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CLASSIFICATION AND PROPERTIES OF SUPERSHORT SOLAR RADIO BURSTS

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ABSTRACT

Characteristics of supershort structures (SSSs) occurring in the metric solar type IV radio bursts are described. The most important property of SSSs is their duration, which, at half-power, ranges from 4 to 60 ms and is thus much shorter than generally expected for the bursts in the metric range. The comparison of the distributions of SSS durations with those of the spikes confirms that these are completely different classes of bursts. Our analysis is focused on the frequency range 200–450 MHz, providing us with the one-to-one identification of individual SSSs in single-frequency records of the INAF–Trieste Astronomical Observatory (Italy) and in the high-resolution spectral data of Artemis IV (Greece). The analysis reveals a number of different bursts that are classified as simple broadband, simple narrowband, and complex SSSs. The diversity of SSSs has a resemblance to the variety of the well-known metric radio bursts characterized by a 1 s timescale.

Subject headings: Sun: corona — Sun: radio radiation

1. INTRODUCTION

For about 40 years, spikes in the decimeter-wavelength range have been considered to be the shortest solar radio bursts (see, e.g., McKim Malville et al. 1967; Benz 1986; Fleishman & Mel'nikov 1998 and references therein). Individual cases of even shorter radio bursts were also occasionally reported but were considered only as very rare and isolated events (Dröge 1967; Elgaroy & Sveen 1979; McConnell 1980). Contrary to these rare bursts, radio spikes are a rather frequent type of bursts and well analyzed. The duration of spikes increases with the decrease of the observing frequency, ranging from 3–4 ms at 3 GHz to 110–150 ms at 200 MHz (Mészárosová et al. 2003; Guedel & Benz 1990). Spikes are considered to be signatures of elementary processes of magnetic field annihilation. The large diagnostic potential of decimetric spikes for analyses of flares is well known (Benz & Kane 1986); in particular, the short duration and narrow bandwidth suggest a small source size and therefore nonthermal emission and an extremely high brightness temperature (10^{15} K and higher; Benz 1986).

In this Letter, we report the existence and describe the characteristics of solar radio bursts with durations 2–10 times shorter than spikes in the frequency range 200–600 MHz. Hereafter, we call these fast bursts supershort structures (SSSs). The aim is not only to report the existence of bursts shorter than spikes but also to present a whole palette of bursts and their complexity, at the timescale of spikes and shorter.

For the analysis, we utilize single-frequency data recorded by the solar multichannel radiopolarimeter of the Trieste Solar Radio System (TSRS; Messerotti et al. 2001) of the INAF–Trieste Astronomical Observatory and the high-resolution dynamic spectra obtained by the solar radiospectrograph Artemis IV (Carabaos et al. 2001) operated by the University of Athens. We use the 1 ms resolution TSRS radio flux measurements at 237, 327, 408, and 610 MHz and the 10 ms resolution Artemis IV spectra in the range 270–450 MHz. From the data set of 15 type IV bursts (recorded by TSRS), abundant with SSSs, we selected 10 events observed also by the radiospectrograph, providing a cross-identification. The main information about the associated flares is reported in Table 1.

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2. BASIC CLASSIFICATION OF SSSs

Our observations reveal a broad variety of SSSs. We classify SSSs in three categories: (1) simple broadband, (2) simple narrowband, and (3) complex. In the following, we briefly describe the characteristics of the SSS categories, by showing typical examples (Figs. 1–3) and outlining their basic properties (Fig. 4).

2.1. *Simple Broadband SSSs*

In this category, we recognized two distinct subclasses and denote them as simple broadband SSS pulses and simple broadband drifting SSSs.

For previous studies of broadband fine structures such as short-duration pulsations, type III–like bursts, blips, etc., see, e.g., Isliker & Benz (1994), Magdalenić et al. (2003), Guedel & Benz (1988), and Benz et al. (1983). These features were most often analyzed at the time resolution of 100–20 ms, whereas still higher time resolution data were mostly used in studies of narrowband spikes and/or narrowband pulsations (Guedel & Benz 1990; Ma et al. 2003). Our high time resolution data (1–10 ms) enable us for the first time to clearly resolve broadband bursts of duration as short as 25 ms.

SSS pulses are instantaneous bursts of frequency drift larger than 5000 MHz s^{-1} (the lower limit of the frequency drift is estimated using $\Delta f = 100$ MHz and the time resolution of $\Delta t = 0.01$ s). Their bandwidth varies from pulse to pulse and is typically about $\Delta f = 100$ MHz (Fig. 1*a*). The duration of the emission is the same over the whole frequency bandwidth, and the average duration at half-power is $d_{1/2} = 10$–20 ms. Some groups of pulses show a quasi-periodic pattern, and they are morphologically analogous to (classical) short-duration pulsations (Elgaroy 1986).

Simple broadband drifting SSSs appear in the dynamic spectrum as drifting emission stripes, having positive, as well as negative, drift rates in the range $|\Delta f/\Delta t| = 400$–1000 MHz s^{-1}. They also appear in groups but are much fuzzier than SSS pulses. The bandwidth of broadband drifting SSSs is $\Delta f \geq 100$ MHz. The duration varies from group to group, and on average it is $d_{1/2} = 30$–70 ms. Sometimes, they look similar to type III bursts; i.e., the duration of negatively drifting bursts is somewhat longer

TABLE 1
Characteristics of the Soft X-Ray Flares Associated with the Type IV Bursts Considered in the Analysis

Date	Flare Start	Location on the Disk (deg)	Flare Importance
2000 Apr 15 ……	09:34	…	C1.1
	10:09	…	M4.3
	12:13	…	C1.0
	13:38	…	C3.0
	14:37	…	M1.1
2000 Jun 19 ……	14:28	N19, W13	C1.9 SF
2000 Jul 07 …….	10:56	N23, W41	M1.3 SN
2000 Sep 23 ……	10:48	…	C1.0
2002 Jul 15 …….	11:35	N18, E01	C9.1
	13:45	…	C3.6 SF

at the lower frequency part of the burst (Fig. 1*b*). Drift rates of these SSSs are comparable to drift rates of broadband pulsations with longer periods (500–1500 ms) reported by Aschwanden & Benz (1986).

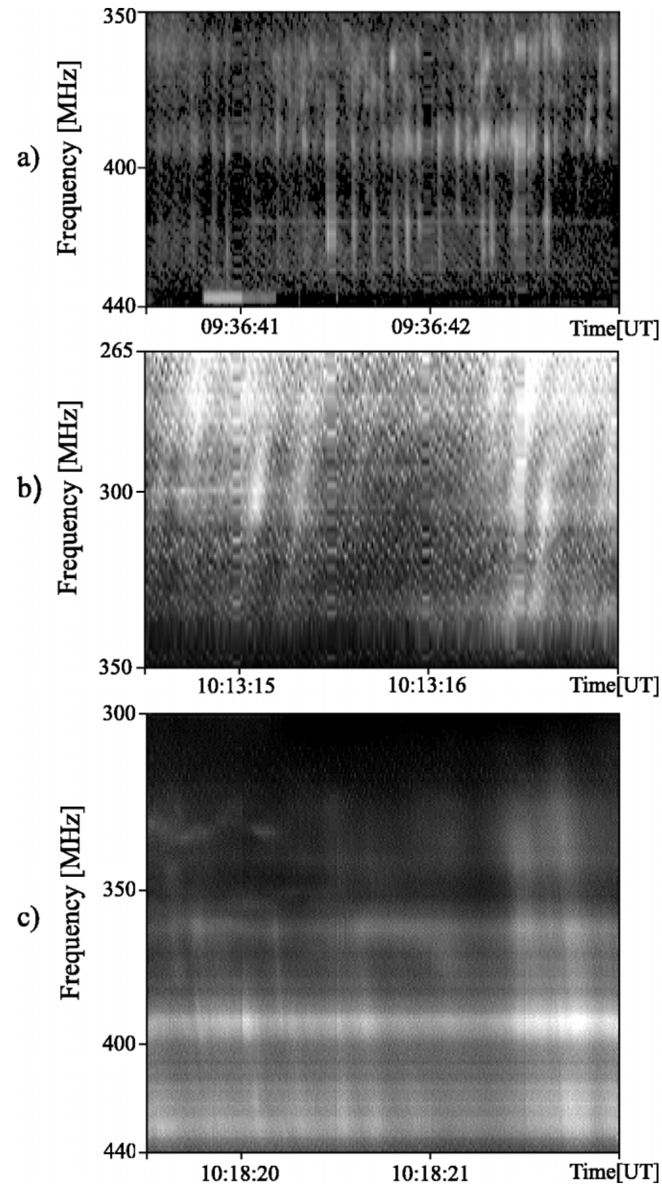

Fig. 1.—Artemis IV dynamic spectra of simple broadband SSSs recorded on 2000 April 15: (*a*) SSS pulses, (*b*) negatively drifting SSSs, and (*c*) positively drifting SSSs.

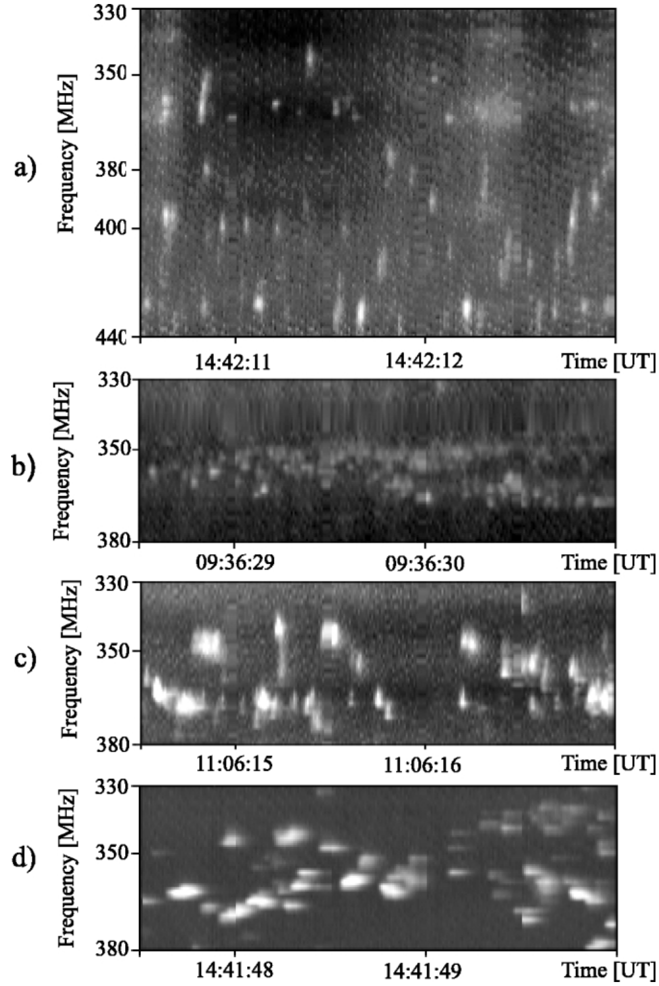

Fig. 2.—Artemis IV dynamic spectra of simple narrowband SSSs: (*a*) spike-like SSSs, (*b*) dot-like SSSs, (*c*) sail-like SSSs, and (*d*) flag-like SSSs. Events *a*, *b*, and *d* are recorded on 2000 April 15, and event *c* on 2000 September 23.

2.2. *Simple Narrowband SSSs*

Narrowband SSSs are bursts with bandwidth smaller than 20 MHz; typically the relative bandwidth is $\Delta f/f = 4\%–7\%$ (for 410–200 MHz, respectively). They can be divided into spike-like and patch-like SSSs.

Spike-like SSSs are the most frequent narrowband SSSs in the frequency range 200–600 MHz. They appear in compact or diffuse clouds consisting of a large number of generally randomly distributed bursts. However, examples of spike-like SSSs forming more regular patterns, e.g., chains or zebra patterns, were also found. Individual bursts are morphologically similar to the "ordinary spikes" (Fig. 2*a*), but the duration at a given frequency can be even 10 times shorter than that expected for spikes (see Fig. 4). Most of the identified spike-like SSSs have durations in the range of 4–30 ms. The duration is only sometimes frequency-dependent (case studies are in progress), that is, distinctly different from the strict frequency dependence of the duration of spikes (Guedel & Benz 1990). Frequently, spike-like SSSs show a positive or negative frequency drift, usually larger than $|\Delta f/\Delta t| \approx 800$ MHz s^{-1}. The measured drift rates are much larger than those reported for spikes (Elgaroy & Sveen 1979).

Patch-like SSSs are bursts with the narrowest bandwidth. We identified different spectral forms and divided them into dot-like, sail-like, and flag-like bursts. Dot-like bursts have symmetric

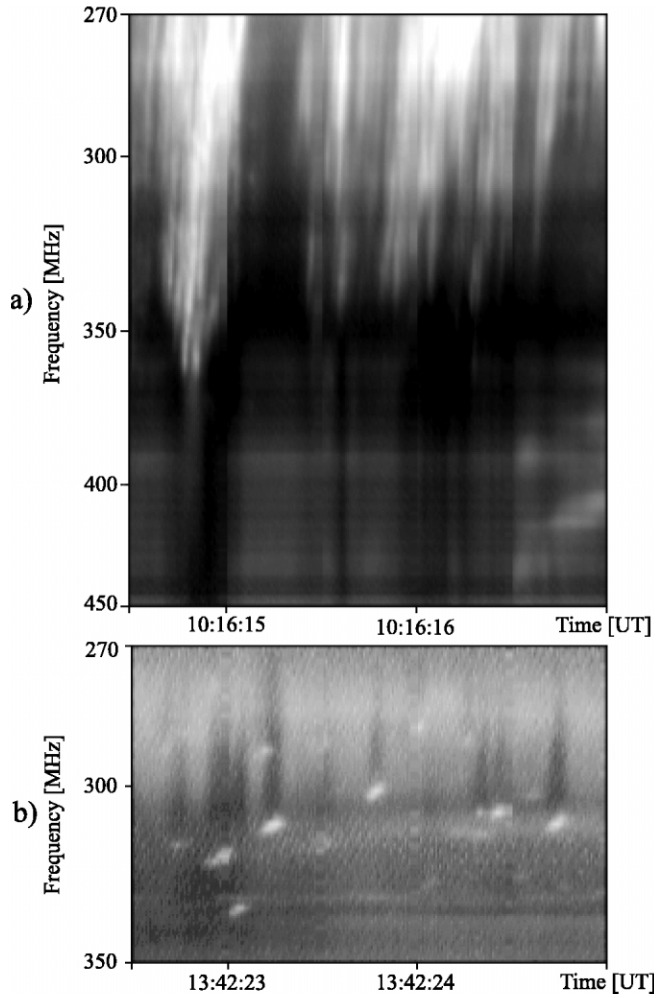

FIG. 3.—Complex SSSs recorded on 2000 April 15: (*a*) blinkers and (*b*) tadpole-like SSSs.

time profiles as well as frequency profiles (Fig. 2*b*). Sail-like and flag-like SSSs have triangular spectral shapes. Sail-like bursts (Fig. 2*c*) have a symmetric time profile, but their frequency profile is asymmetric, showing a larger gradient at the high-frequency part of the burst. Flag-like bursts (Fig. 2*d*) have a symmetric frequency profile, whereas the time profile is much steeper in the rising phase. Due to the peculiar morphology of the patch-like SSS, the derived durations (4–50 ms) depend on the frequency at which they are estimated.

2.3. *Complex SSSs*

The most extraordinary SSSs in our sample are *complex SSSs*, consisting of an emission and an absorption component. We identified two distinct subcategories, which we call blinkers and tadpole-like SSSs.

Blinkers are drifting SSSs (on average $\Delta f/\Delta t \approx -650$ MHz s^{-1}) that consist of a broadband emission and a broadband absorption component (Fig. 3*a*). Each component extends over more than 100 MHz. The absorption component is usually at the high-frequency part of the burst. The absorption switches to emission rather abruptly over $\Delta f < 10$ MHz. This "switch-on" frequency bandwidth is approximately the same for all the bursts in a group. The duration, $d_{1/2} = 30$–40 ms, is approximately the same along the whole absorption and emission component.

Tadpole-like SSSs are composed of a narrowband emission patch on the high-frequency side of the burst attached to an absorption element stretching toward lower frequencies (Fig. 3*b*). The emission patch has a duration $d_{1/2} \approx 50$ ms, has a bandwidth $\Delta f \approx 5$ MHz, and shows a frequency drift $\Delta f/\Delta t = -60 \pm 10$ MHz s^{-1}. The absorption element has a duration generally shorter than $d_{1/2} \leq 20$ ms and bandwidth $\Delta f \approx 40$ MHz, and it is characterized by fast drift $\Delta f/\Delta t = -1000 \pm 400$ MHz s^{-1}.

To a certain degree, tadpole-like SSSs are similar to the tadpole bursts reported by Slottje (1972). Tadpoles are comprised of an emission "eye" at the high-frequency side of the burst, a stretched absorption "body," and an emission "tail" continuing beyond the absorption body. The emission eye of tadpoles (full duration $d \leq 100$ ms) is imbedded within the body ($d = 200$–300 ms). On the other hand, the emission patch ($d \approx 70$ ms) of our tadpole-like SSSs is longer than the absorption element ($d \leq 30$ ms). Furthermore, we clearly see the drift of the emission patch, not resolved in the emission eye of tadpoles. The duration of the whole drifting emission patch is comparable to the duration of the eye, but the bandwidth is somehow larger (5 MHz for tadpole-like SSSs and 1–2 MHz for tadpoles), which could be a consequence of the drift. In addition, the emission tail of tadpoles is not visible in our tadpole-like SSSs. Bearing in mind different observational techniques (analog/digital) and differences in the background emission, it is possible that, in spite of distinctive differences, the Slottje tadpoles and our tadpole-like SSSs belong to a broader class of physically equivalent bursts.

3. DISCUSSION

The basic characteristics of the SSS classes are summarized in Table 2. Inspecting the table, one finds that all of the features presented have a duration considerably shorter than that of spikes, which in the frequency range 450–250 MHz exhibit durations of 50–100 ms.

Without doubt, broadband and complex SSSs are features entirely different from spikes. Broadband SSS pulses (Fig. 1*a*) have a morphology similar to longer period (1 s) pulsations

TABLE 2

BASIC CHARACTERISTICS OF DIFFERENT SSS CLASSES

Name	Spectral Category	$d_{1/2}$ (ms)	Δf (MHz)	$\lvert\Delta f/\Delta t\rvert$ (MHz s^{-1})
		Simple		
Pulses	Broadband	10–20	≈100	∞
Drifting broadband	Broadband	30–70	≥100	400–1000
Spike-like	Narrowband	4–30	<20	>800
Patch-like	Narrowband	4–50	<15	…
		Complex		
Blinkers	Broadband	30–40	>100	600–700
Tadpole-like (emission patch)	Narrowband	≈50	≈5	50–70
Tadpole-like (absorption element)	Broadband	≤20	≈40	600–1400

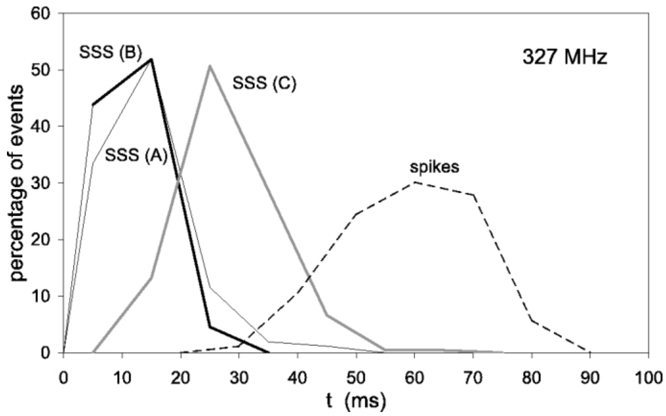

FIG. 4.—Distributions of spike-like SSS durations at 327 MHz shown in 10 ms bins: SSS(A) and SSS(B) represent bursts constituting zebra patterns in the events observed on 2002 July 15; SSS(C) represents bursts from the cloud of spike-like SSSs recorded on 2002 July 18. The distributions include 260, 375, and 227 bursts, respectively. The SSS distributions are compared with the 327 MHz distribution of spikes recorded on 1991 June 15.

(e.g., Aurass et al. 2003) and are therefore possibly a "short-duration version" of the same phenomenon. Similarly, the drifting broadband SSSs (Fig. 1*b*) are quite likely the short-duration counterpart of type III bursts. On the other hand, for complex bursts it is difficult to identify the 1 s duration analogs. According to our knowledge, the only feature that consists of an emission and an absorption element on the 1 s scale is the fiber-burst (Aurass et al. 2005), which has a completely different morphology.

Regarding the narrowband SSSs, one can conclude that the flag-like and sail-like bursts (Fig. 2) also show a morphology considerably different from that of spikes. On the other hand, dot-like bursts might be conceived as spike-like bursts with very small bandwidth.

Since the spike-like bursts represent the most numerous class of SSSs, and have the shortest durations, they deserve special attention in our study. In particular, the question arises whether the spike-like bursts represent just a short-duration tail in the distribution of spikes. To get the clue to this question, we compare the distribution of durations of spikes recorded at 327 MHz on 1991 June 15 (the event described in Zlobec & Karlický 1998), with the distribution of spike-like SSSs in three events (events A, B, and C in Fig. 4.). All three events are related to flares in the same active region, NOAA AR 30. Spike-like bursts in events A and B [SSS(A) and SSS(B), respectively] are the constitutive elements of zebra patterns observed in the two type IV bursts related to two homologous flares on 2002 July 15. The average durations of SSS(A) and SSS(B) are 13 ± 7 and 11 ± 4 ms, respectively, that is, 6–7 times shorter than the average duration of spikes, which is 77 ± 29 ms; i.e., they are members of entirely different statistical populations. A similar situation holds for the distribution of spike-like bursts, related to the flare on 2002 June 18 (event C), which are clustered in a cloud similar to that formed by spikes (Zlobec & Karlický 1998). Their average duration (28 ± 7 ms) is also significantly shorter than that of spikes.

In the preliminary analysis of the duration of spike-like SSSs, we noted another interesting characteristic. The sample SSS(A) shows a significant dependence of the duration on frequency: at $f = 408$ MHz, the average duration (7 ± 4 ms) is significantly shorter than that at $f = 327$ MHz (13 ± 7 ms). Such a difference corresponds to a decrease as $\approx f^{-3}$, which is much steeper than in the case of spikes, since Guedel & Benz (1990), as well as Zlobec & Karlický (1998), found $\approx f^{-1.3}$. The same dependence $\approx f^{-1.3}$ was recently obtained by G. D. Fleishman (2005, private communication), for spikes that extend into the GHz range.

On the other hand, the durations of SSS(B) show only a weak dependence $\approx f^{-0.5}$, where the difference between the 327 and the 408 MHz distributions has the *t*-test statistical significance of only 93%. Furthermore, we noted that the distributions can significantly change in time, which indicates that the distribution of durations and the $d(f)$ relationship probably depend on the characteristics of the environment in which a group of bursts is excited; i.e., they can be different in different events and/or different phases of an event. However, a more detailed treatment is needed before drawing final conclusions on the nature of the spike-like SSSs. Since it is still not clear what are the emission processes of solar radio spikes, the interpretation of the SSSs provides an additional challenge for theory.

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