ON THE RELATION BETWEEN DECIMETRIC AND HARD X-RAY EMISSIONS IN THE IMPULSIVE FLARE PHASE

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Abstract. The emission of decimetric flare radiation, in particular narrowband spikes and pulsations, is generally considered to originate from accelerated, non-thermal particles. On the other hand, non-thermal hard X-rays (HXR) are well accepted results of such acceleration. Are radio emissions and HXR signatures of the same acceleration process? Good correlation of the light curves in the radio and HXR range may evidence it.

The correlation of decimetric radio emission and HXR in solar flares was analysed using data from the RHESSI spacecraft and the Phoenix-2 spectrometer in Bleien (Switzerland). For the first time we have the possibility of a systematic search on the radio-HXR relation in the range from 100 MHz to 4 GHz.

The measured delays have a distribution with a FWHM of 4.9 s and 4.7 s for pulsations and spikes, respectively, evaluated from a Gauss fitting method. The mean delay for pulsations was found to be $-1.4 \pm 0.9$ seconds (minus indicates that hard X-rays emission comes first), and for narrowband spikes to $-2.5 \pm 2.5$ seconds. The delays do not depend on frequency, cross-correlation coefficient, duration of the correlating sequence and position on the disc. However, we find an increase in delay for the spikes with GOES magnitude (peak soft X-ray emission) of the flare and with peak hard X-ray flux.

Key words: flares - corona - radio radiation - X-rays - particle acceleration

1. Introduction

The intense emissions of decimetric radiation of solar and stellar flares are generally considered to originate from non-thermal electron velocity distributions. Such distributions can be unstable to maser emission or plasma waves that couple coherently into radio waves. Non-thermal velocity distributions originate directly from acceleration processes in flares, or may be driven to instability by particle trapping or propagation.

On the other hand, HXR emitted by non-thermal electrons are well accepted results of such acceleration. If the radio and X-ray emitting electrons
were accelerated by the same process, correlation is expected between the two emissions. Conversely, radio emissions correlating with HXR carry possibly complementary information on acceleration or particle propagation and trapping. Benz et al. (2005) have shown that practically every HXR flare is associated with coherent radio emission, where "associated" means that the radio event occurs during the enhanced HXR emission. However, for correlation we require that both light curves, radio and X-ray emission, evolve at the same time.

Among the different types of coherent emissions in the decimetre range, narrowband spikes are of greatest interest as possible radiations from close or within the acceleration region. A close correlation between narrowband spikes in the decimetre range and HXR has first been reported by Benz (1985) and Benz and Kane (1986). Around 95% of the radio events with narrowband decimetric spikes are associated with HXR emission (Güdel et al., 1991). The time profile integrated over the band, in which spikes were observed, and the time profile of HXR have been found to have a high cross-correlation coefficient (Güdel et al., 1991; Aschwanden and Güdel, 1992; Fărău and Karlický, 2005). However, Güdel et al. (1991) noted that the X-rays are observed 4±9 s earlier than the radio emission. Aschwanden and Güdel (1992) reported that the spikes appear later by 2 up to 5 seconds, the larger the HXR flux, the later radio emission. However, Fărău and Karlický (2005) find no such correlation in a smaller sample. The reported delay of decimetric spikes has generally been taken to suggest that the spikes are a secondary effect due to propagation and/or trapping.

As suggestive narrowband spikes may be as tracers of acceleration, they are relatively rare. Among all solar flares observed in SXR by GOES, only 2% of them are associated with decimetric spikes (Dąbrowski et al., 2005). The number increases to 14% when starting from flares observed in HXR by the RHESSI satellite (Benz et al., 2005).

For quasi-periodic, broadband decimetric pulsations, the association rate is 80% (Benz et al., 2005). The first systematic research on the association of decimetric pulsations with HXR were conducted by Aschwanden et al. (1990). They found also occasional correlation. Investigating the correlation in more detail, Kliem et al. (2000) reported an anti-correlation of the fine structures in pulsating radio emission with HXR. Anti-correlation could also be interpreted as a phase shift or delay of 1.3 s. Arzner and Benz (2005) report a delay of HXR relative to decimetric pulsations between −6
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s and 0.46 s. The mean delay is $-1.1$ s (HXR first) and is statistically not significantly different from zero.

Here we present an investigation of the relation between coherent decimetric emission and HXR. The radio emission was observed by Phoenix-2 (Benz et al., 1991; Messmer et al., 1999). For the first time we have the possibility of a systematic search on the radio-HXR relation in the range from 300 to 3000 MHz. HXR observations have been made by RHESSI (Lin et al., 2002). The high spectral resolution of RHESSI made it possible to carefully choose the energy range and to maximize the non-thermal counts, excluding thermal emission. We are using the method developed by Arzner and Benz (2005).

2. Observations

Phoenix-2 is a broadband radio spectrometer located at Bleien, Switzerland. The frequency-agile spectrometer measures the total flux density and the circular polarization (bandwidth: 1, 3 or 10 MHz). It records the full Sun radio emission from 100 MHz to 4 GHz from sunrise to sunset. The time resolution of 0.1 second in each channel. The radio spectrogram is integrated over a finite bandwidth in order to obtain a single time profile. The broad bandwidth of Phoenix-2 allows selecting any emission in the full decimetre range. The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite observes X-rays in the range from 3 keV to 17 MeV.

The accuracy of the timing of the two instruments is essential for temporal correlation. Time delays may have instrumental origins. The maximum possible delay is given by the radius of the Earth, thus 20 ms. In generally the radio signal thus is systematically delayed by $0.072 \pm 0.07$ s. The mean delay has been corrected in the following where relevant.

Solar effects may cause much larger delays. Important are the reduced propagation speed of radio waves in the coronal plasma and the possibly larger distance of X-rays from the footpoints. These effects will be discussed later.
3. Data Selection

As there are decimetric pulsations without enhanced X-ray emission and X-ray flare emission without decimetric pulsations or spikes, the selection is very important. There may thus be radio and X-ray emissions without a direct relation to each other. The selection must exclude chance coincidences on the one hand, but include directly connected emissions having considerable delays. The quality of the new data and the new selection tools allow a more effective search for correlations than previous investigations.

The selection was made from flare radio emissions classified as decimetric emissions from the Phoenix-2 burst list since February 5, 2002 (date launch of RHESSI satellite) until the end 2007. We found 169 well observed joint events. Out of these, 107 radio events were of the type of decimetric pulsations and in 32 events we found narrowband spikes. For the detailed analysis, 33 groups (26 radio events) of pulsations and 11 groups (9 radio events) of spikes were chosen. These date include all associated events, when HXR were observed during decimetric pulsations and spikes.

4. Radio – HXR Correlation and Data Analysis

The delay between decimetric radio emission and HXR is determined by cross-correlation. We are using the code described in details by Arzner and Benz (2005). The delay is defined as the time difference between the radio signal and HXR. It is defined positive if the radio emission precedes. There are two definitions for the delay:

- The time shift of the peak of the cross-correlation function. This will be referred to as the "maximum method" in the following.
- As the cross-correlation coefficient sometimes has a rather flat peak, the delay measurement can be improved by a Gauss fit to the cross-correlation function ("Gauss method").

For both the maximum method and the Gauss method, the peak value of the cross-correlation function was also determined to quantify the quality of the correlation. It is simply called "correlation coefficient" in the following.

To determine possible relations between the delay and other parameters, we use linear regression analysis.
Table I: Mean delay for groups of decimetric pulsations and spikes. The standard deviation of the mean value is indicated by the ± margin.

<table>
<thead>
<tr>
<th></th>
<th>Pulsations</th>
<th>Spikes</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Gauss</td>
<td>Maximum</td>
</tr>
<tr>
<td>Mean delay [s]</td>
<td>$-1.4 \pm 0.9$</td>
<td>$-1.7 \pm 0.7$</td>
</tr>
<tr>
<td>Gauss fit to delay distribution [s]</td>
<td>$-0.9 \pm 0.3$</td>
<td>$-2.0 \pm 0.5$</td>
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<tr>
<td></td>
<td>Gauss</td>
<td>Maximum</td>
</tr>
<tr>
<td>Mean delay [s]</td>
<td>$-2.5 \pm 2.5$</td>
<td>$-2.1 \pm 2.5$</td>
</tr>
<tr>
<td>Gauss fit to delay distribution [s]</td>
<td>$-0.6 \pm 0.7$</td>
<td>$-0.5 \pm 0.2$</td>
</tr>
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5. Results

The difference between the delays determined by the Gauss method and the maximum method is of the order seconds (in general).

Negative delays mean that HXR emission precedes radio emission. Note that there are both positive and negative delays. In the majority, the delays determined by the maximum and Gauss methods have the same sign. Using the Gauss method, 18 groups of 33 (55%) of pulsating decimetric emissions show negative delay. The statistics is smaller for spikes, but very similar: 7 groups of 11 (64%) have a negative delay. For both pulsations and spikes the differences between Gauss method and maximum method are not significant. The mean delays of pulsations and spikes are presented in Table I.

Figure 1 presents the delay distributions for pulsations and spikes. This fitting of the delay distribution yields an alternative estimate of the FWHM, the mean delay and its error. The results are given in Table I.

The fitting weights the result towards the kernel of the distribution around zero delay. For the standard deviation analysis, the wings have more weight. Thus the difference suggests that the distribution is not Gaussian, but composed of a kernel around zero delay and broad wings.

We conclude from the various statistics of the delay signs and the mean value of the delays that individual pulsation and spike groups may have delays by several seconds in positive and negative direction. Note that in both emissions there are wings in the distribution of delays up to ±10 s and
more. There is a trend for negative delays. This results in average delays of about $-1$ second. However, this trend is statistically not significant and not robust. Thus we conclude that the average delays for both pulsations and spikes are consistent with zero.

6. Discussion

The following results from the analysis of the delays need to be discussed:
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Figure 2: The delay value of the radio emission (against HXR) connected with spikes versus GOES magnitude of the flare (top panel) and versus peak HXR flux observed by RHESSI (bottom panel). The mixed events marked with an asterisk. A straight line presents the regression relation.

- The delay of individual HXR groups or all events relative to associated decimetric pulsations and spikes is of the order of several seconds and can be positive or negative.
- The distribution of the delays in time has two components: a kernel and broad wings.
- The distribution of the kernel has a mean shift that is compatible with zero.

We suggest the following interpretations:


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1. Decimetric pulsation or spike emissions and X-rays occurring during a flare have two kinds of relation: (i) chance associations that do occur in the same flare, but have different acceleration sites and (ii) pairs with a direct causal link and common acceleration event. The first kind (i) appears as broad wings in the delay distributions. The second kind (ii) forms the kernel of the delay distribution.

2. The width of the kernel may be produced by several opposing effects:
   (i) Let us assume that flare electrons precipitate less than $2 \cdot 10^9$ cm to the thick target sources in the chromosphere. At 20 keV, it takes the electrons up to 0.2 s, and the X-ray emission is accordingly delayed.
   (ii) Benz et al. (2002a) reported the location of decimetric spike sources some 20" to 400" away from the HXR source. Their observations refer to a frequency of 420 MHz and 432 MHz. Allowing for projection and lower altitudes at higher frequencies, we conclude that different source distances imply another delay up to about one second. The non-observation of a centre-to-limb effect seems to be due to its small amount relative to other effects.
   (iii) The delay of radio emission due to group velocity $v_{gr}$ reduced relative to the speed of light $c$ is called group delay and amounts

\[
\tau \approx \frac{1}{2\omega^2} \int \omega_p^2 ds = \frac{2\pi e^2}{cm_e} \frac{1}{\omega^2} \int n_e ds = 1.345 \cdot 10^{-3} \nu^{-2} n_e^0 H_n, \tag{1}
\]

to first order in $(\omega_p/\omega)^2$ (Benz, 2002b), where $n_e$ is the electron density in cm$^{-3}$, $n_e^0$ the electron density in the radio source, $\omega$ is the observing frequency, $\omega_p$ is the plasma frequency, and $H_n$ the density scale height in cm. For $\nu = 1$ GHz, $n_e^0 = 10^{10}$ cm$^{-3}$, and $H_n = 10^{10}$ cm, the group delay $\tau$ amounts to 0.13 s, assuming vertical propagation. It is considerably larger for fundamental emission, where $(\omega \approx \omega_p)$.

We note that these delays of solar origin are much larger than the instrumental delays (Section 2), but not enough to interpret the observed 4.5 s FWHM width of the delay distributions of spikes and pulsations.

The broad distribution of delays reported here agree with the previous results reported in Section 1. This holds for pulsations (Arzner and Benz, 2005) as well as for spikes (Güdel et al., 1991; Aschwanden and Güdel, 1992; Fárník and Karlický, 2005). However, the mean value of the delay.
distribution of spikes differs from previous studies. Both Aschwanden and Güdel (1992) and Fárník and Karlický (2005) claim a negative value (radio emission delayed) that is statistically significant.

To understand the disagreement, it should be noted first that the number of events in all studies was relatively small. If there is a broad population of chance coincidences, their large positive and negative delays will dominate the mean value. Thus, the sign of the mean has a large random scatter. In addition, the relatively broad distribution of the kernel population reduces the accuracy of the mean. The present study includes a much larger number of events than most previous ones.

A second reason for the different result is the quality of the new data and software tools reducing the scatter in the measurements. This allows to distinguish more precisely between the two populations and reduce the effect of the chance coincidence population. Finally, the timing of both instruments is more accurate than in previous studies.

7. Conclusions

An extensive comparison of coherent flare radio emission of the type of decimetric pulsations and narrowband spikes with non-thermal HXR has been made using data collected during half a solar activity cycle. The data from Phoenix-2 include 102 groups of decimetric pulsations and 25 groups of decimetric spikes well covered by good RHESSI observations. From these initially radio-selected emissions we find $32 \pm 6\%$ of the pulsations correlating in time with HXR emission, allowing for delays up to $\pm 20$ s. In $44 \pm 24\%$ of the decimetric spikes there is correlated HXR emission.

The delays between radio and HXR emissions vary from group to group. The FWHM width of the delay distribution is about 10.6 s for both emissions. The delay distributions (Figure 1) show that the population consists of a narrow kernel with FWHM of some 4.5 s (Gauss method) and an overpopulation of delays in the wings. We interpret these wings as chance coincidences. This concurs with the observation noted above that a large fraction of decimetric pulsations and spikes are associated with HXR, but only a third is correlated.

The delays by solar effects that shift possible emissions of the same population of electrons include a longer propagation path of X-rays and the delay of the radio emission by propagation in a plasma. These two effects
can explain a distribution width of about 1.5 s. Instrumental and terrestrial effects contribute less than 0.2 s. Thus the observed broad distribution having a FWHM of ±2.3 s can only partially be explained by delays.

The kernel of the delay distribution is nearly symmetric to zero (Figure 1). The radio emissions are delayed on the average by about 1 s, but the mean values are not significantly different from zero, contradicting earlier reports. The identification of a population of decimetric emissions having good correlation with a mean value consistent with zero suggests that there exists coherent radio emission by particles originating from the same acceleration process as the HXR emitting electrons. This close radio/HXR correlation may usually be hidden by low radio emissivity or by absorption.

The correlation of the delay of decimetric spikes relative to SXR peak flux, previously reported, has been found to be statistically significant. However, the regression is dominated by two groups with delays of 10 s and more (Figure 2 – top panel). Such groups may be correlated by chance. Thus the correlation is not beyond doubt and needs further confirmation.

Radiation correlating with the HXR is related to the main energy release and may provide information on the primary flare process. An occasionally good correlation may indicate a more general, but usually hidden close association. Having identified a population of decimetric pulsations and spikes correlated to HXR, the next step will be to locate such events spatially and compare them to other imaging data. Together with this information, it will be possible to answer the question whether such radio emissions originate from the acceleration region or are a secondary effect caused by propagation or trapping.

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