The Astrophysical Journal, 697:L108–L110, 2009 June 1 doi:10.1088/0004-637X/697/2/L108

TADPOLES IN WAVELET SPECTRA OF A SOLAR DECIMETRIC RADIO BURST

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Received 2009 January 29; accepted 2009 April 23; published 2009 May 6

ABSTRACT

In the solar decimetric type IV radio event observed on 2001 June 13, we have found wavelet tadpole patterns for the first time. They were detected simultaneously at all radio frequencies in the 1.1–4.5 GHz frequency range. The characteristic period of the wavelet tadpole patterns was found to be 70.9 s. The parameters of the tadpoles on different frequencies are very similar and the correlations between individual radio fluxes are high. These tadpoles are interpreted as a signature of the magnetoacoustic wave train moving along the flare loop through the radio source and modulating its gyrosynchrotron emission.

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

1. INTRODUCTION

It has been theoretically predicted (Roberts et al. 1983, 1984) that the periodicity of magnetoacoustic modes can be modified by the time evolution of an impulsively generated signal. One of the obvious sources of such a disturbance is the impulsive flare process. These magnetoacoustic waves are trapped in regions with higher density (e.g., in coronal loops) acting as waveguides. The impulsively generated wave in such a coronal waveguide exhibits three phases: (1) periodic phase (long-period spectral components arrive as the first ones at the observation point), (2) quasi-periodic phase (both long- and short-period spectral components arrive and interact), and finally (3) decay phase. The numerical simulation of characteristic time signatures of impulsively generated magnetoacoustic wave trains propagating along a coronal loop with different density contrast ratios has been studied by Nakariakov et al. (2004). 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 analyzed using wavelet transforms (Katsiyannis et al. 2003; Williams et al. 2001).

In this Letter, for the first time we report the tadpoles detected in the wavelet spectra of decimetric (dm) type IV radio burst. The Letter is organized as follows: in Section 2 we present observations and their analysis. In Section 3 we discuss and conclude our results.

2. OBSERVATIONS AND STATISTICAL ANALYSIS

The 2001 June 13 flare (classified as M7.8, GOES X-ray maximum at 11:42 UT) was observed during 11:22–12:18 UT in the active region NOAA AR 9502. In H_α the flare has the importance 1N. The observed 17 minute duration (11:32–11:49 UT) dm type IV radio event was recorded by the Ondřejov radio spectrograph (Jiřička et al. 1993) with 0.1 s time resolution. The radio dynamic spectrum of this event is shown in Figure 1. Within the frequency range 1.1–4.5 GHz, we have chosen several individual frequencies and the resulting time series have been analyzed in their power and global wavelet spectra, inverse wavelet transform, and cross correlations.

2.1. Wavelet Analysis of the dm Radio Time Series

The analyzed type IV radio event consists of smooth continua (without fine structures) in the whole frequency range under study. We have studied 419 radio flux time series at individual frequencies (cuts of the radio spectrum) from 1.1 to 4.5 GHz during the time interval 11:32–11:49 UT. Characteristic periods with tadpole pattern were searched for in the radio flux time series by three different wavelet methods (Torrence & Compo 1998). (1) Wavelet power spectrum: here we have to determine the cone of influence (COI) where edge effects become important due to finite-length time series and the confidence level (CL) relative to red noise. In the analysis of each time series only the regions outside the COI with CL above 99% are considered as significant. (2) Global wavelet spectrum, where we consider only peaks above the 99% global CL. (3) Inverse wavelet transform, where the reconstructed flux time series is computed only for the period range around the characteristic period P related to individual tadpoles in the power spectrum.

The tadpole wavelet signatures with a dominant characteristic period of $P = 70.9$ s were recognized at all the 419 frequencies in the time subinterval $T = $ 11:40–11:47 UT (Figure 1) and all of them have similar characteristic parameters, which are presented in Table 1 for 10 selected radio time series. The duration of the tadpole and the number of wave oscillations of the inverted tadpole flux with the period P measured outside of the COI (i.e., lower limit of the oscillations) at each of the 419 individual radio frequencies range from 300–370 s and 4–5, respectively.

Three characteristic examples of these tadpoles are presented in Figure 2. Panels A show original time series (1203, 1592, and 2283 MHz). Panels B show the corresponding wavelet power spectrum with the tadpole pattern and the characteristic period $P = 70.9$ s. The spectrum is plotted with the lighter areas indicating greater power. The hatched region belongs to the COI. The solid contour shows the 99% CL. Panels C show the reconstructed time series of individual tadpoles by the inverse wavelet transform. These inverse fluxes are computed for the period range 40–100 s around the characteristic period P.

2.2. Cross-Correlations of the dm Radio Time Series

Using the methods by Bailey (1977) and Gömöry et al. (2004), we computed the cross-correlation coefficients between the time series at 4500 MHz and all of the other 418 radio time series in the tadpole time subinterval T (Figure 1). We found that the cross-correlation coefficient decreases from 0.9 to 0.4 in direction from higher to lower frequencies (i.e., from 4.5 GHz to 1.1 GHz), and there is no significant time shift among all of these

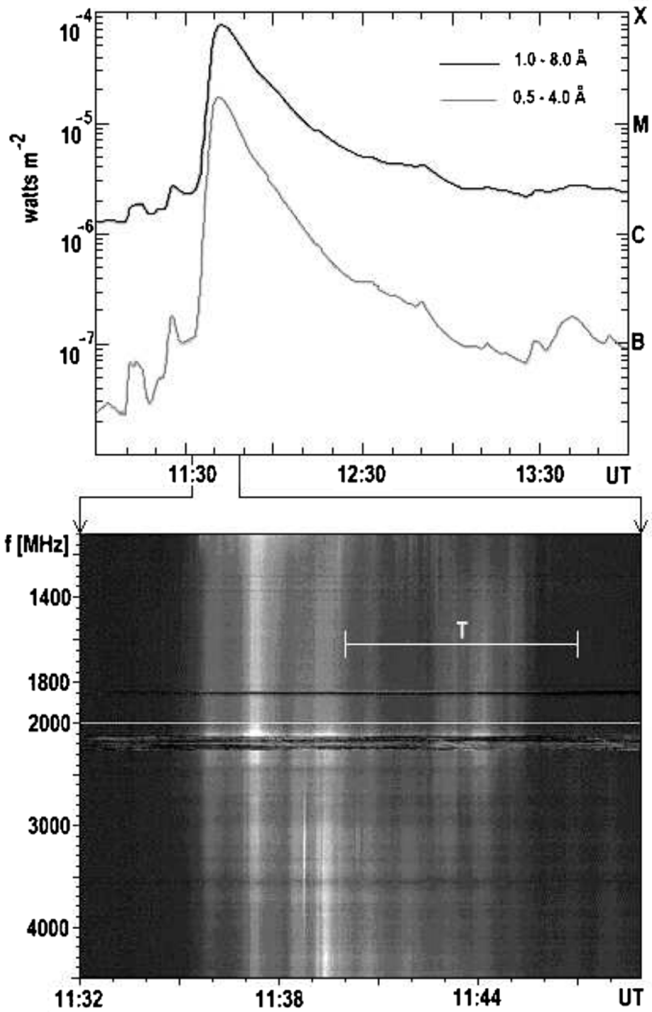

Figure 1. Top: GOES X-ray fluxes of the 2001 June 13 flare with maximum at 11:42 UT. Bottom: the decimetric type IV radio spectrum recorded during the maximum of this flare by the Ondřejov radio spectrograph. Tadpole wavelet patterns were recognized in the time subinterval T (11:40–11:47 UT).

Table 1
Basic Parameters of the Tadpole Wavelet Patterns (Period $P = 70.9$ s) at 10 Selected Frequencies

Frequency (MHz)	Start Time (UT)	Duration (s)	Number of Oscillations[a]	Cross-correlation Coefficient
1138	11:40:25	360	5.1	0.48
1203	11:40:26	365	5.1	0.54
1433	11:40:26	330	4.6	0.61
1592	11:40:27	343	4.8	0.59
1700	11:40:27	361	5.1	0.57
2049	11:40:25	319	4.5	0.64
2283	11:40:28	307	4.3	0.67
3396	11:40:25	319	4.5	0.89
3777	11:40:26	307	4.3	0.94
4314	11:40:27	326	4.6	0.95

Notes. The cross-correlation coefficients of the radio fluxes on different frequencies in the subinterval T (see Figure 1), computed with respect to the 4500 MHz time series, are added.
[a]Of the inverted tadpole flux.

time series. The cross-correlation coefficients for 10 selected frequencies are shown in Table 1. As can be seen, all time series in the tadpole time interval are significantly correlated, although the correlation decreases as the frequency difference increases.

3. DISCUSSION AND CONCLUSIONS

We have investigated the 17 minute interval of the dm type IV solar radio event of the 2001 June 13 flare, recorded by the Ondřejov radio spectrograph in the 1.1–4.5 GHz frequency band. All the flux time series have been analyzed in their wavelet spectra and cross-correlations. The tadpole patterns are evident in the wavelet power spectra in the time subinterval T (11:40–11:47 UT, Figure 1) in all of the 419 time series. We can see the rather periodical tail as well as the quasi-periodical head of the tadpole. This pattern is very similar to the results of numerical simulations in Figures 3–5 in Nakariakov et al. (2004). The long-period spectral components (tadpole tail) with the characteristic period P propagate faster than the medium and short-period ones (tadpole head). We have presented three examples of tadpoles (Figure 2) as well as their basic properties (Table 1). These tadpoles last 300–370 s. They have the characteristic period $P = 70.9$ s and their flux profiles show a low number of wave oscillations (4–5) which means that their damping is rather strong. All of the radio fluxes are significantly correlated (cross-correlation coefficient ranges 0.4–0.9) which agrees with the commonly accepted fact that this type of the dm-radio burst (broadband smooth continuum) is generated by the gyrosynchrotron emission mechanism. On the other hand, the lower cross-correlation coefficient at the lowest frequencies (1.1–2.0 GHz) may be caused by weak plasma emission superimposed here.

In accordance with previous studies (e.g., Nakariakov et al. 2004), we interpret the presented tadpoles as a signature of the magnetoacoustic wave train moving along a flare loop through the radio source and modulating its gyrosynchrotron emission.

Let us assume that the time of the 3–4 GHz peak (11:39:20 UT—see the time of the bright vertical feature in Figure 1) is the time of the magnetoacoustic wave initiation. The arrival times of the fastest (f) and slowest (s) magnetoacoustic waves to the radio source can be estimated from the tadpoles in Figure 2 as about 11:41 and 11:44 UT, i.e., the wave travel times are $t_f = 100$ s and $t_s = 280$ s, respectively. The ratio of these times is 2.8, which corresponds to the range of velocities in Figure 1 in the paper by Nakariakov et al. (2004). Now, let us assume that the Alfvén velocity inside the dense guide-loop is $v_A = 500$ km s^{-1}. Then according to the relations ($L = v_A \Delta t$, $kw \sim 1$, where k is the k-vector magnitude and w is the half-width of the waveguide) in Nakariakov et al. (2004), the distance from the location of wave initiation to the radio source and the half-width of the guide-loop are $L = 140{,}000$ km and $w = 5600$ km, respectively. For the flare these values seem to be reasonable, nevertheless they can be larger or smaller in dependence on the Alfvén velocity in the loop. In future studies with a spatial resolution of the radio source these values could be checked and used to estimate the Alfvén velocity in the loop. We expect that the wave train modulates the gyrosynchrotron emission through a variation of the magnetic field in this train. Alternatively, this wave train can modulate the process accelerating superthermal particles producing the gyrosynchrotron emission.

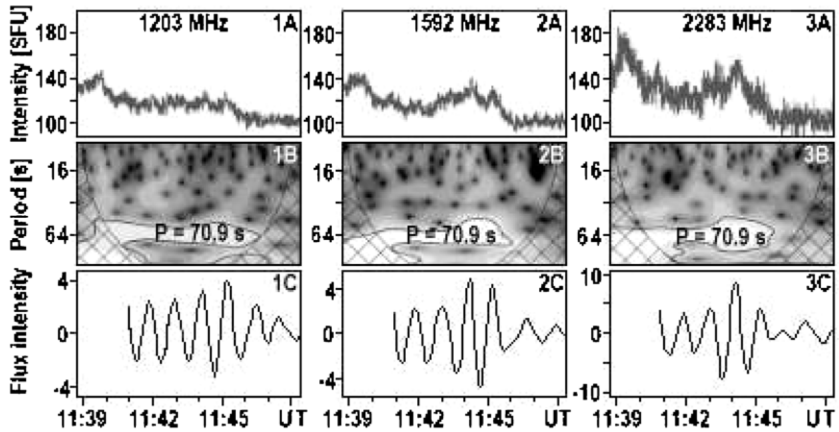

Figure 2. Characteristic examples of the tadpoles detected on selected radio frequencies in the subinterval *T* (see Figure 1). Panels A show original time series. Panels B show corresponding wavelet power spectra with tadpole patterns outlined by contours at the 99% CL. Panels C show the radio fluxes computed by the inverse transform from the tadpole wavelet spectra for the period range 40–100 s around the characteristic period *P*.

Finally, the existence of these tadpole wavelet patterns can provide evidence of the wave train in the flare loops, and their characteristics (e.g., period, longevity, and shape) can provide information about the parameters of the oscillating loops.

We thank the referee for very useful comments that improved the Letter. H.M., M.K., and K.J. acknowledge the support from the grant IAA300030701 of the Academy of Sciences of the Czech Republic. Work of J.R. was partly supported by the Slovak Research and Development Agency under the contract APVV-0066-06. The wavelet analysis was performed using the software based on tools provided by C. Torrence and G. P. Compo at http://paos.colorado.edu/research/wavelets.

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