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Sawtooth oscillations in solar flare radio emission

A. Klassen, H. Aurass, and G. Mann

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

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Abstract. For the first time, we found a spectral fine structure of solar meter wave radio burst emission which can be due to sawtooth oscillations in the hot flare plasma. This finding newly underlines an analogy between coronal and laboratory plasma processes. The sawteeth occur during the impulsive flare phase hard X–ray emission and consist of a sequence of almost identical narrow band ($\delta f/f \simeq 1\%$) drift bursts. All cases of our sample were associated with a radio emitting coronal shock wave (type II burst). Similar oscillations are familiar in tokamak plasmas and understood as signature of the kink instability of the toroidal current. We argue that the radio sawteeth are nonthermal plasma emission due to 2–4% density fluctuations of the flare plasma. The fluctuations can be excited by a current instability in a coronal flare loop or in a vertical flaring current sheet e.g. occuring behind a rising magnetic flux rope. This is in analogy to kink instability effects observed in laboratory plasmas.

Key words. Sun: flares – radio radiation – corona – plasmas

1. Introduction

Solar flares are violent eruptions suddenly releasing magnetically stored free energy in the form of plasma heating, mass motions, energetic particles, and electromagnetic radiation from radio waves to γ-rays. They occur in the corona above active regions around sunspot groups. X-ray and extreme-ultraviolet observations (Masuda et al. 1994; Yokoyama et al. 1995; Priest & Schrijver 1999) and flare models (Spicer 1977; Priest & Forbes 2000) seem to confirm magnetic reconnection between flux tubes or in cusp field structures as flare mechanism. There are some analogies between solar flare and tokamak plasma processes because the shape of coronal loops is similar to the toroidal magnetic field curvature in a tokamak. The attention was especially pointed to sawtooth oscillations seen by X-ray diagnostic in tokamak plasmas during the kink instability (Spicer 1977). Therefore the current instabilities in coronal loops can play an important role (as in tokamaks, Biskamp 1993). On the other hand tokamak experiments cannot replicate the conditions at the Sun concerning the scale size, density and other parameters (Priest & Forbes 2000). We observed for the first time signatures of sawtooth oscillations in solar flare radio emission.

Flare burst radio emission is nonthermal plasma radiation excited by energetic electrons sensitively indicating energy release in the corona of the Sun. The frequency of radio emission is near to the fundamental or harmonic mode of the plasma frequency f_{p} (Hz) $\simeq 9\ 10^3 \cdot n_{\mathrm{e}}^{1/2}$ in the source volume (n_{e} – electron number density in cm^{-3}). Solar radio bursts are usually shown in dynamic frequency spectra, a grey scale coded intensity versus frequency and time–plot, like the spectra of two flares in Figs. 1a, d. Spectral fine structures of radio emission can be used for plasma diagnostic. We present a new spectral pattern appearing as a quasi-periodic sequence of almost identical, narrow band, slowly drifting emission lanes – the sawtooth pattern. The pattern is sketched in Fig. 1c and shown in Figs. 1b and 1e.

2. Observations

The observations were carried out with the radio spectrograph of the Astrophysical Institute Potsdam (Mann et al. 1992) covering the frequency range 40–800 MHz with a time resolution of 0.1 s. In 1995–1998 we found 12 more or less well expressed sawtooth events indicating that the effect is rare but not unique. We show the two best examples of our sample. Due to the narrow bandwidth of the sawtooth pattern no metric radio imaging facility succeeded in observing an sawtooth until now.

The flare on 3 November 1997 occurred in the active region NOAA 8100 and was associated with type III/ IV radio emission (Fig. 1a). No hard X-ray observations are available. The sawteeth (Fig. 1b) occurred during the impulsive flare phase before the onset of a strong type II

Send offprint requests to: A. Klassen, e-mail: aklassen@aip.de

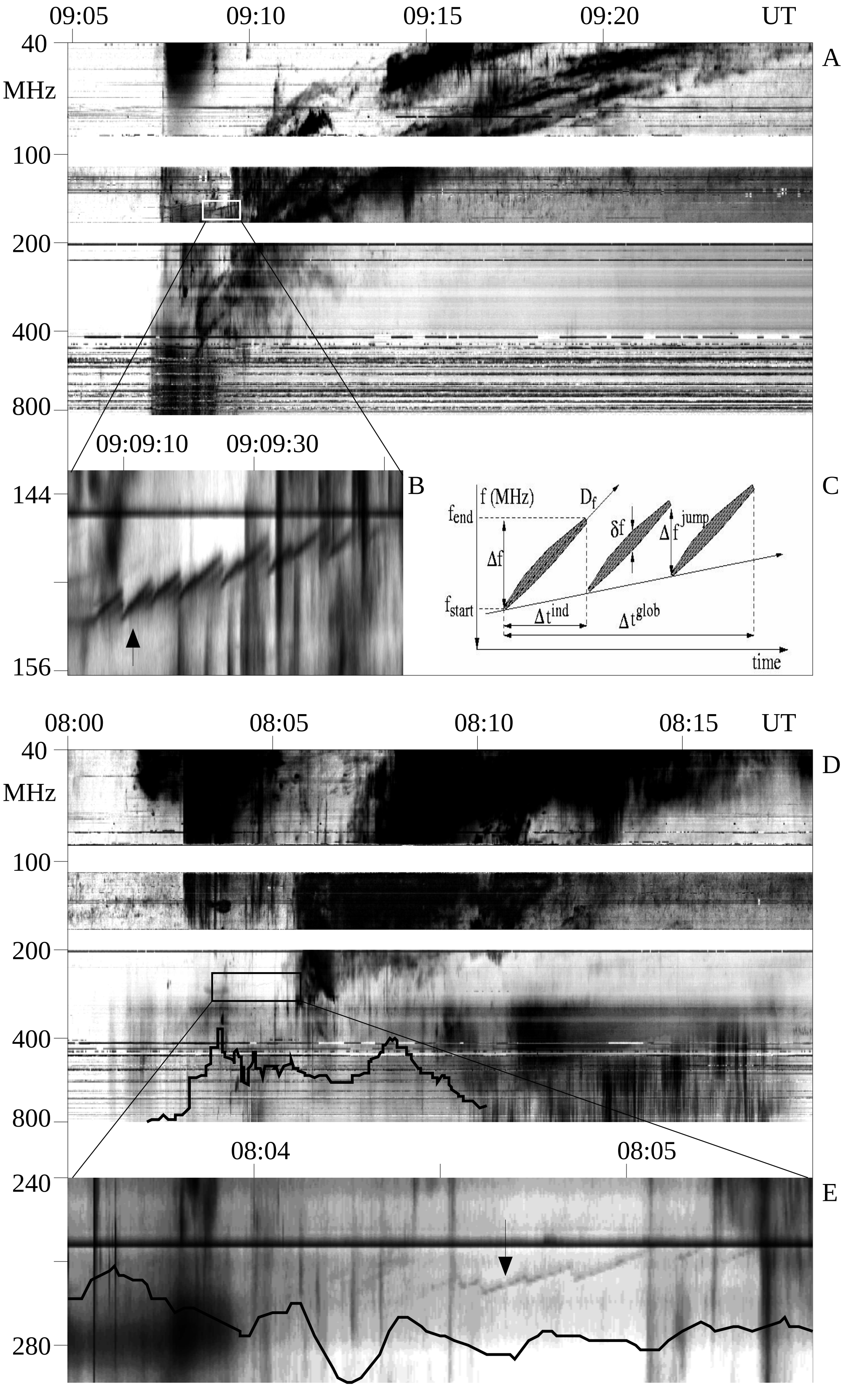

Fig. 1. Dynamic radio spectra of two solar flares (Figs. 1a, d; see also Table 1). The radio intensity is grey scale coded where dark means bright emission. The spectrum displays the evolution of radio emission in the corona at heights between about 10^4 km and 5.7 10^5 km (800–40 MHz). The white and black time-parallel stripes are due to terrestrial interferences. In the enlargements **b, e)** the arrow points to the sawtooth pattern. The scheme **c)** explains the terms used in the text. **Panel a, b)**: the event on 3 November 1997. The sawtooth (arrow) has a slow drift to lower frequencies. At the impulsive phase of the flare fast drift bursts (type III) occur indicating the propagation of electron beams across the solar corona. The type II burst as a signature of a coronal shock wave appears later yielding emission lanes slowly drifting towards lower frequencies. **Panel d, e)**: the event on 6 May 1998 with superposed hard X–ray lightcurve (thick black line, CGRO/BATSE, energy range 25–58 keV, scale linear **d)**, logarithmic **e)**, peak = 1.5 10^5 counts, time resolution = 1.024 s). The sawtooth pattern occurs at 08:02.3–08:05.3 UT during the onset of the hard X–ray burst and disappears shortly before the type II shock emission

burst. The transition jumps between single teeth appear sometimes synchronized with sharp type III-like emission revealing simultaneous electron beam generation. In the spectrum, these fast drift bursts can emanate from the sawtooth pattern but can also arrive from higher frequencies partly crossing the pattern, partly stopping there (Figs. 1a, b).

Table 1. Sawtooth pattern and associated flares

Event	Associated flare Class	Location	Start–Max [UT]	Sawtooth pattern Start–End [UT]	Freq. [MHz]	$\delta f/f$	$\Delta f/f$	Duration [s]	$D_{\rm f}$ [MHz/s]
3 Nov. 1997	1B/M1.4	S18W16	09:03–09:10	09:09.2–09:09.5	150	0.010	0.025	25	−0.52
6 May 1998	1N/X2.7	S15W64	07:58–08:09	08:02.3–08:05.3	260	0.008	0.030	180	−0.63

$\delta f/f$ and $D_{\rm f}$ – relative bandwidth and drift rate of individual sawtooth, $\Delta f/f$ – covered frequency range of sawtooth, duration = $\Delta t^{\rm glob}$ (cf. Fig. 1c for explanation).

The flare on 6 May 1998 (NOAA 8210) was also associated with type III/ IV and II burst emission (Fig. 1d). Khan & Hudson (2000) have shown that this event is associated with the disappearance of an interconnecting loop structure. Hudson et al. (2000) described the soft X-ray observations of flare-excited wave phenomena. The sawtooth pattern (Fig. 1e) is observed during a first hard X-ray enhancement of the impulsive phase. Compared with the first event it appears at higher frequencies (260 versus 150 MHz). Again, some sawtooth jumps are synchronized with type III emission. The pattern ceases shortly before the onset of the type II burst above the type II start frequency.

More information about both presented events is given in Table 1. All sawteeth of the sample (12 events) occur during the impulsive flare phase and are associated with a type II burst – the formation of the radio signature of a traveling coronal shock wave (Nelson & Melrose 1985). The duration of individual sawteeth is between 3 ÷ 15 s. Its relative bandwidth $\delta f/f$ is 1%, only. The sawtooth pattern is stable in frequency and the whole pattern covers an extremely small range $\Delta f/f$ of up to 3% (see also Fig. 1c).

3. Discussion

The properties of the sawteeth require a mechanism acting at a stable frequency, i.e. at a stable density level, since the radio emission occurs near the local electron plasma frequency, and in a quasi–periodic regime with a very narrow bandwidth $\delta f/f \simeq 0.01$. These requirements, together with the short transition time between single sawteeth ($\tau < 0.1$ s), point to plasma emission from a small radio source site generated at a constant density level with a life time of 0.5–3 min. We estimate a scale of $L_{\rm source} \simeq \tau V_{\rm a} \simeq 100$ km, by assuming a coronal Alfvén speed $V_{\rm a} \simeq 1200\ {\rm km\,s^{-1}}$, an emission frequency of $f = 150$ MHz (corresponding to $n_{\rm e} = 2.8\ 10^8\ {\rm cm^{-3}}$), and a magnetic field strength of $B = 1$ mT.

Morphologically similar sawtooth patterns were first observed in the ST-tokamak using soft X-ray diagnostic (von Goeler et al. 1974). The emission from the hot plasma core in the current sheet is modulated by periodic relaxation oscillations. One period consists of a slowly rising part followed by rapid drop (the collapse). The variation in X-ray emission is mainly due to temperature and density changes. The density fluctuation $\Delta n_{\rm e}/n_{\rm e} = 1-2\%$ is smaller than the temperature variation $\Delta T_{\rm e}/T_{\rm e} = 10\%$ (Hastie 1998). The sawtooth collapse can be interpreted in terms of the internal kink instability in the toroidal current in the tokamak which then undergoes resistive kink modes and thus reconnection (Kadomtsev 1975; Biskamp 1993). The reconnection process leads to impulsive Joule heating and subsequent X-ray emission, possibly also to electron beam generation. It can quasi-periodically repeat itself. Such repetition should occur with periods between 1 and 30 s.

We report on observations of the corresponding features in nonthermal meter wave radio emission of solar flare plasma. The feature occurs in all cases in the impulsive flare phase and before the formation of a shock wave (seen as radio type II burst) in the corona. The association with hard X-ray emission (Fig. 1d) supports the assumption that the sawteeth belong to the primary coronal energy release process. Some sawteeth are well correlated with X–ray peaks, but of course there is no detailed correlation between the X–ray flux curve and the sawtooth pattern (see the enlargement in Fig. 1e). That is even difficult to expect because of the absence of one-to-one correlation between radio bursts and hard X–ray emission was already referenced (e.g. Aschwanden & Güdel 1992). We believe that spatial information about hard X–ray and radio emission can help us to understand the relation between both phenomena.

We suppose that the sawteeth are due to the current instability in a flaring loop (Spicer 1977) or in a vertical flaring current sheet occuring behind a rising flux rope (e.g. Forbes & Priest 1984). If the sawtooth emission is generated at the plasma frequency one obtains for the electron density variations in the sawtooth source volume a $\Delta n_{\rm e}/n_{\rm e}$ of 3–4% from $\Delta f_{\rm jump}/f = 1.7–2.0\%$. On the other hand, assuming cyclotron emission instead of plasma emission the effect can also be explained by magnetic field variations. But in the corona – where the meter wave radio bursts are emitted – the plasma emission process is more probable than cyclotron emission.

The new features – that we found in the solar flare radio emission for the first time – offer an interesting aspect for understanding the mechanism of flare energy release. It observationally confirms a close link between reconnection processes at the Sun and in the tokamak plasma.

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