Narrowband Spikes Observed During the 13 June 2012 Flare in the 800 – 2000 MHz Range

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Received: 15 December 2021 / Accepted: 12 April 2022 / Published online: 9 May 2022
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Abstract
Narrowband (∼5 MHz) and short-lived (∼0.01 s) spikes with three different distributions in the 800 – 2000 MHz radio spectrum of the 13 June 2012 flare are detected and analyzed. We designate them as SB (spikes distributed in a broad band or bands), SZ (spikes distributed in zebra-like bands) and SBN (spikes distributed in broad and narrow bands). On analyzing AIA/SDO images of the active region NOAA 11504, a rough correspondence between groups of the spikes observed at 1000 MHz and peaks in the time profiles of AIA channels taken from the flare subarea close to the leading sunspot is found. Among the types of spikes the SZ type is the most interesting because it resembles zebras. Therefore, using autocorrelation and crosscorrelation methods we compare SZ and SBN spikes with the typical zebra observed in the same frequency range. While the ratio of SZ band frequencies with their frequency separation (220 MHz) is about 4, 5, and 6, in the zebra the frequency stripe separation is about 24 MHz and the ratio is around 50. Moreover, the bandwidth of SZ bands, which consists of clouds of narrowband spikes, is much broader than that of zebra stripes. This comparison indicates that SZ spikes are generated in a different way from the zebra, but in a similar way to SBN spikes. We successfully fit the SZ band frequencies by the Bernstein modes. Based on this fitting we interpret SZ and SBN spikes as those generated in the model of Bernstein modes. Thus, the magnetic field and plasma density in the SZ spike source are estimated to be about 79 G and $8.4 \times 10^{9}$ cm$^{-3}$, respectively.

Keywords Flares · Dynamics · Radio bursts · Dynamic spectrum

1. Introduction

Solar radio spikes are observed from tens of MHz up to the GHz range (Droege, 1977; Karlický, 1984; Staehli and Magun, 1986; Bouratzis et al., 2016; Melnik et al., 2014; Clarkson et al., 2021). They are characterized by short duration (10 – 1000 ms) which decreases with
increasing frequency, narrow bandwidth ($\Delta f/f = 0.002 – 0.01$) and a brightness temperature up to $10^{15}$ K (Benz, 1986; Messmer and Benz, 2000). While Messmer and Benz (2000) studied the spike parameters in two frequency ranges (320 – 383 MHz and 873 – 1000 MHz), Nita et al. (2014) presented results for the 1000 – 1500 MHz range that is a subrange of the present study (800 – 2000 MHz). Using statistical methods they found the minimal and maximal spike bandwidth as (according to their Figure 11): $(\Delta f)^{\text{min}} \sim 1$ MHz and $(\Delta f)^{\text{max}} \sim 100$ MHz for 1000 MHz and $(\Delta f)^{\text{min}} \sim 1$ MHz and $(\Delta f)^{\text{max}} \sim 10$ MHz for 1500 MHz. The spikes are of high interest because their understanding can provide detailed information about plasma processes in solar flares on kinetic scales.

Among them, the decimetric spikes belong to the most interesting ones because in some cases they are recorded close to the starting frequency of Type-III bursts and in relation to hard X-ray emissions (Dabrowski and Benz, 2009). As concerns their spatial localization, such observations are relatively rare. For example, at 327 MHz and 410.5 MHz frequencies of the Nancay Radio Heliograph (Kerdraon and Delouis, 1997), clusters of spikes were observed above the soft and hard X-ray flare sources (Khan and Aurass, 2006). Furthermore, based on the spikes observed in the 1 – 1.6 GHz range by the Karl G. Jansky Very Large Array (VLA), Luo et al. (2021) proposed that spikes are generated at the termination shock formed above the flare arcade, where a diffuse supraarcade fan and multitudes of plasma downflows are present. This interpretation is close to the idea that the narrowband dm spikes are generated by superthermal electrons in the magnetohydrodynamic turbulence in the magnetic reconnection outflows (Karlický, Sobotka, and Jiřička, 1996; Bártá and Karlický, 2001).

At lower frequencies, the LOw Frequency ARray (LOFAR) recorded spikes in the 30 – 70 MHz range that were similar to individual Type-IIIb striae observed in the same event (Clarkson et al., 2021). The authors estimated the spike emission region of the order of $\sim 10^8$ cm and a brightness temperature as high as $10^{13}$ K. For these spikes they suggested fundamental plasma emission generated likely by weak/slow electron beams.

Several models of the spikes were suggested. In some of them, runaway electrons, accelerated in a direct-current electric field, were proposed (Kuijpers, van der Post, and Slottje, 1981; Tajima et al., 1990; Wentzel, 1991). The electron-cyclotron maser (ECM) mechanism, that directly generates electromagnetic waves (spikes), was suggested by Melrose and Dulk (1982), Fleishman and Mel’nikov (1998), Ni et al. (2020) and Melrose (2017). Moreover, Stepanov et al. (1999) and Bártá and Karlický (2001) presented the model where spike frequencies correspond to those of the upper-hybrid waves, and Willes and Robinson (1996) presented the model with spike frequencies corresponding to the Bernstein modes.

There is an important additional aspect of the narrowband dm spikes that is not frequently considered in theoretical models. Namely, seeing them in radio spectra, dm spikes are in many cases clustered in bands (clouds) of spikes, as was shown for the first time by Krucker and Benz (1994). The authors also found that the frequencies of neighboring bands are in the noninteger ratio (1.06 – 1.54). In the paper by Karlický, Benáček, and Rybák (2021) this result was not only confirmed, but very narrow bands of spikes in the 7 November 2013 event enabled a successful fit of the band frequencies by the Bernstein modes.

In the model of the Bernstein modes the loss-cone distribution of superthermal electrons together with a much denser Maxwellian background plasma is assumed. In this case, the dispersion relations for the Bernstein modes can be written as (Zhelezniakov and Zlotnik, 1975; Karlický, Benáček, and Rybák, 2021)

$$\epsilon^{(0)} = 1 - 2\omega_{pe}^2 \frac{e^{-\lambda}}{\lambda} \sum_{l=1}^{\infty} \frac{l^2 I_l(\lambda)}{\omega^2 - l^2 \omega_{ce}^2} = 0,$$

(1)
\[
\omega_{pe}^2 = \frac{n_e e^2}{m_e \epsilon_0}, \quad \lambda = \frac{k^2 \nu_{lb}^2}{\omega_{ce}^2},
\]

where \(\epsilon_\parallel\) is the parallel component of the permittivity tensor, \(\epsilon_0\) is the permittivity of free space, \(\omega_{pe}\) is the electron plasma frequency, \(n_e\) is the plasma density of the Maxwellian background plasma, \(\omega_{ce}\) is the electron cyclotron frequency, \(k = (k_\parallel, k_\perp)\) is the wave vector parallel and perpendicular to the direction of the magnetic field, respectively, \(\omega\) is the wave frequency of the electrostatic wave, \(I_l(\lambda)\) is the modified Bessel function of \(l\)th order, \(\lambda\) is the dimensionless parameter, \(m_e\) is the electron mass, and \(e\) is the electron charge.

While the Maxwellian background plasma determines the dispersion relation of the Bernstein modes, generation of these electrostatic waves is due to the instability caused by electrons with the loss-cone distribution. The Bernstein modes can be unstable if the double plasma resonance condition is fulfilled

\[
\omega - \frac{k_\parallel u_\parallel}{\gamma_{rel}} - s \omega_{ce} \gamma_{rel} = 0,
\]

where \(\gamma_{rel} = (1 - v^2/c^2)^{-\frac{1}{2}}\) is the relativistic Lorentz factor and \(s\) is the resonance gyroharmonic number. Their growth rate for some specific \((\omega, k_\perp)\) can be calculated as (Zhelezniakov and Zlotnik, 1975)

\[
\gamma(\omega, k_\perp) = -\frac{\text{Im} \epsilon^{(1)}(0)}{\left[\frac{\partial \text{Re} \epsilon_\parallel^{(0)}}{\partial \omega} \epsilon_\parallel^{(0)}\right]} = 0.
\]

We note that exactly the same equations are used for generation of the upper-hybrid waves in the double-plasma resonance (DPR) model of solar radio zebras (Zlotnik, 2013). In both these models it is assumed that the Bernstein or upper-hybrid (electrostatic waves) modes are converted to the observed electromagnetic waves by coalescence processes with the low-frequency waves or mutual coalescence of the Bernstein modes. However, there is an essential difference in these models. While in the model of the Bernstein modes, the Bernstein modes and escaping electromagnetic waves are produced in one source, in the case of the zebra model with the upper-hybrid wave the zebra-stripes are generated at different locations.

In this paper, after a brief statistical analysis of spikes observed in the 800–2000 MHz range by the Ondřejov radiospectrograph (Jiřička and Karlický, 2008), we present the narrowband spikes, observed during the 13 June 2012 flare. We study these spikes because three different types of spike distributions were detected in the radio spectrum of a single flare: a) spikes distributed in a broad band or bands, b) spikes distributed in zebra-like bands, and c) spikes distributed in broad and narrow bands. We also search for their counterparts in intensity variations in localized places of a flare in AIA/SDO images. We compare the spikes in zebra-like bands with a typical zebra in the same frequency range in order to distinguish their generation mechanisms. Finally, we discuss the model of the presented spikes.

2. Observations

In Table 1 we present 18 spike events (consisting sometimes of several groups of spikes) observed in years 2007–2020 by the 800–2000 MHz Ondřejov radiospectrograph with
Table 1  Spike events and corresponding hard X-ray (HXR) emission and GOES flares. HXR energy range corresponds to the highest range detected during the radio spike time interval. RHESSI data were the primary source for the HXR emission.

| Spike event | Time interval (UT) | Range (GHz) | Flares (HXR, GOES) | Notes |
|-------------|-------------------|-------------|--------------------|-------|
|             |                   |             | Start (UT)         |       |
|             |                   |             | Max (UT)           |       |
|             |                   |             | Class              |       |
|             |                   |             | Notes              |       |
| 12-Feb-10 09:40:40 – 09:41:20 | 0.8 – 1.1 | 25 – 50 | 09:38 | 09:42 | B9.6 | BM |
| 16-Feb-11 14:23:00 – 14:25:40 | 0.8 – 2.0 | 50 – 100 | 14:19 | 14:25 | M1.6 | BM, M |
| 18-Feb-11 10:13:30 – 10:14:30 | 0.8 – 2.0 | 50 – 100 | 09:55 | 10:11 | M6.6 | AM |
| 04-Mar-12 10:37:40 – 10:41:10 | 0.8 – 1.6 | 50 – 100 | 10:29 | 10:52 | M2.0 | BM |
| 13-Jun-12 13:02:40 – 13:30:00 | 0.8 – 1.8 | 50 – 100 | 11:29 | 13:17 | M1.2 | BM, AM |
| 14-Jun-12 10:39:30 – 10:42:30 | 0.8 – 2.0 | 12 – 25 | 10:45 | 10:50 | C2.5 | PF |
| 14-Jun-12 11:00:10 – 11:00:50 | 0.8 – 2.0 | no data | 11:05 | 11:12 | C5.0 | PF |
| 11-Apr-13 06:56:00 – 07:02:00 | 0.8 – 2.0 | 50 – 100 | 06:55 | 07:16 | M6.5 | BM |
| 07-Nov-13 12:26:00 – 12:28:30 | 0.8 – 2.0 | no data | 12:22 | 12:29 | C5.9 | BM |
| 08-May-14 10:02:10 – 10:04:00 | 0.8 – 2.0 | 100 – 300 | 09:59 | 10:07 | M5.2 | BM |
| 09-Jun-14 12:27:10 – 12:37:00 | 0.8 – 2.0 | 50 – 100 | 12:24 | 12:29 | C9.0 | BM, BAM |
| 11-Jun-14 05:41:10 – 05:42:00 | 0.8 – 1.6 | 12 – 25 | 05:30 | 05:34 | M1.8 | BAM |
| 11-Jun-14 07:11:40 – 07:12:00 | 0.8 – 2.0 | 25 – 50 | 07:09 | 07:12 | C2.8 | BM |
| 12-Jun-14 09:33:50 – 09:36:50 | 0.8 – 1.3 | 100 – 300 | 09:23 | 09:37 | M1.8 | BM |
| 12-Jun-14 15:59:30 – 15:59:50 | 0.8 – 1.6 | 25 – 50 | 15:57 | 16:03 | C7.8 | BM |
| 04-Sep-14 13:17:50 – 13:18:50 | 1.1 – 1.8 | 12 – 25 | 13:10 | 13:30 | C6.3 | BM |
| 12-Sep-14 09:31:20 – 09:32:00 | 1.0 – 1.4 | 14 – 25 | 08:24 | 09:55 | C3.2 | BM |
| 22-Aug-15 06:41:40 – 06:42:50 | 0.8 – 1.6 | no data | 06:39 | 06:49 | M1.2 | BM |

If RHESSI data were not available, Fermi GBM data were used, see mark ‡. For the 04-Sep-14 event, RHESSI HXR data, denoted by *, are available several seconds after the spike event, from 13:19 UT. Abbreviations in Notes mean: BM spikes before the GOES maximum, M spikes at the maximum, AM spikes after the maximum, BAM spikes during the bump on the GOES flare decay profile, and PF spikes in the preflare phase.

time and frequency resolutions of 0.01 s and 4.7 MHz, respectively (Jiřička and Karlický, 2008). As can be seen here, these events are always associated with flares (one flare classified as a B flare, eight classified as C flares, and nine classified as M flares). Most of the events were recorded before the GOES (Geostationary Operational Environmental Satellites) soft X-ray flare maximum (12 BM, see Table 1), one before and during the maximum (1 BM, M), one before and after the maximum (1 BM, AM), one before and after the maximum, but during the bump on the GOES X-ray profile (1 BM, BAM), one after the maximum, but during the bump on the GOES X-ray profile (1 BAM), and two events during the preflare phase (2 PF). As shown in Table 1, most of these spike events were associated with the hard X-ray (HXR) emission observed by RHESSI or Fermi GBM instruments (Lin et al., 2002; Meegan et al., 2009). All these facts indicate that spikes are generated during the impulsive phases of solar flares.

2.1. The 13 June 2012 Spike Event

Among these spike events the most interesting examples of spikes were observed during the 13 June 2012 flare. During this flare we registered many groups of spikes and also their
Figure 1  The 800 – 2000 MHz overview radio spectrum observed at 13:10:00 – 13:30:00 UT during the 13 June 2012 flare by the Ondřejov radiospectrograph. Black parts of the radio spectrum at 13:00:00 – 13:02:00 and 13:04:00 – 13:10:00 UT indicate that we have no data in these intervals because they were not recorded owing to no bursts being present.

Table 2  Basic parameters of groups of spikes observed during the 13 June 2012 flare: times, frequency range, types, maximal number of the frequency bands of spikes (MNFB) and characteristic ratios of neighboring bands of spikes (BR). SB denotes spikes in broad bands, SZ in zebra-like bands, and SBN in broad and narrow bands.

| No | Time (UT) | Range (GHz) | Type | MNFB | BR |
|----|-----------|-------------|------|------|----|
| 1  | 13:02:42 – 13:02:58 | 0.8 – 1.3 | SB | 1 | - |
| 2  | 13:11:48 – 13:12:40 | 0.8 – 1.2 | SZ | 2 | 1.21 |
| 3  | 13:13:06 – 13:14:06 | 0.8 – 1.8 | SZ | 4 | 1.16, 1.19, 1.21 |
| 4  | 13:14:38 – 13:14:50 | 0.8 – 1.6 | SZ | 4 | 1.15, 1.18, 1.23 |
| 5  | 13:16:55 – 13:17:25 | 0.8 – 1.5 | SB | 1 | - |
| 6  | 13:21:08 – 13:21:26 | 0.8 – 1.6 | SB | 1 | - |
| 7  | 13:22:21 – 13:23:18 | 0.8 – 1.8 | SB | 1 | - |
| 8  | 13:24:25 – 13:24:57 | 0.8 – 1.8 | SBN | 3 | 1.25, 1.26 |
| 9  | 13:26:12 – 13:26:36 | 0.8 – 1.8 | SBN | 3 | 1.22, 1.24 |
| 10 | 13:26:59 – 13:27:30 | 1.0 – 1.6 | SZ | 2 | 1.08 |
| 11 | 13:28:55 – 13:29:05 | 0.8 – 1.6 | SB | 1 | - |

different types. According to the GOES X-ray observation this M1.2 flare started at 11:29 UT, had its maximum at 13:17 UT, and ended at 14:31 UT. In Hα observation it started at 11:36 UT, had its maximum at 14:41, and ended at 16:23 UT; lasting thus about 5 h. It occurred at the position S16E18 in the active region NOAA AR 11504 with an importance of 1N.

In this flare in the time interval 13:00 – 13:30 UT we observed eleven groups of spikes, see Figure 1. This time interval covers only a part of this long flare around its GOES X-ray maximum. Detailed radio spectra of three groups of spikes (group 1, 3, and 9 in Table 2) are shown in Figure 2. As can be seen here, spikes in these groups differ. Therefore, we classified them according to their appearance in the radio spectrum as SB (spikes distributed in a broad band or bands) (Figure 2a), SZ (spikes distributed in zebra-like bands) (Figure 2b), and SBN (spikes distributed in broad and narrow bands) (Figure 2c). Owing to the resemblance of SZ and zebras, in the following we will make a comparison of SZ spikes with a typical zebra
Figure 2  Examples of spikes observed during the 13 June 2012 flare: a) The radio spectrum observed at 13:02:42 – 13:02:54 UT showing spikes classified as SB (group 1, see Table 2 and Figure 1). b) The radio spectrum observed at 13:13:47 – 13:13:53 UT showing spikes classified as SZ (part of group 3). c) The radio spectrum observed at 13:26:12 – 13:26:36 UT showing spikes classified as SBN (group 9).
observed in the same frequency range (Figure 6). We will also compare SZ spikes with SBN spikes.

Using this classification we classified all groups of spikes in the 13 June 2012 flare, see Table 2. In this table the basic parameters of these spike groups are also summarized: type, maximal number of the frequency bands of spikes (MNFB) and characteristic ratios of neighboring bands of spikes (BR). These ratios were computed from the frequencies at flux maxima of spike bands. At lower frequencies in the 200–400 MHz range at 13:08–13:24 UT these spike groups were associated with Type-II bursts (Callisto-BLEN7M observation).

AIA/SDO UV (Lemen et al., 2012), HMI/SDO (Scherrer et al., 2012; Schou et al., 2012) and RHESSI X-ray (Lin et al., 2002) observations associated with these groups of spikes are shown in Figures 3 and 4. As seen in Figure 4 (middle panel), in the time interval of spike groups, the RHESSI X-rays exhibit a slow decrease in time with some enhancements; see, e.g., that just before the GOES flare maximum. They indicate the presence of superthermal electrons with energies up to 100 keV at these times. Owing to RHESSI technical problems, X-ray source positions could not be constructed. Therefore, using AIA/SDO observations we tried to localize a part of the flare where temporal-intensity variations correspond to variations at the 1000-MHz time profile (Figure 4). Searching the time profiles in AIA channels (1700, 304, 171, 335, and 94 Å and the continuum) in small regions (starting from those with 20 × 20 arcsec) in the whole flare site we found the most interesting correspondence with the 1000-MHz radio profile in the white rectangle with the coordinates X = −270 to −235 and Y = −298 to −280 arcsec (Figures 3 and 4). It is interesting that this position corresponds to one end of the sigmoidal flare structure where many magnetic-field lines of flare loops are concentrated; rooted in the area of the northern part of the active region leading sunspot, see HMI continuum and magnetogram in Figure 3. In other positions, AIA profiles were smoother and without such distinct variations, or with some variations, but only in one AIA channel. As seen in Figure 4, there are peaks in several AIA channels observed simultaneously that correspond to peaks in the 1000-MHz radio profile. While the 94-Å peaks indicate the presence of a hot plasma (6.3 × 10⁶ K), the 1700-Å peaks show a heating of deep atmospheric layers with a temperature of 5.0 × 10³ K, probably owing to precipitating superthermal particles. The peaks in radio and AIA are of varying sizes, not all peaks on the 1000-MHz radio profile have corresponding peaks in AIA channels. This indicates a complex relation. In fact, a simple relation cannot be expected because it is commonly assumed that spikes are generated by superthermal electrons with the loss-cone distribution, but peaks in the AIA channels express plasma-density enhancements at the AIA channel characteristic temperature.

3. Analysis of Spikes, Comparison with Typical Zebra in the Same Frequency Range and Modeling of SZ Frequencies

Radio observations show three types of spike distributions: a) in one cloud of spikes (SB), b) in several zebra-like bands (SZ), and c) clouds of spikes with very narrow bands of spikes (SBN). The presented SBN type of spikes is similar to the event from 7 November 2013 that was interpreted as emission in Bernstein modes (Karlický, Benáček, and Rybák, 2021). To confirm this similarity we computed crosscorrelation at three spike-band frequencies from the ending part of SBN: 990, 1220, and 1490 MHz (Figure 5), where the spike bands are the narrowest. We found that the time lag is ≤ 0.01 s, in agreement with the 7 November 2013 case. The maximal crosscorrelation in Figure 5 is even higher than that in Figure 3 in the paper by Karlický, Benáček, and Rybák (2021). Thus, we think that the present SBN
spikes have the same origin as the spikes observed at 7 November 2013, i.e., the emission is generated in Bernstein modes. Furthermore, we compare SB and broad part of SBN spikes. Owing to the similar parameters of individual spikes we think that the SB type is one broad part of SBN type.

3.1. Comparison of Zebra-Like Spikes (SZ) with a Zebra in the Same Frequency Range

The most interesting type of spikes is the SZ type because it resembles zebras. Therefore, let us compare it with a typical zebra in the same frequency range, e.g., with the zebra ob-
Figure 4  Time profiles in the interval of the radio spectrum (Figure 1, at 13:00–13:30 UT) of the flux at 1000 MHz (upper panel) and RHESSI counts (middle panel) together with AIA light curves (bottom panel, expressed as the ratio to the AIA intensity at times around 13 UT) taken from the small white rectangle in Figure 3. The vertical full, dashed, and dotted lines in plots of time profiles indicate the time of AIA images in Figure 3, the GOES flare maximum, and the times of some peaks in the 94-Å time profile, respectively.

served at 1 August 2010 (Figure 6 upper panel). First, we use the autocorrelation method. We computed the time evolution of the autocorrelations at different frequencies. We made these computations for SZ shown in Figure 2b and also for the ending part of SBN in Figure 2c and the zebra shown in Figure 6 upper panel. The results are shown in Figure 7. The autocorrelations of types SZ and SBN are similar. Their frequency lag is about 220 and 250 MHz, respectively, and this lag is practically constant in time. When we divide the mean SZ band frequencies (\(\sim 960, \sim 1120, \sim 1330,\) and \(\sim 1550\) MHz) by the lag frequency (\(\sim 220\) MHz) the ratios \(\sim 4.4, \sim 5.1, \sim 6.0,\) and \(\sim 7.0\) are obtained. Similarly, dividing the mean SBN band frequencies at the ending part of SBN (\(\sim 990, \sim 1220,\) and \(\sim 1490\) MHz) by the lag frequency (\(\sim 250\) MHz) the ratios \(\sim 4.0, \sim 4.9\) and \(\sim 6.0\) are obtained. On the other hand, the autocorrelations of the zebra differ significantly. The frequency lag at first harmonic is about 24 MHz. When the mean zebra frequency (\(\sim 1250\) MHz) is divided by the lag frequency (\(\sim 24\) MHz) then this ratio is about 52.
Moreover, the frequency lag in the zebra case is varying in time, as seen in higher harmonics of time lags. To understand better what this means, we calculated the frequency intervals between neighboring zebra stripes at three time instants (Figure 6 bottom panel). As shown here, for the zebra stripes numbered 1 and 2 the frequency interval between them (see the short horizontal lines) changes from 23.5 MHz to 28.2 MHz, and for the zebra stripes numbered 4 and 5 the frequency interval between them changes from 14.1 MHz to 18.8 MHz and to 28.2 MHz. (Note that the frequency resolution of the radio spectrum is 4.7 MHz.) This means that the frequency interval between the neighboring zebra stripes changes and this frequency interval can be different from those between other zebra stripes. This irregular variation of the separation frequency indicates that zebra-stripe sources cannot be generated by Bernstein modes in one source region. In the double-plasma resonance models of zebras this variation is interpreted by waves propagating along the loop where the zebra-stripe sources are located (Karlický and Yasnov, 2021). We also found that the bandwidth of SZ bands is much broader than that of zebra stripes, while in the SZ case it is about 200 MHz in the zebra case it is about 10 MHz.

### 3.2. Modeling of SZ Frequencies by Bernstein Modes

To confirm a similarity between SZ and SBN of the 13 June 2012 flare given by autocorrelations (Figure 7) and SBN observed in 7 November 2013 with the Bernstein modes, we fitted the mean SZ band frequencies in the same way as in the SBN 7 November 2013 case (Karlický, Benáček, and Rybák, 2021), see also Benáček and Karlický (2019). First, we searched for the time where the bandwidth of SZ spike bands is the narrowest. We found it for 13:13:50.8 UT where we determined the mean spike band frequencies as 860, 1070, 1290, and 1510 MHz (for $s = 4 – 7$). Then, using Equations 1 and 3 we fitted these band frequencies by calculating the dispersion curves of the Bernstein modes and corresponding growth rates and assuming that Bernstein modes correspond to the observed radio frequencies. The best fit is shown in Figure 8. This fit was obtained with the following parameters: $n_e/n_h = 15$, $v_i/c = 0.25$, $v_{th}/c = 0.01834$ ($T_b = 2$ MK), $\omega_{pe}/\omega_{ce} = 3.85$, and $f_{pe} = 827$ MHz, where $f_{pe} = \omega_{pe}/(2\pi)$, $n_e/n_h$ is the ratio between the electron plasma densities of the background and hot component plasma, $v_i$ and $v_{th}$ are the characteristic velocities of hot and Maxwellian background plasmas, $T_b$ is the temperature of the background plasma, and $c$ is the light speed.
Figure 6  Upper: The 1200 – 1400 MHz radio spectrum showing the zebra observed during the 1 August 2010 flare. The white vertical lines and numbers 1 – 5 show the times of the frequency profiles and selected zebra stripes shown in the bottom panel of the figure. Bottom: Radio flux vs. frequency profiles: the full line shows the radio flux at 08:21:57.9 UT, dashed line shows the radio flux $+3500$ a.u. at 08:21:58.8 UT, and dashed-dotted line shows the radio flux $+7000$ a.u. at 08:22:00.0 UT. Numbers 1 – 5 designate zebra stripes; see the upper panel. Short horizontal lines show the frequency intervals between zebra stripes 1 and 2 and zebra stripes 4 and 5 at three instants 08:21:57.9, 08:21:58.8, and 08:22:00.0 UT.
Figure 7  Autocorrelation of the radio fluxes vs. radio spectrum frequency. a) SZ case in the time interval 13:13:47 – 13:13:53 UT. b) SBN case in the time interval 13:26:30–13:26:36 UT. c) Zebra case in the 1200 – 1400 MHz range observed at 08:21:56 – 08:22:02 UT on 1 August 2010.

Now, considering the frequency separation between spike bands as follows from the above analysis (220 MHz) and the plasma frequency as $f_{pe} = 827$ MHz, the magnetic field and plasma density in the spike source can be estimated as about 79 G and $8.4 \times 10^9$ cm$^{-3}$, respectively.

A question also arises as to what is the expected bandwidth of spikes in the model of Bernstein modes. However, it is a very complex problem. Therefore, let us estimate only the Bernstein mode bandwidth for several gyroharmonic numbers $s$, assuming that this bandwidth is formed only by density variations. We take these variations as $\Delta n/n \approx 1/\sqrt{n} \approx$.
Figure 8  Growth rates of the Bernstein modes as a function of the frequency and perpendicular k-wave vector for parameters $\omega_{pe}/\omega_{ce} = 3.85$, $v_{tb}/c = 0.01834$, $v_t/c = 0.25$, $n_e/n_h = 15$. The values of $f$ in MHz correspond to the radio emission in Bernstein modes, i.e., $\omega_{pe} = 2\pi f_{pe}$, $f_{pe} = 827$ MHz. Green lines: Dispersion branches computed from Equation 1, $s$ is the gyroharmonic number of each branch. White dashed horizontal line: Plasma frequency.

$1.1 \times 10^{-5}$ (statistical noise). Then, the frequency variation at the present plasma frequency (827 MHz) is about 2.7 MHz. We estimated the linearized bandwidths in the region of each branch, where its growth rate is maximal. We found the bandwidth of Bernstein modes with $s = 4, \ldots, 7$ as $0.9$, $3 \times 10^{-3}$, $5 \times 10^{-5}$, and $5 \times 10^{-5}$ MHz, respectively. The bandwidths narrow as the permittivity derivation nonlinearly increases with increasing gyroharmonic number. For all $s$, the Bernstein mode bandwidth is smaller than the minimal spike bandwidth found by Nita et al. (2014) ($\sim 1$ MHz). However, the problem of the spike bandwidth is much more complex. It is due not only to effects of density and magnetic-field variations, but also due to the conversion of Bernstein modes into electromagnetic waves. Moreover, density and magnetic-field variations are probably interconnected.

4. Discussion and Conclusions

We confirmed that the narrowband dm spikes are mostly observed during the impulsive flare phases, see Table 1. As follows from Table 2 and analysis of the 13 June 2012 spike event, dm spikes are observed in bands with noninteger ratio in the range 1.08 – 1.26; in agreement with the result of Krucker and Benz (1994). We note that this result is not frequently considered in theoretical models of dm spikes.

In the analysis of the 13 June 2012 spike event we tried to search for some relation between the 1000-MHz time profile (with groups of spikes) and variations of intensities in selected flare locations using AIA/SDO observations. The most interesting relation was found for AIA intensities taken from one end of the sigmoidal flare structure where many magnetic-field lines of flare loops are concentrated (Figures 3 and 4). The peaks in radio
and AIA (Figure 4) are of varying amplitudes, not all peaks on the 1000-MHz radio profile have corresponding peaks in AIA channels. This indicates that their relation is not simple. In reality, a simple relation cannot be expected because spikes are generated by superthermal electrons with a loss-cone distribution, while peaks in the AIA channels indicate plasma density enhancements at the AIA channel characteristic temperature.

During one flare from 13 June 2012 we observed spikes of three different types: SB, SZ, and SBN spikes. Analyzing SBN spikes in their narrowband part by the crosscorrelation method we found that the SBN spikes are similar to those presented by Karlický, Benáček, and Rybáček (2021). Thus, we interpret SBN similarly, i.e., as generated in Bernstein modes. We also found a similarity in autocorrelations of SZ and SBN ending part that speaks in favor of the same generation mechanism for these spikes.

We made a detailed comparison of the 13 June 2012 SZ (zebra-like) spikes with a typical zebra in the same frequency range that was observed on 1 August 2010. We found the following differences. In the SZ case: The separation frequency \( \Delta f \) between neighboring spike bands is about 220 MHz. The autocorrelation in SZ indicates low variability in time. The ratios between four spike bands and separation frequencies were found to be 4.4, 5.1, 6.0, and 7.0. Similarly, in the SBN case these ratios for three spike bands are 4.0, 4.9, and 6.0. On the other hand, in the zebra case: The separation frequency \( \Delta f \) between neighboring zebra stripes is about 24 MHz. The variability of the autocorrelation in time in the zebra case is higher than in the SZ case. Furthermore, the ratio between the mean zebra-stripe frequency and separation frequency is about 1250 MHz/24 MHz \( \sim 52 \).

Moreover, we found that the separation frequency between neighboring zebra stripes changes in a different way for different pairs of the neighboring zebra stripes (Figure 5). This irregular variation of the separation frequency excludes that the analyzed zebra is generated in one source as it is in the model of the Bernstein modes.

The bandwidth of SZ spike bands (consisting of many narrowband spikes) is much broader than that of zebra stripes. Hence, it was impossible to make a similar analysis of time evolution of band (or spike) separation frequencies as in the zebra case shown in Figure 6 bottom panel.

Nevertheless, at the time of the narrowest SZ bands we successfully fitted SZ frequencies to the model of the Bernstein modes. Using the parameters in this model we estimated the mean magnetic-field strength and plasma density in the SZ source as about 79 G and \( 8.4 \times 10^9 \) cm\(^{-3} \), respectively. We propose that broad bands of SZ spikes correspond to a region with some interval of the magnetic field and density. In accordance with our previous ideas (Karlický, Sobotka, and Jiřička, 1996; Bártá and Karlický, 2001) we think that this region is in the magnetic reconnection outflow, where the plasma is in turbulent state.

Considering all these facts, we conclude that SZ and SBN spikes observed on 13 June 2012 were generated according to the model of the Bernstein modes. We believe that the parameters, e.g., the ratio between the band (stripe) and separation frequencies, found in the analysis of SZ spikes and the 1 August 2010 zebra, can help in interpretations of other observed SZ spikes and zebras.

In Section 3.2 we tried to estimate the spike bandwidth in the model of Bernstein modes. We considered only the Bernstein mode bandwidth assuming only an effect of the density variations. However, this problem is much more complex. This is due not only to the effects of density and magnetic-field variations, but also due to the conversion of Bernstein modes into the electromagnetic waves. Moreover, density and magnetic-field variations are probably interconnected. Therefore, the question about the spike bandwidth remains open and further theoretical analysis is necessary.

Similarly as in other solar radio bursts, the radio-wave scattering can play a role also in spikes. The scattering is proportional to \( (f_{pe}/f)^2 \) (Benz, 1993), where \( f_{pe} \) is the plasma
frequency and $f$ is the frequency of the radio emission. The scattering depends on the size of the scattering region, and the sizes and density of irregularities. The scattering enhances the sizes of the radio sources and causes temporal smoothing of time variations of the burst intensity. Moreover, there is wave ducting of the radio emission (Duncan, 1979) that requires “fibrous” structures of the plasma density (Kuznetsov et al., 2020). To provide a scattering rate comparable with that of the observations, magnetic tubes would need to have a density contrast of $\Delta n/n \gg 1$ (e.g., Robinson (1983) requested a 25-fold increase of the plasma density over dense fibers in the ducting model). The existence of such structures in the solar corona is not supported by EUV observations (e.g., Motorina, Fleishman, and Kontar, 2020). Hence, the “ducting” model is quantitatively inconsistent with the observations and anisotropic scattering is required.

In the present study without spike-source imaging, the scattering can only smooth and prolong the duration of spikes. However, the parameters of the scattering region are not known. We found that the plasma frequency for the narrowest spike bands at 13:13:50.8 UT is 827 MHz and the Bernstein-mode frequencies are 860, 1070, 1290, and 1510 MHz. As the lowest Bernstein frequency, 860 MHz, is 33 MHz above the plasma frequency the scattering of spike emission in the model of Bernstein modes is less important than the scattering in the case of the radio emission at the fundamental frequency ($f \sim f_{pe}$) as, e.g., in the Type-III bursts. For Bernstein modes with increasing $s$ the effect of scattering decreases.

Acknowledgments M.K. acknowledges support from the project RVO-67985815 and GA ČR grants 20-09922J, 20-07908S, 21-16508J and 22-34841S. J.R. acknowledges support by the Science Grant Agency project VEGA 20048/20 (Slovakia). J.B. acknowledges support by the German Science Foundation (DFG) project BU 777-17-1, and J.K. acknowledges support by GA ČR grant 19-09489S. Help of the Bilateral Mobility Project SAV-18-01 of the SAS and CAS is acknowledged as well. We also acknowledge the use of the Fermi Solar Flare Observations facility funded by the Fermi GI program. Data supplied courtesy of the SDO/HMI and SDO/AIA consortia.

Declarations

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

References

Bárta, M., Karlický, M.: 2001, Turbulent plasma model of the narrowband dm spikes. Astron. Astrophys. 379, 1045. DOI. ADS.
Benáček, J., Karlický, M.: 2019, Growth rates of the electrostatic waves in radio zebra models. Astrophys. J. 881, 21. DOI. ADS.
Benz, A.O.: 1986, Millisecond radio spikes. Solar Phys. 104, 99. DOI. ADS.
Benz, A.O.: 1993, Plasma Astrophysics: Kinetic Processes in Solar and Stellar Coronae 184. DOI. ADS.
Bouratizis, C., Hillaris, A., Alissandrakis, C.E., Preka-Papadema, P., Moussas, X., Caroubalos, C., Tsitispis, P., Kontogeorgos, A.: 2016, High resolution observations with Artemis-IV and the NRH. I. Type-IV associated narrow-band bursts. Astron. Astrophys. 586, A29. DOI. ADS.
Clarkson, D.L., Kontar, E.P., Gordovskyy, M., Chrysaphi, N., Vilmer, N.: 2021, First frequency-time-resolved imaging spectroscopy observations of solar radio spikes. Astrophys. J. Lett. 917, L32. DOI. ADS.
Dabrowski, B.P., Benz, A.O.: 2009, Correlation between decimetric radio emission and hard X-rays in solar flares. Astron. Astrophys. 504, 565. DOI. ADS.
Drooge, F.: 1977, Millisecond fine-structures of solar burst radiation in the range 0.2–1.4 GHz. Astron. Astrophys. 57, 285. ADS.
Duncan, R.A.: 1979, Wave ducting of solar metre-wave radio emission as an explanation of fundamental/harmonic source coincidence and other anomalies. Solar Phys. 63, 389. DOI. ADS.
Fleishman, G.D., Mel’nikov, V.F.: 1998, Reviews of topical problems: millisecond solar radio spikes. Phys. Usp. 41, 1157. DOI. ADS.
Jiříčka, K., Karlický, M.: 2008, Narrowband pulsating decimeter structure observed by the new Ondřejov solar radio spectrograph. Solar Phys. 253, 95. DOI. ADS.
Karlický, M.: 1984, Narrowband DM spikes as indication of flare mass ejection. Solar Phys. 92, 329. DOI. ADS.
Karlický, M., Benáček, J., Rybák, J.: 2021, Narrowband spikes observed during the 2013 November 7 flare. Astrophys. J. 910, 108. DOI. ADS.
Karlický, M., Sobotka, M., Jiříčka, K.: 1996, Narrowband dm-spikes in the 2 GHz frequency range and MHD cascading waves in reconnection outflows. Solar Phys. 168, 375. DOI. ADS.
Karlický, M., Yasnov, L.V.: 2021, Spatial quasi-periodic variations of the plasma density and magnetic field in zebra radio sources. Astron. Astrophys. 646, A179. DOI. ADS.
Kerdraon, A., Delouis, J.-M.: 1997, In: Trottet, G. (ed.) The Nançay Radioheliograph 483, 192. DOI. ADS.
Khan, J.I., Aurass, H.: 2006, Observations of the coronal dynamics associated with solar radio spike burst emission. Astron. Astrophys. 457, 319. DOI. ADS.
Krucker, S., Benz, A.O.: 1994, The frequency ratio of bands of microwave spikes during solar flares. Astron. Astrophys. 285, 1038. ADS.
Kuijpers, J., van der Post, P., Slottje, C.: 1981, Runaway acceleration in a radio flare. Astron. Astrophys. 103, 331. ADS.
Kuznetsov, A.A., Chrysaphi, N., Kontar, E.P., Motorina, G.: 2020, Radio echo in the turbulent corona and simulations of solar drift-pair radio bursts. Astrophys. J. 898, 94. DOI. ADS.
Lemen, J.R., Title, A.M., Akin, D.J., Boerner, P.F., Chou, C., Drake, J.F., Duncan, D.W., Edwards, C.G., Friedlaender, F.M., Heyman, G.F., Hurlburt, N.E., Katz, N.L., Kushner, G.D., Levay, M., Lindgren, R.W., Mathur, D.P., McFeaters, E.L., Mitchell, S., Rehe, R.A., Schrijver, C.J., Springer, L.A., Stern, R.A., Tarbell, T.D., Wuelser, J.-P., Wolfson, C.J., Yanari, C., Bookbinder, J.A., Cheimets, P.N., Caldwell, D., Deluca, E.E., Gates, R., Golub, L., Park, S., Podgorski, W.A., Busch, R.I., Scherrer, P.H., Gummim, M.A., Smith, P., Auker, G., Jerram, P., Pool, P., Souffle, R., Windt, D.L., Beardsley, S., Clapp, M., Lang, J., Waltham, N.: 2012, The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). Solar Phys. 275, 17. DOI. ADS.
Lin, R.P., Dennis, B.R., Hurford, G.J., Smith, D.M., Zehnder, A., Harvey, P.R., Curtis, D.W., Pankow, D., Turin, P., Bester, M., Ciislaghy, A., Lewis, M., Madden, N., van Beek, H.F., Appleby, M., Raudorf, T., McTiernan, J., Ramaty, R., Schmah, E., Schwartz, R., Krucker, S., Abiad, R., Quinn, T., Berg, P., Hashii, M., Sterling, R., Jackson, R., Pratt, R., Campbell, R.D., Malone, D., Landis, D., Barrington-Leigh, C.P., Slassi-Sennou, S., Cork, C., Clark, D., Amato, D., Orwig, L., Boyle, R., Banks, I.S., Shirey, K., Tolbert, A.K., Zarro, D., Snow, F., Thomsen, K., Henneck, R., McDhelshvili, A., Ming, P., Fivian, M., Jordan, J., Wanner, R., Crubb, J., Preble, J., Matranga, M., Benz, A., Hudson, H., Canfield, R.C., Holman, G.D., Crannell, C., Kosugi, T., Emslie, A.G., Vilmer, N., Brown, J.C., Johns-Krull, C., Aschwanden, M., Metcalf, T., Conway, A.: 2002, The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI). Solar Phys. 210, 3. DOI. ADS.
Luo, Y., Chen, B., Yu, S., Bastian, T.S., Krucker, S.: 2021, Radio spectral imaging of an M8.4 eruptive solar flare: possible evidence of a termination shock. Astrophys. J. 911, 4. DOI. ADS.
Meegan, C., Lichti, G., Bhat, P.N., Bissaldi, E., Briggs, M.S., Connaughton, V., Diehl, R., Fishman, G., Greiner, J., Hoover, A.S., van der Horst, A.J., von Kienlin, A., Kippen, R.M., Kouveliotou, C., McBreen, S., Paciesas, W.S., Peece, R., Steinle, H., Wallace, M.S., Wilson, R.B., Wilson-Hodge, C.: 2009, The Fermi gamma-ray burst monitor. Astrophys. J. 702, 791. DOI. ADS.
Melnik, V.N., Shevchuk, N.V., Konovalenko, A.A., Rucker, H.O., Dorovskyy, V.V., Poedts, S., Lecacheux, A.: 2014, Solar decameter spikes. Solar Phys. 289, 1701. DOI. ADS.
Melrose, D.B.: 2017, Coherent emission mechanisms in astrophysical plasmas. Rev. Mod. Plasma Phys. 1, 5. DOI. ADS.
Melrose, D.B., Dulk, G.A.: 1982, Electron-cyclotron masers as the source of certain solar and stellar radio bursts. Astrophys. J. 259, 844. DOI. ADS.
Messmer, P., Benz, A.O.: 2000, The minimum bandwidth of narrowband spikes in solar flare decimetric radio waves. Astron. Astrophys. 354, 287. ADS.
Motorina, G.G., Fleishman, G.D., Kontar, E.P.: 2020, Spatiotemporal energy partitioning in a nonthermally dominated two-loop solar flare. Astrophys. J. 890, 75. DOI. ADS.
Ni, S., Chen, Y., Li, C., Zhang, Z., Ning, H., Kong, X., Wang, B., Hosseinpour, M.: 2020, Plasma emission induced by electron cyclotron maser instability in solar plasmas with a large ratio of plasma frequency to gyrofrequency. Astrophys. J. Lett. 891, L25. DOI. ADS.
Nita, G.M., Fleishman, G.D., Gary, D.E., Marin, W., Boone, K.: 2014, Fitting FFT-derived spectra: theory, tool, and application to solar radio spike decomposition. Astrophys. J. 789, 152. DOI. ADS.
Robinson, R.D.: 1983, Scattering of radio waves in the solar corona. Proc. Astron. Soc. Aust. 5, 208. DOI. ADS (ISSN 0066-9997).
Scherrer, P.H., Schou, J., Bush, R.I., Kosovichev, A.G., Bogart, R.S., Hoeksema, J.T., Liu, Y., Duvall, T.L., Zhao, J., Title, A.M., Schrijver, C.J., Tarbell, T.D., Tomczyk, S.: 2012, The Helioseismic and Magnetic Imager (HMI) investigation for the Solar Dynamics Observatory (SDO). *Solar Phys.* **275**, 207. DOI. ADS.

Schou, J., Scherrer, P.H., Bush, R.I., Wachter, R., Couvidat, S., Rabello-Soares, M.C., Bogart, R.S., Hoeksema, J.T., Liu, Y., Duvall, T.L., Akin, D.J., Allard, B.A., Miles, J.W., Rairden, R., Shine, R.A., Tarbell, T.D., Title, A.M., Wolfson, C.J., Elmore, D.F., Norton, A.A., Tomczyk, S.: 2012, Design and ground calibration of the Helioseismic and Magnetic Imager (HMI) instrument on the Solar Dynamics Observatory (SDO). *Solar Phys.* **275**, 229. DOI. ADS.

Staehli, M., Magun, A.: 1986, The microwave spectrum of solar millisecond spikes. *Solar Phys.* **104**, 117. DOI. ADS.

Stepanov, A.V., Kliem, B., Krüger, A., Hildebrand t, J., Garaimov, V.I.: 1999, Second-harmonic plasma radiation of magnetically trapped electrons in stellar coronae. *Astrophys. J.* **524**, 961. DOI. ADS.

Tajima, T., Benz, A.O., Thaker, M., Leboeuf, J.N.: 1990, Enhanced radiation driven by a DC electric field. *Astrophys. J.* **353**, 666. DOI. ADS.

Wentzel, D.G.: 1991, Direct radiation from a strong DC electric field. *Astrophys. J.* **373**, 285. DOI. ADS.

Willes, A.J., Robinson, P.A.: 1996, Electron-cyclotron maser theory for noninteger ratio emission frequencies in solar microwave spike bursts. *Astrophys. J.* **467**, 465. DOI. ADS.

Zhelezniakov, V.V., Zlotnik, E.I.: 1975, Cyclotron wave instability in the corona and origin of solar radio emission with fine structure. I: Bernstein modes and plasma waves in a hybrid band. *Solar Phys.* **43**, 431. DOI. ADS.

Zlotnik, E.Y.: 2013, Instability of electrons trapped by the coronal magnetic field and its evidence in the fine structure (zebra pattern) of solar radio spectra. *Solar Phys.* **284**, 579. DOI. ADS.

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