RADIO SIGNATURES OF FAST OSCILLATORY PHENOMENA IN THE SOLAR CORONA

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ABSTRACT

During type IV solar radio bursts different types of periodic fine structures (PFSs) are frequently observed, which can be interpreted as radio signatures of fast oscillatory phenomena in the coronal plasma. We analyze a large set of type IV bursts containing PFSs, recorded with high time resolution at single frequencies in the metric and decimetric bands. Focusing on the association with flares and flare-like phenomena we found:

- PFSs can be found in about 50% of type IV bursts characterized by fine structures;
- 10% of PFS-containing events are weak/short type IV-like radio bursts that occur in absence of any flare-like activity. In the weakest events the whole radio burst was in fact just one short PFS-episode recorded at only one observing frequency;
- In flare associated events we found two distinct classes of PFSs - impulsive phase and decay phase related PFSs; yet, no statistically significant difference in the characteristic periods and amplitudes is found between the two classes;
- PFS-rich radio events are characterized by large SXR and radio peak fluxes – neither one of the weak type IV bursts was PFS-rich. The opposite is not true: many powerful bursts are PFS-poor.

Key words: solar radio bursts; type IV bursts; solar radio fine structures; radio pulsations.

In previous two papers (Magdalenić et al. 2002, Magdalenić et al. 2003) we discussed statistical properties of PFSs focusing on polarization, periods, and amplitudes of PFSs. In this paper we investigate the characteristics of type IV and type IV-like radio bursts (events) that contain periodical fine structures (PFSs), emphasizing the association with flares and flare-like energy release processes. We utilize the radio data recorded at single frequencies by the Trieste Solar Radio System of the Trieste Astronomical Observatory (TSRS-OAT), providing high sensitivity measurements with high time resolution, in the meter-to-decimeter wavelength range (237, 327, 408, 610, 1420 and 2695 MHz). The radio-polarimetric sampling rate was generally 10 ms (in some events 100 ms) in the two circular polarization modes.

1. INTRODUCTION

Type IV solar radio bursts frequently expose fine structures. Fine structures include a wide range of phenomena from the entirely irregular activity, up to quasi-periodical structures and very regular sinusoidal oscillations. They are of large interest as a plasma diagnostic tool in flare energy release process, giving information about magnetic field, plasma density, dimensions of the source region, etc.

2. DATA SET

The selected radio events were recorded by TSRS in the period from October 1997 to August 2000. A large set of type IV bursts was examined, and in 101 events we detected fine structures (zebra patterns, fibers, spikes, pulsations, absorptions). Out of these, we analyze 56 events that contain PFSs.

For each analyzed radio burst we determined:
- starting time $T$ (UT);
- duration $\Delta T$ (minutes);
- maximum of the background continuum $F_{\text{max}}$ (solar flux units, sfu);
- number $N$ of individual PFS events comprised in each type IV burst.

The majority of events are ordinary type IV bursts, covering a frequency range of $\Delta f > 100$ MHz and having a duration $> 5$ min. However, the weakest radio burst containing PFS was lasting about 15 s and was recorded only at 1420 MHz. In Fig. 1 we present the distribution of the analyzed radio bursts.

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Figure 1. Maximum flux of the background continuum in the analyzed radio bursts versus the duration of the burst. Black dots indicate the events associated with M & X class soft X-ray flares, crosses B & C class flares, and triangles the events during which no distinct soft X-ray enhancement was reported. The corresponding power law least squares fits are shown by the thick-black, thin-black, and thick-gray lines, respectively.

in the $F_{\text{max}}(\Delta T)$ space, dividing the sample in three subsamples according to the importance of the associated soft X-ray burst. The distribution clearly shows that PFSs appear in a broad palette of radio events, and are not exclusively associated with flares. The energy release can be very brief and weak.

In total, we isolated more than 600 PFS intervals. In some events (usually weaker ones) there was only one PFS identified, and in extreme cases more than 100 PFSs were detected. The selected PFSs are exhibiting a periodical or quasi-periodical time profile and only gradual changes in the intensity amplitude. Each PFSs interval is constituted of at least 5 pulses. For the selected PFS events superimposed on the background radio continuum we estimated:
- starting time $t_{\text{start}}^{\text{PFS}}$ (UT);
- duration $\Delta t$ (s);
- period $\tau$ (s);
- intensity amplitude $S$ (sfu)
(for details see Magdalenić et al. 2002).

The radio data were confronted with the flare characteristics utilizing the following flare parameters:
- onset of soft X-ray (SXR) burst $t_{\text{start}}^{\text{SXR}}$ (UT);
- SXR peak time $t_{\text{max}}^{\text{SXR}}$
- SXR peak flux $F_{\text{SXR}}$.

The association of radio events with flares is mainly determined by the timing argument, but in a number of events the radio positions were checked also utilizing the Nançay Multifrequency Radioheliograph (NRH; Kerdraon & Delouis 1997; http://bass2000.obspm.fr/)

Figure 2. a) PFS in the weak radio type IV-like event of 2 February 1998 (11:22:35 UT). The event was associated with the weakest flare-like event (flaring bright point, f.b.p.) in our sample. The Yohkoh images are taken at 11:13 UT (panel b) and 11:48 UT (panel c).

3. RESULTS

3.1. Association with flares

Inspecting the association of the selected 56 radio bursts with solar flares we found that in 12 cases (21%) no associated flares were reported. However, inspecting the EIT-SOHO (Delaboudiniere et al. 1995) and Yohkoh-SXT (Tsuneta et al. 1991) data we have found that in one event there was a system of postflare loops at the limb indicating that there were large flares behind the limb. Furthermore, in three events we found weak flares in Yohkoh images, not strong enough to cause a distinct enhancement of the soft X-ray flux in GOES recordings (Donnelly & Unzicker 1974). In Fig. 2 we show the event of 2 February 1998 as an example. For further two events Yohkoh data are not available. So, in fact, only six out of 54 events ($\approx$10%) could be really classified as non-flare events. These events were the shortest/weakest radio bursts from our sample (Fig. 1). It should be noted that in two of them we found signatures of coronal magnetic field restructuration.

We evaluated the timing of individual PFS with respect to the evolution (rising or decay phase) of the soft X-ray (SXR) flare using the normalized delay $d$, defined as:

$$d = \frac{t_{\text{PFS}} - t_{\text{start}}^{\text{SXR}}}{t_{\text{max}}^{\text{SXR}} - t_{\text{start}}^{\text{SXR}}}$$

The delay $d = 0$ indicates the coincidence with the start of the SXR flare, $d = 1$ the coincidence with the...
Figure 3. a) Cumulative distribution of PFS time delays relative to the soft X-ray burst onset and normalized with respect to the SXR rise-time. Histogram presentation of the normalized time delays for: b) 237 MHz and c) 610 MHz, with the 9th-degree polynomial least squares fit.

SXR flare maximum, 0 < d < 1 indicates that PFS appeared in the impulsive phase of the flare (rise of SXR flux), d < 0 that it appeared before the flare start, and d > 1 that it appeared in the decaying phase of the SXR flare.

Figure 3 shows the distribution of the delays for all flare-associated PFSs. In Fig. 3a we show the cumulative distributions for all observing frequencies (steeper slope corresponds to a larger occurrence rate). For matter of illustration, in Figs. 3b and c the histogram presentation is provided for 237 and 610 MHz. One finds at least two distinct classes of events. The first one is related to the impulsive phase of a flare (d ≤ 1) and the second one to the decay phase (d > 1). The second class reflects the fact that almost 40% of flares with PFSs were related to the prolonged SXR decay phase during which repeated revivals of radio emission were frequently observed. Whereas at low frequencies the second class prevails, at high frequencies the first class is absolutely dominant. In Fig. 4 we show an example of three successive events where the PFS intervals were clearly associated with the impulsive phases of the associated flares.

Comparing the characteristics of the two classes of PFSs we found that there are no statistically significant differences in the relationship between PFS period at different observing frequencies (7f), see Magdalenić et al. 2002, 2003). Similarly, both classes do not show any difference in the distribution of intensity amplitudes S, which generally do not depend on the observing frequency (S(f) ≈ const.).

3.2. Characteristics of type IV bursts with PFSs

As already mentioned, from 101 type IV and IV-like bursts with fine structures, only 56 of them (55%) were containing PFS episodes. Bearing in mind the fact that the number of PFS episodes in these 56 events varied from only one to > 100 per event, the question arises why some radio bursts are PFS-rich and others are PFS-poor.

In Fig. 5 the number of PFSs in a given event, N, is presented as function of the duration of the corresponding radio event, ΔT. The events are separated into three classes depending on their importance. In Figs. 5a-c the events are sorted by the maximum flux of background continuum Fmax, and in Fig. 5d by the SXR peak flux. Figure 5a shows the complete sample, whereas in Fig. 5b and c the 237 and 327 MHz data are shown independently to illustrate that the pattern present in Fig. 5a is not an artifact caused by the dependence of Fmax and ΔT on the observing frequency.

Figure 5 shows that there is an upper limit to the occurrence rate of PFSs (bold line in Fig. 5a). In short events (ΔT ≤ 1 min) it is about 3 PFS/min and in long-duration radio events (ΔT > 10 min) the limit decreases to 1 PFS/min. Weak-lasting events (Fmax < 50 sfu; triangles in Fig. 5) tend to be PFS-poor. Similar holds if soft X-ray fluxes are considered (Fig. 5d). On the other hand, large radio and/or SXR peak flux is not a sufficient condition to guarantee the PFS-richness: there are powerful and long-duration type IV bursts which show only one PFS event. Furthermore, let us recall that 45% of all radio events characterized by fine structures do not show PFSs, and a significant fraction of these were powerful events too. Finally, let us stress that PFSs always appear mixed with other types of radio fine structures.
3.3. "Isolated" PFS events

Our sample includes several radio bursts of short duration and weak background continuum increase, recorded only at one frequency. In some of these events the whole radio burst was dominated by the PFS episode (e.g., the event shown in Fig. 2): practically, the PFS interval represents the whole burst.

In Fig. 6 we show two such examples. Unlike the burst shown in Fig. 2, in the case of these two events we could not identify an association with flare, or flare like activity. In Figs. 6c and d the results of the wavelet analysis are shown to expose clearly the \( \approx 100 \) ms pulsation period.

The two events shown in Fig. 6 illustrate that PFSs are not an exclusive characteristic related to flares, but they can occur in very weak energy release processes. Furthermore, the event shown in Fig. 6a evidences that pulsation periods can be shorter than 100 ms (Fig. 6c).

4. SUMMARY

The results of the presented analysis can be summarized as follows:

- PFSs can be found in about 50% of type IV bursts characterized by fine structures;

- Some 10% of PFS-containing events are weak/short radio bursts that occur in absence of any flare-like activity. In the weakest events the whole radio burst was in fact just one short PFS-episode recorded at only one observing frequency;

- In flare associated events we found two distinct classes of PFSs - impulsive phase and decay phase related; yet, no statistically significant difference in the characteristic periods and amplitudes is found between the two classes;

- PFS-rich radio events are characterized by large SXR and radio peak fluxes - neither one of the weak type IV bursts was PFS-rich. The opposite is not valid: many powerful bursts are PFS-poor.

- There is an upper limit on the occurrence rate of PFSs within a radio burst - in PFS-rich events the number of PFSs can be up to 3 min\(^{-1}\).

- As a side result we found that pulsation periods can be shorter than 100 ms.
Figure 6. Two examples of PFS that represent the dominant feature in an entire radio burst: a) 13 February 1999; b) 8 October 1999. Both bursts were recorded only at 1420 MHz. In c) and d) we show the results of wavelet analysis for the two events, respectively. The thin-white isolines represent the 95% confidence level, clearly evidencing the periodicity in the range of 100 ms.
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