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LETTER TO THE EDITOR

"Drifting tadpoles" in wavelet spectra of decimetric radio emission of fiber bursts

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ABSTRACT

Aims. The solar decimetric radio emission of fiber bursts was investigated searching for the "drifting tadpole" structures proposed by theoretical studies.

Methods. Characteristic periods with the tadpole pattern were searched for in the radio flux time series by wavelet analysis methods.

Results. For the first time, we have found drifting tadpoles in the wavelet spectra of the decimetric radio emission associated with the fiber bursts observed in July 11, 2005. These tadpoles were detected at all radio frequencies in the 1602−1780 MHz frequency range. The characteristic period of the wavelet tadpole patterns was found to be 81.4 s and the frequency drift of the tadpole heads is −6.8 MHz s^{-1}. These tadpoles are interpreted as a signature of the magnetoacoustic wave train moving along a dense flare waveguide and their frequency drift as a motion of the wave train modulating the radio emission produced by the plasma emission mechanism. Using the Aschwanden density model of the solar atmosphere, only low values of the Alfvén speed and the magnetic field strength in the loop guiding this wave train were derived which indicates a neutral current sheet as the guiding structure. The present analysis supports the model of fiber bursts based on whistler waves.

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

1. Introduction

The periodicity of magnetoacoustic modes of propagating waves can be modified by the time evolution of an impulsively generated signal (Roberts et al. 1983, 1984) e.g. the impulsive flare process. These magnetoacoustic waves are trapped in regions (coronal loops) with higher density acting as waveguides. Nakariakov et al. (2004) studied characteristic signatures of these impulsively generated magnetoacoustic waves propagating along a coronal loop by numerical simulations. It was found that these wave trains have a characteristic tadpole wavelet signature where narrow-spectrum tails precede broadband heads. Such tadpole signatures were observed in solar eclipse data (Katsiyannis et al. 2003) and in dm-radio bursts of gyrosynchrotron emission (Mészárosová et al. 2009).

The decimetric radio emission is characterized by many fine structures. One of the most typical structures is a group of fiber bursts. They are defined as short-lasting bursts with nearly regular repetition and with a frequency drift of about −100 MHz s^{-1} (Jiřička et al. 2001).

In this Letter, we report for the first time such tadpole patterns which drift towards low frequencies. Furthermore, the tadpoles were found at the time of observation of dm-fiber bursts. Thus, the presented tadpoles differ essentially from the non-drifting tadpoles found in the pulsating (gyro-synchrotron) continuum (Mészárosová et al. 2009). The Letter is organized as follows: in Sect. 2 we present our observations, in Sect. 3, the wavelet analysis of these data is described and in Sect. 4 we interpret and discuss our results and conclude.

2. Observations

The July 11, 2005 radio burst (GOES X-ray class C0.1, maximum 16:38 UT) was observed after the flare (class C8.4, maximum 15:08 UT, H_α importance SF) in the active region NOAA AR 10786. The observed 10-minute duration (16:34−16:44 UT) decimetric radio event was recorded by the Ondřejov radio spectrograph (Jiřička et al. 1993) with 0.1 s time resolution. GOES X-ray flux and two characteristic dm-radio time series at 1420 and 1700 MHz of the these bursts are shown in Fig. 1.

The radio spectrum of the fiber bursts recorded by the Ondřejov radio spectrograph is presented in Fig. 2. The dm-radio event under study consists of fiber bursts in the frequency range 800−2000 MHz. The most remarkable property is the frequency drift of the individual fibers in the 1400−1800 MHz frequency range, which is −107 MHz s^{-1} on average.

3. Wavelet analysis of the dm-radio time series

We studied 39 radio flux time series at individual frequencies (cuts of the radio spectrum) from 1602 to 1780 MHz during the time interval 16:36−16:43 UT. Characteristic periods with tadpole patterns were searched for in the radio flux time series with two different wavelet methods (Torrence & Compo 1998): 1) *The wavelet power spectrum* where both the cone of influence (COI) (here edge effects become important due to finite-length time series) and the confidence level (CL) (relative to red noise) were taken into account. In each time series, only the regions outside the COI with CL above 99% are considered as

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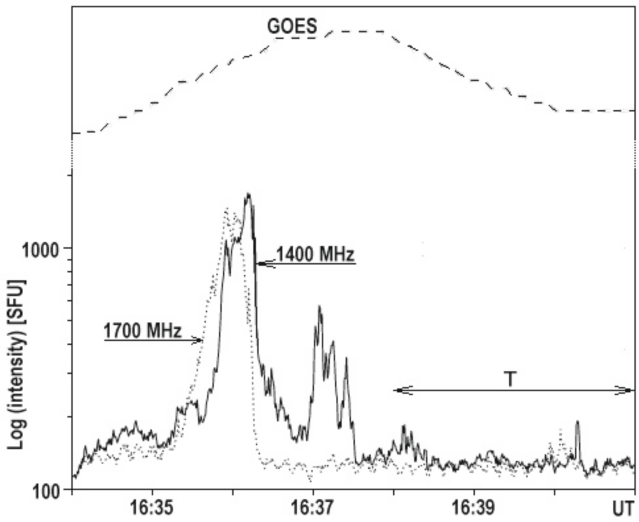

Fig. 1. GOES X-ray (in arbitrary units) and dm-radio fluxes (1400 and 1700 MHz) of the July 11, 2005 bursts. Tadpole wavelet patterns were recognized in the time interval T (16:38−16:41 UT).

significant. 2) *Global wavelet spectrum*, where we consider only peaks above the 99% global CL.

The tadpole wavelet signatures were recognized with a dominant characteristic period at all the 39 frequencies in the time interval T = 16:38−16:41 UT (see Fig. 1). The duration of the tadpoles of the 39 individual radio frequencies ranges from 89−184 s. Four characteristic examples of the tadpoles detected in selected radio frequencies (Table 1) are shown also in Fig. 3. The individual panels show the wavelet power spectrum with the tadpole pattern and a characteristic period P = 81.4 s. The spectra are plotted with the lighter areas indicating greater power. Tadpoles are outlined by contours at the 99% CL and the hatched regions belong to the COI. The dashed line represents time $t_{\max}$ at the point of the head tadpole maximum at 1752 MHz and the dotted line shows the frequency drift of these $t_{\max}$ values towards lower frequencies. The tadpole characteristic parameters are presented in Table 1 for four selected radio time series (1602, 1653, 1700 and 1752 MHz) from the frequency range under study.

Finally, the four white dots (Fig. 2) indicate the time $t_{\max}$ of the tadpole head maximum at four selected frequencies (Table 1). These tadpoles drift towards low frequencies with a negative frequency drift –6.8 MHz s^{-1} (see the white arrow in Fig. 2).

4. Discussion and conclusions

In accordance with the papers by Katsiyannis et al. (2003), Nakariakov et al. (2004), and Mészárosová et al. (2009), we interpret the tadpoles found in the wavelet spectra of radio emission fluxes as a signature of the magnetoacoustic wave train moving along a dense flare waveguide. But contrary to the non-drifting tadpoles (found during the pulsating radio continuum), whose heads were observed at the same time and interpreted through the gyrosynchrotron emission (Mészárosová et al. 2009), the heads of the present tadpoles clearly drift towards low frequencies. This shows that the radio emission, which is modulated by the wave train and results in the wavelet tadpole structure, is produced by plasma emission mechanisms. The simultaneous observation of fiber bursts with tadpole structures supports this idea.

Table 1. Basic parameters of the tadpole wavelet patterns with a period P = 81.4 s at four selected frequencies ($t_{\max}$ is the tadpole head maximum in the wavelet power spectra).

Frequency [MHz]	Start time [UT]	Duration [s]	Time $t_{\max}$ [UT]
1602	16:38:09	89	16:40:19
1653	16:38:09	184	16:40:12
1700	16:38:07	170	16:40:06
1752	16:38:05	160	16:39:57

Comparing the tadpoles presented in Mészárosová et al. (2009) with those presented here, we can conclude that both are a radio signature of the magnetoacoustic wave train. But while in the first case the wave train influences the decimetric radio emission produced by the gyro-synchrotron emission mechanism in the localized radio source, in the present case the wave train modulates the plasma radio emission along the wave train trajectory in the upward direction in the solar atmosphere (similarly to shock waves in the type II radio bursts).

There are two types of models of the fiber bursts: a) the model considering whistler wave packets (Kuijpers 1975; Mann et al. 1987, 1989; Aurass et al. 1987), and b) that with Alfvén solitons (Bernold & Treumann 1983; Treumann et al. 1990). Benz & Mann (1998) compared both these models and they found that the model with whistlers is more realistic than that with the Alfvén waves. Furthermore, Aurass et al. (2005) and Rausche et al. (2007) used the model with the whistlers successfully for the magnetic field estimation in the coronal loops. But still there is a debate about the role of these two models in the interpretation of fibers, especially for the fibers observed at high decimetric frequencies.

First, let us consider the model of fibers based on whistler wave packets. In such a model (Kuijpers 1975) the loss-cone instability of the superthermal electrons trapped in the loop produces the whistler as well as Langmuir waves. The whistlers (w) propagate along the loop with the velocity of 10−28 $v_{\rm A}$, where $v_{\rm A}$ is the Alfvén speed, and coalesce with the Langmuir waves l to form the electromagnetic waves ($l + w \rightarrow t$), observed as the fiber bursts. Simultaneously, the plasma processes ($l + i \rightarrow l$, where i is the ion-acoustic plasmon) and ($l + l \rightarrow t$) generate the background plasma emission. We think that in the same loop, due to flare perturbation, the magnetoacoustic wave train is generated and propagates upwards – towards lower plasma densities with the velocity 1−3 $v_{\rm A}$ depending on the waveguide density profile (Nakariakov et al. 2004). This wave train modulates the loss-cone instability (through the wave varying magnetic field) as well as the resulting radio emission carrying the tadpole signature. This concept can be supported by the fact that the ratio of the frequency drifts of the fibers and tadpole heads is -107 MHz s^{-1}/ – 6.8 MHz s^{-1} = 15.7, which corresponds to the ratio of the group velocities of whistler and Alfvén waves (for $x = \omega_{\rm w}/\omega_{\rm ce}$ = 0.038, where $\omega_{\rm w}$ and $\omega_{\rm ce}$ are the whistler and electron-cyclotron frequencies). Thus, in the plasma emission models the frequency drift is given by the propagating agents (whistlers or the magnetoacoustic wave train in our case).

Now, let us use the Aschwanden density model of the solar atmosphere (Aschwanden 2002) for an estimation of the Alfvén speed as well as the magnetic field strength in the loop guiding the magnetoacoustic wave train. From the frequency drift of the tadpole heads we have the Alfvén speed $v_{\rm A}$ = 33 km s^{-1}; the altitude of the wave train above the photosphere at the instant of the tadpole head (16:39:57 UT) at 1752 MHz is 9220 km. The corresponding magnetic field in the the wave-guiding loop

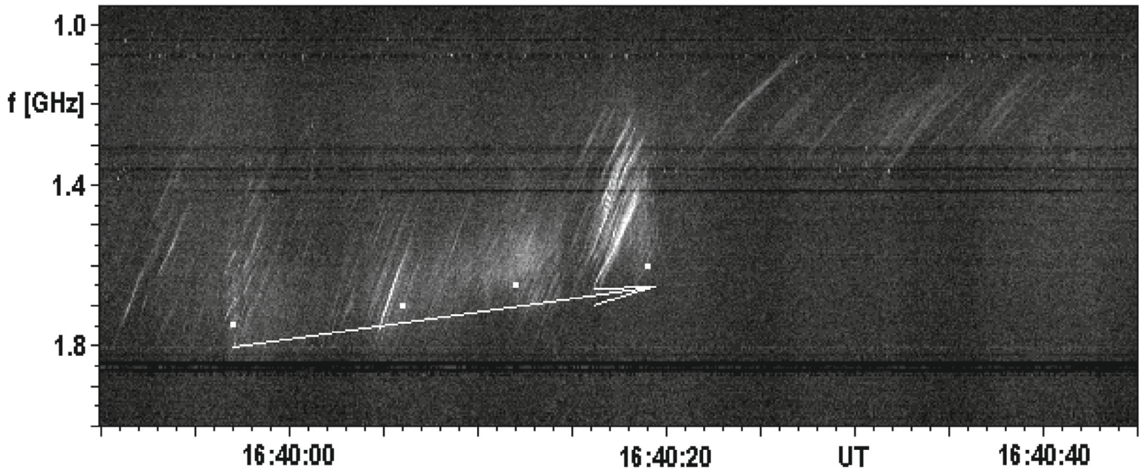

Fig. 2. Decimetric radio spectrum of the July 11, 2005 bursts recorded by the Ondřejov radio spectrograph. Frequency drift of the individual fibers in the 1400−1800 MHz frequency range is −107 MHz s^{-1} on average. The frequency drift of the tadpole heads is −6.8 MHz s^{-1} (see arrow). Four white dots indicate the time $t_{\max}$ of tadpole head maximum at four selected frequencies (Table 1).

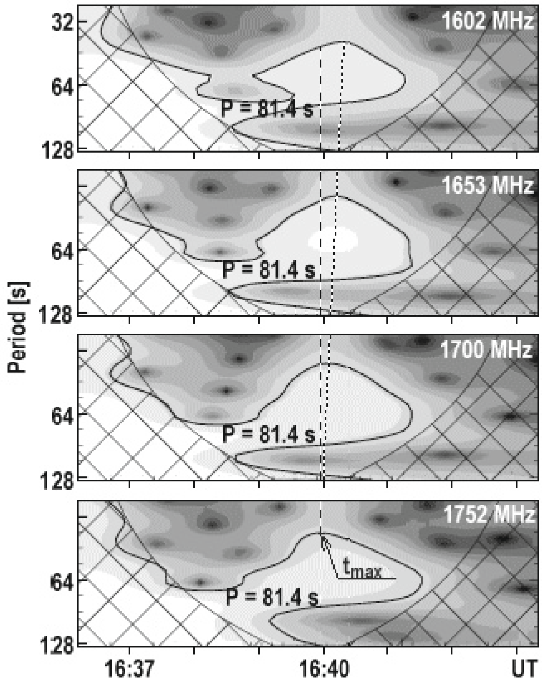

Fig. 3. Characteristic examples of wavelet power spectra with tadpole patterns detected in four selected radio frequencies. Tadpoles are outlined by contours at the 99% CL. The dashed line represents time $t_{\max}$ of the head tadpole maximum at 1752 MHz. The dotted line shows the frequency drift of the $t_{\max}$ value towards lower frequencies.

is $B = 3$ G. Such a low Alfvén speed and low value of the magnetic field strength give an impression that the whistlers and the magnetoacoustic wave train move along the neutral current sheet, where the magnetic field is low and the plasma density enhanced. We have recognized a period (∼80 s) in the tadpole structure, but to determine the arrival time of the wave train at the specific source altitude is difficult. Therefore, we can only speculate that the wave train was produced at the time of the main peak of the radio burst (at 16:36 UT, i.e. 4 periods) or later.

The present observation of fiber bursts and the drifting tadpole structures cannot be explained within the model of fibers based on Alfvén solitons (Bernold & Treumann 1983; Treumann et al. 1990). The frequency drift of fibers is much higher than that of the drifting tadpoles, whose drift is given by the group velocity of the magnetoacoustic wave train.

Thus, in the case of the present fiber bursts (the July 11, 2005 event), it was found that the model of fibers based on whistler waves (e.g. Kuijpers 1975) is valid also for these high-frequency fibers. On the other hand, the model based on Alfvén solitons is excluded in this case.

In this Letter we present for the first time the drifting tadpoles recognized in the wavelet spectra of the dm-radio emission associated with fibers. This drift was interpreted as the motion of the magnetoacoustic wave train modulating the radio emission produced by the plasma emission mechanism. This drift enabled us to determine the Alfvén speed and the magnetic field strength in the loop guiding the wave train. Their low value indicates that the guiding structure is consistent with a neutral current sheet. The present analysis supports the model of fiber bursts based on whistler waves.

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