duration are $\leq 1000$ s (Ref. 21) and those flares as extended solar flares whose HXR bursts are $> 1000$ s. Further, at 3.75 and 9.4 GHz, 112 and 156 MW bursts were recorded during impulsive solar flares, and 6 and 8 MW bursts during extended solar flares (Table 1).

![Fig. 1—Histogram showing the time difference in seconds between the onset of the HXR and the MW emissions during solar flares versus the number of flares with HXR and MW emissions bursts](image)

<table>
<thead>
<tr>
<th>HXR profiles observed during 1981-82</th>
<th>HXR with uncertainty in onset/peak times</th>
<th>Number of HXR FTPs available for comparison study</th>
<th>Number of MW emission bursts (simple/complex) observed against HXR profiles available for comparison at 3.75 GHz</th>
<th>Number of impulsive solar flares</th>
<th>Number of extended solar flares</th>
</tr>
</thead>
<tbody>
<tr>
<td>609</td>
<td>65</td>
<td>544</td>
<td>112*</td>
<td>118</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.4*</td>
<td>156*</td>
<td>69*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17*</td>
<td>6*</td>
<td>8*</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>118</td>
<td>164</td>
</tr>
</tbody>
</table>

*Number of impulsive solar flares
+Number of extended solar flares
2.2 Peak Flux Relation between HXR and MW Emissions

In studying peak flux relation between the HXR (17-40 keV) emissions and the MW emissions at 3.75, 9.4 and 17 GHz, we have calculated the correlation coefficient between the HXR and the MW emissions at various frequencies. The correlation coefficients have been calculated during impulsive flares and the values are shown in Table 2. The peak flux rates at 3.75, 9.4 and 17 GHz versus 17-40 keV HXR emissions are plotted in Figs 3-5, where the

after 60 s. The time delay between MW at various frequencies and HXR during impulsive flares is shown by diagonal hatchings, and that between MW and HXR during extended flares by vertical hatchings (Figs 1 and 2).

The salient results of the time delay between HXR bursts and MW bursts at various frequencies are as follows:

(1) Some impulsive flares produced MW (3.75, 9.4 and 17 GHz) and HXR (17-40 keV) emissions simultaneously at onset and at peak (Figs 1 and 2).

(2) Impulsive flares also produced HXR emissions up to 12 s earlier or up to 18 s after the onset of MW emissions at 3.75 and 9.4 GHz. The HXR emissions are observed up to 6 s earlier or up to 12 s after the onset of MW emissions at 17 GHz.

(3) At maxima during impulsive flares, the HXR emissions are observed 12 s before or 6 s after at 17 GHz MW emissions and up to 18 s before or up to 6 s after at 9.4 and 3.75 GHz MW emissions, respectively.

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cross symbol stands for impulsive solar flares and the cross-in-circle symbol for extended solar flares; in Figs 3-5, sfu stands for solar flux unit and 1 sfu = 10^{-22} \text{ Wm}^{-2} \text{ Hz}^{-1}. The criterion for calling a flare as impulsive or extended is explained earlier. We have fitted the linear equation in Figs 3-5 for impulsive flares only, since the number of points belonging to extended solar flares is less and the scatter is also very large. Therefore we have not fitted any linear curve to data of extended solar flares. The values of \( m \) and \( c \) with their errors are shown in Table 2 for impulsive solar flares, where \( m \) and \( c \) are constants.

The brief results of peak flux relation between the HXR and the MW bursts at various frequencies are as follows:
(1) During impulsive solar flares, correlation coefficient between HXR bursts and MW bursts at 3.75, 9.4 and 17 GHz lies between 69 and 79%.
(2) Further peak flux of MW and HXR emissions during impulsive solar flares increases linearly.

### 3 Discussion

The time relationship between the MW and the HXR emissions observed during solar flare is not the same as found by earlier investigators. Kundu\(^2\), Zirin \(et \text{al.}\)\(^2\) and Vorphal\(^3\) found that MW and HXR emissions occur simultaneously while McKenzie\(^5\), Cranell \(et \text{al.}\)\(^6\), Takakura \(et \text{al.}\)\(^7\) and Cornell \(et \text{al.}\)\(^9\) found delays up to 10 s at peak. The basic aim of these investigators had been to study the origin and evolution of energetic electrons and particles produced during impulsive phase of solar flares; that is why they limited their study to the maxima of MW and HXR emissions.

On the basis of simultaneous observations of MW and HXR emissions, many investigators have suggested that these two radiations come from a common source\(^4\).

The number of electrons required to produce HXR emissions is \(10^2\)-\(10^3\) times more than those required to produce MW emissions. Since the electron density decreases with height in the solar atmosphere, we may say that the HXR and the MW emissions may not be emanating from a common source. Perhaps the HXR emissions come from

<table>
<thead>
<tr>
<th>HXR emissions solar bursts and MW emissions bursts at</th>
<th>3.75 GHz</th>
<th>9.4 GHz</th>
<th>17 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of impulsive solar flares</td>
<td>112</td>
<td>156</td>
<td>69</td>
</tr>
<tr>
<td>Correlation, ( % )</td>
<td>78</td>
<td>79</td>
<td>69</td>
</tr>
<tr>
<td>Fitted straight line parameters ( m )</td>
<td>(1.08 \times 10^{-1})</td>
<td>(8.43 \times 10^{-2})</td>
<td>(4.62 \times 10^{-2})</td>
</tr>
<tr>
<td>and ( c )</td>
<td>82.53</td>
<td>48.52</td>
<td>56.68</td>
</tr>
<tr>
<td>Errors in ( m )</td>
<td>(1.38 \times 10^{-2})</td>
<td>(5.35 \times 10^{-3})</td>
<td>(3.56 \times 10^{-3})</td>
</tr>
<tr>
<td>and ( c )</td>
<td>63.60</td>
<td>15.17</td>
<td>11.26</td>
</tr>
</tbody>
</table>

Table 2—Correlation and Fitted Straight Line Parameter between MW Emissions (at 3.75, 9.4 and 17 GHz) and HXR (17-40 keV) Emissions during Impulsive Solar Flares
deeper layer in the solar atmosphere. Recently, Ho- 
yng et al.23 observationally found differences in the 
respective locations of MW and HXR sources.

In the present investigation (Fig. 1), we have 
found that 13 impulsive flares show simultaneous 
emission at 17 GHz between MW and HXR emis­ 
sions at onset [see HXR FTPs (Ref. 18)]. The dura­ 
tion of these 13 FTPs in HXR is ~ 1 min. Also be­ 
tween HXR (17-40 keV) and MW emissions at 
9.4 GHz, 22 impulsive flares show simultaneous 
emission [see HXR FTPs (Ref. 18)]. Out of these, 15 
flares have HXR profiles of duration ~ 1 min, 4 
flares of ~ 2 min, and 3 flares of ~ 4 min. Ac­ 

The relation between the peak flux rate of the 
HXR and the MW emissions has been studied by 
many investigators12–14. Since the physical condi­ 
tions are thought to be different for impulsive and 
extended solar flares, the peak correlation has been 
examined separately during the two types of flares 
by us. Therefore, in the present analysis, we have 
examined the peak flux rate correlation between the 
MW emissions at 3.75, 9.4 and 17 GHz and the 
HXR (17-40 keV) emissions during impulsive and 
extended solar flares separately. 

Figs 3-5 show that the peak fluxes in HXR and 
MW at various frequencies are linearly related, 
which suggests that in flares, both the radiations are 
produced by the accelerated electrons.

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o-mical Observatory, Japan, for supplying HXR 
emissions bursts data observed on board Hinotori 
Satellite.

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