Solar Fast-drifting Radio Bursts in an X1.3 Flare on 2014 April 25

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Abstract

One of the most important products of solar flares is nonthermal energetic particles, which may carry up to 50% of the energy released in the flaring processes. In radio observations, nonthermal particles generally manifest as spectral fine structures with fast frequency-drifting rates, named as solar fast-drifting radio bursts (FDRBs). This work demonstrated three types of FDRBs, including type III pair bursts, narrowband stochastic spike bursts following the type III bursts, and spike-like bursts superimposed on a type II burst in an X1.3 flare on 2014 April 25. We find that although all of them have fast frequency-drifting rates, they are intrinsically different from each other in frequency bandwidth, drifting rate, and statistical distribution. We suggest that they are possibly generated from different accelerating mechanisms. The type III pair bursts may be triggered by high-energy electron beams accelerated by the flaring magnetic reconnection, spike bursts are produced by the energetic electrons accelerated by a termination shock wave triggered by the fast reconnecting plasma outflows impacting the flaring loop top, and spike-like bursts are possibly generated by nonthermal electrons accelerated by moving magnetic reconnection triggered by interaction between coronal mass ejection and the background magnetized plasma. These results may help us to understand the generation mechanism of nonthermal particles and energy release in solar flares.

Unified Astronomy Thesaurus concepts: Solar coronal loops (1485); Solar radio emission (1522); Solar energetic particles (1491)

1. Introduction

In the physics of solar flares and coronal mass ejections (CMEs), radio observations play a key role in explaining the primary energy release, triggering mechanism of eruptions, and the related plasma instabilities. They can provide the most sensitive direct evidence of magnetic reconnections, nonthermal particle accelerations and propagations, and variations of magnetic fields in the corona (Dulk 1985; Bastian et al. 1998). In broadband dynamic radio spectral observations especially, there are various kinds of radio bursts, such as radio type I, II, III, and IV bursts, and overlapping complex spectral fine structures with timescales of sub-seconds, including spike bursts (Benz et al. 1982; Tan 2013 etc.), fiber bursts (Chernov et al. 2010), Zebra patterns (Tan et al. 2014), quasi-periodic pulsations (Tan et al. 2010), etc. These different radio bursts and their related fine structures reflect the different physical processes in their source regions, namely different physical conditions, coupling interactions, accelerations, and kinetic energy of the nonthermal particles, among other variables.

The various kinds of radio bursts feature an important feature: frequency-drifting rate $D = \frac{df}{dt}$, which manifests as a slope of the radio burst pattern on the spectrogram and reflects the motion of the emitting medium. In order to make a reasonable comparison among different kinds of bursts at different frequency ranges, we generally define a relative frequency-drifting rate:

$$D = \frac{df}{f_0 dt}$$

Here, $f_0$ is the central frequency of the burst. Type II radio bursts at meter wavelengths present slow frequency drift rates, $D \leq 0.01 \text{s}^{-1}$, which reflects the motion of a CME (a large cloud of fast plasma flow), type III radio bursts have very fast frequency drift rates, $D \geq 0.1 \text{s}^{-1}$, which implies the fast flight of nonthermal electron beams in corona, and the moving type IV radio bursts has a very slow frequency drift rate, $D \leq 0.01 \text{s}^{-1}$, which reveals the motion of the emitting corona loops. Additionally, the frequency-drifting rate may have a positive or negative sign. A positive drifting (PD) rate means the emission drifts from low frequency to high frequency and the emitting source may move from a high place down to a lower place under solar corona conditions. The negative drifting (ND) rate means the emission drifts from high frequency to low frequency and the emitting source moves from a low place up to a higher place (e.g., it flies out from the solar surface up to the high corona). Therefore, solar radio bursts can be classified into two types: PD bursts and ND bursts.

Generally, according to the magnitude of $D$, solar radio bursts can be classified into another two categories:

1. Slow-drifting radio burst (SDRB). Its frequency-drifting rate is very slow ($D < 0.01 \text{s}^{-1}$ in most cases) and the corresponding moving velocity of the emitting medium is near or slower than the local Alfvén speed ($v_A$). They are possibly produced by plasma flows, jets, or the motions of coronal loops. Examples of SDRBs are type II radio bursts (Dulk 1985) and moving type IV radio bursts (Dulk & Altschuler 1971).

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Figure 1. Radio spectrogram observed by IPRT/AMATERAS in an X1.3 flare on 2014 April 25. The spectrogram shows a group of normal type III bursts (N type III) and a group of reverse-sloped type III bursts (RS type III) forming a group of type III pair bursts at the flare start time. A group of spike bursts (in the blue ellipse) follows the type III pair bursts around a separate frequency. Then, a type II burst occurs with fundamental (F) and harmonic (H) branches and is superimposed by a group of spike-like bursts. The white curve is the SXR flux observed by GOES. The dashed green, blue, and yellow curves show the emission counts of HXR at energies of 12–25 keV, 25–50 keV, and 50–100 keV, respectively.

(2) Fast-drifting radio burst (FDRB). The frequency-drifting rate is very fast ($\Delta > 0.1 \text{s}^{-1}$ in most cases) and its corresponding moving velocity of the emitting medium is much faster than the local $v_A$. Sometimes the velocity is close to a relativistic level. FDRBs provide key information on the motion of nonthermal electron beams. Examples of FDRBs are type III bursts (Reid & Ratcliffe 2014) and spike bursts (Tan 2013). Type III bursts are believed to be a sensitive signature of the energetic electron beams generated and propagated in the corona (Lin & Hudson 1971; Lin et al. 1981; Achwanden et al. 1993; and a recent review in Reid & Ratcliffe 2014).

FDRBs are related to the motion of energetic electrons; it is very important to study their characteristics to understand the primary energy release, particle acceleration, and the energy transportation in flaring processes (Miller et al. 1997). This work reports three distinctly different groups of FDRBs in a powerful X1.3 flare on 2014 April 25. It is very interesting to observe a group of spike bursts following a group of type III pair bursts around a separate frequency with a stochastic distribution, and a group of spike-like bursts superimposed on a type II radio burst. Section 2 presents the observing features of the three kinds of FDRBs, including their possible relationship with hard X-ray emission (HXR), extreme ultraviolet (EUV) bursts, and the flare and CME processes. Section 3 presents discussions of possible physical mechanisms. Our main conclusions are summarized in Section 4.

2. Observations of the SFDRBs

The related flare occurred at the solar west limb on 2014 April 25, which was fully observed by several telescopes at multiple wavelengths: in the soft X-ray (SXR) at 0.5–4 Å and 1–8 Å by the Geostationary Operational Environmental Satellite (GOES); EUV images observed from the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA); Lemen et al. 2012; the HXR by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002); a radio dynamic spectrogram at a frequency of 100–500 MHz from the Iitate Planetary Radio Telescope (IPRT/AMATERAS; Iwai et al. 2012); and microwave images at a frequency of 17 GHz observed by the Nobeyama Radio Heliograph (NoRH).

The SXR light curve shows that the flare starts at 00:17 UT, peaks at 00:25 UT, and ends at 00:45 UT with a magnitude of X1.3 class in the NOAA active region 12035 located just behind the solar limb. In the flare impulsive phase, a lower arcade takes off as a strong expansion CME at about 00:22 UT, with an average speed of 600 km s$^{-1}$ (Chen et al. 2016). Accompanying the flare are several groups of radio bursts, which will be presented in the following sections.

2.1. Main Characteristics of the FDRBs

Figure 1 presents the solar radio dynamic spectrogram at a frequency of 100–500 MHz observed by IPRT/AMATERAS, overplotted SXR flux at 1–8 Å (white solid line) observed by GOES, and HXR light curves (green:12–25 keV, blue: 25–50 keV, yellow: 50–100 keV) observed by RHESSI.

The HXR 50–100 keV and 25–50 keV light curves reach maximum around 00:20 UT, about 5 minutes before the SXR peak times, which are cotemporal with the onset of a group of type III radio bursts. The flare light curve shows a sharp and smooth rising phase and a long smooth decay phase in which
the impulsive phase can be defined as the FWHM of the HXR 50–100 keV light curve, e.g., about 00:20:00 to 00:23 UT.

IPRT/AMATERAS is a solar radio spectral polarimeter at the Iitate Observatory in Fukushima prefecture, Japan. Its minimum detectable flux is less than 0.7 sfu, with a cadence of 10 ms and frequency resolution of 61 kHz. Both left and right circular polarizations are simultaneously observed (Iwai et al. 2012). With such high performance, we have identified several groups of FDRBs around the flare: a group of type III pair bursts (N type III and RS type III), a group of spike bursts, following the type III pair bursts around a separate frequency, and a great group of spike-like bursts superimposing on type II bursts with fundamental (F) and harmonic (H) branches.

2.1.1. Type III Pair Bursts

The type III bursts occur around 00:20:28 UT at a frequency range of 100–500 MHz. The type III bursts can be plotted into two groups. One group has negative frequency-drifting rates; we label these normal type III bursts (N type IIIs). The other group has positive frequency-drifting rates; we refer to these as reverse-sloped type III bursts (RS type IIIs).

The N type IIIs have frequency-drifting rates from $-150$ to $-290 \text{ MHz s}^{-1}$, composed with 8 type III bursts. $D$ ranges from $-0.85$ to $-1.25 \text{ s}^{-1}$. They start at frequencies of about 310 MHz and extend down to below 100 MHz (lower limit of the instrument). The duration of each single normal type III burst is in the range of 0.2–0.6 s, with an average of 0.41 s. The frequency bandwidth $f_w$ is from 45 MHz to about 110 MHz, with an average of 75 MHz; the relative bandwidth $f_w = f_w / f_0$ ranges from 0.25 to 0.53, and the average is about 0.38.

The RS type III bursts have positive frequency-drifting rates from 230 to 370 MHz s$^{-1}$, composed with 7 type III bursts, $D \approx 0.70$ to 1.29 s$^{-1}$. They start at frequencies of about 330 MHz and extend up to beyond 500 MHz (the upper limit of the instrument). The duration of each single RS type III burst is about 0.3–0.7 s, with an average of 0.48 s. The frequency bandwidth $f_w$ is from 50 to 120 MHz, with an average of 89 MHz, and $f_w$ ranges from 0.29 to 0.55, with an average of 0.41.

It is well known that type III radio bursts are FDRBs, which are associated with nonthermal electron beams. The separation frequency ($f_s$) between the normal and RS type III bursts is about 310 MHz and the frequency gap is around 20–25 MHz. The two groups of bursts form a group of radio type III pairs (Ning et al. 2000; Robinson & Benz 2000). The whole group of type III pairs lasts for about 5 s.

Figure 1 shows that the type III pairs appear around the peak frequency of the high-energy HXR light curve at 50–100 keV and the fast rising phase of HXR emission at 12–25 keV and 25–50 keV. Imaging observations (Figure 6) show that the HXR source and microwave source at 17 GHz are located around the same cusp-shaped structure. Chen et al. (2016) proposed that breakout magnetic reconnection and particle acceleration occurred around this magnetic configuration. The cospatial and cotemporal relationships between HXR source, microwave source, and cusp-shaped structures indicate that the type III pair bursts could be associated with energetic electron beams with energies of 50–100 keV. These energetic electrons should be accelerated in the above magnetic reconnections.

2.1.2. Spike Bursts Following Type III Pair Bursts

Just following type III pair bursts, there is a group of radio spike bursts occurring from 00:20:30 to 00:21:25 UT at a frequency range of 220–410 MHz. Figure 1 shows that the radio spike bursts deviate from the extension zone of the type II bursts. They are located very close to the separation frequency ($f_s$) of the type III pair bursts and the peak time of the HXR at 25–50 keV, the rapid rising time of the HXR at 12–25 keV, and the slowly decay time of the HXR at 50–100 keV. This implies that the spike bursts are possibly relevant to the magnetic reconnection, but the related nonthermal electrons should have relatively lower energies than the above type III pair bursts.

Figure 2 presents an enlarged spectrum of type III pair bursts and the following spike bursts during the flare impulsive phase. The spike bursts are distributed randomly on the time-frequency spectrogram. We perform a figure auto-recognition and quantize these spike bursts with the following parameters: central frequency ($f_0$), frequency bandwidth ($f_w$), lifetime ($\tau$), and frequency-drifting rate ($D$). Here, we recognized 245 spikes during 00:20:30–00:21:27 UT in the frequency range of 240–410 MHz.

Statistical analysis shows that the occurrence rate of spike bursts is about 4.6 spikes per second. Among these spikes, there are about 88 spike bursts (34%) with positive frequency-drifting rates from 26.5 to 66.9 MHz s$^{-1}$. $D = 0.11 \sim 0.26 \text{ s}^{-1}$; we refer to these as PD spikes. The average positive frequency-drifting rate is about 47.5 MHz s$^{-1}$ and the average $D$ is about 0.19 s$^{-1}$. The other 157 spike bursts (66%) have negative frequency-drifting rates from $-39.2$ to $-138.2 \text{ MHz s}^{-1}$. $D = -0.13 \sim -0.39 \text{ s}^{-1}$; we refer to them as ND spikes. The averaged negative frequency-drifting rate is about $-68.1 \text{ MHz s}^{-1}$ and the average $D$ is about $-0.29 \text{ s}^{-1}$. The frequency-drifting rates of spike bursts are smaller by about one order than that of the type III pair bursts. But they are still much faster than type II bursts. The analysis in Section 3 shows that the spike bursts still belong to FDRBs.

Figure 3 presents the statistical distributions of central frequency (a), frequency bandwidth (b), frequency-drifting rate (c), and lifetime (d) of spike bursts. It shows that the central frequencies of PD and ND spikes range from 250 to 410 MHz and from 170 to 410 MHz, respectively, and their profiles reach maximum at almost the same frequency. In other words, differing from the distributions of normal type III and RS type III bursts, PD and ND spikes are distributed stochastically in the same frequency range. The frequency bandwidths of the PD and ND spikes range from 2.6 to 12.0 MHz and from 3.3 to 14.0 MHz, respectively. The relative bandwidth $f_w$ ranges from 0.01 to 0.04, with averaged values of 6.4 MHz and 6.8 MHz, respectively, only at the order of one or several percents of the central frequency. The frequency bandwidths of spike bursts are narrower by at least one order than that of the above type III pair bursts. The lifetimes of each single PD and ND spike range from 10 ms to 90 ms and from 10 to 80 ms, with averaged lifetimes of 35.4 ms and 39.8 ms, respectively. The lifetime is shorter at about one order than that of the type III bursts.

In brief, the spike bursts are distributed randomly following the type III pair bursts around the separation frequency. They are short lifetimes, narrow frequency bandwidths, and mild frequency-drifting rates. Compared to the type III pair bursts relating high-energy nonthermal electrons, the narrowband
stochastic radio spike bursts are possibly related to low-energy nonthermal electrons.

2.1.3. Spike-like Bursts on Type II Bursts

A type II burst occurred from 00:22:20 to 00:31:20 UT below the frequency of 280 MHz, about 1 minute after the above spike bursts and about 2 minutes after the type III pair bursts. It is composed of two branches and forms a harmonic structure (Figure 4). The fundamental branch (F) extends from about 184 MHz down to below 100 MHz, while the second harmonic branch (H) extends from about 286 MHz down to near 100 MHz. The frequency ratio between the fundamental and harmonic branches is about 1.55. The frequency bandwidth of the type II burst strips is in the range of 40–80 MHz. The frequency-drifting rates of the fundamental and the second

Figure 2. Enlargement of the radio dynamic spectrogram of type III pair bursts and the following spike bursts.

Figure 3. Statistical distributions of the central frequency (a), frequency bandwidth (b), frequency-drifting rate (c), and lifetime (d) of spike bursts. The solid and dashed lines are the PD and ND spike bursts, respectively.
harmonic branches are very slow, about 0.3 and 0.5 MHz s\(^{-1}\), with a \(D\) of about \(-0.002\) and \(-0.003\) s\(^{-1}\), respectively. These rates are about one or two orders lower than those of the spike bursts, and three orders lower than those of the type III pair bursts. Therefore, the type II burst can be categorized as an SDRB.

Similar to most type II radio bursts reported in the literature (e.g., Armatas et al. 2019, etc.), we found that the type II burst
also contains super-fine structures, with groups of spike-like bursts. Figure 4 presents an enlarged version of the radio dynamic spectrogram of the type II burst and its fine structures. We identify 140 spike-like bursts on the fundamental and second harmonic branches and measure their central frequency, frequency bandwidth, frequency-drifting rates, and lifetime. Figure 5 presents their statistical distribution. We find that the frequency bandwidth of each single spike-like burst is in the range of 7–25 MHz, with an average value of 12 MHz; the relative bandwidth $f_u$ ranges from 0.04 to 0.12, almost two times greater than the above spike bursts. The lifetime of each single spike-like burst is about 30–60 ms, with an averaged value of about 42 ms, which is very similar to the spike bursts.

As for the frequency-drifting rate of each single spike-like burst, 65 of the 140 identified spike-like bursts are negative from $-71$ to $-133$ MHz s$^{-1}$, with $\Delta$ ranging from $-0.37$ to $-0.71$ s$^{-1}$; the other 75 spike-like bursts are positive from 83 to 143 MHz s$^{-1}$, with $\Delta$ ranging from 0.41 to 0.67 s$^{-1}$. The drifting rates are about two times faster than the spike bursts and slower than the type III pair bursts. Differing from the stochastic distribution of the spike bursts, Figure 5(a) shows that the ND spike-like bursts mainly appear on the lower-frequency side of the ridges (the white dotted–dashed lines in Figure 4) of the fundamental (F) and harmonic (H) branches of the type II burst, while the PD spike-like bursts mainly appear on the higher-frequency side of the ridges. This distribution is very similar to that of the type III pair bursts.

Chen et al. (2016) reported that during the flare rising phase, a lower arcade above the flaring region takes off as a CME with a rapid expansion and averaged speeds of about 600 km s$^{-1}$. The above radio type II burst occurred at the same period, indicating that both of them may have close relationships with each other. We will discuss this further in Section 3.

Table 1 compares the main parameters of the three kinds of fast frequency-drifting radio bursts. Spike-like bursts have about 2 times the bandwidth and about 3 times the drifting rate of spike bursts; type III pair bursts have the biggest relative frequency bandwidths and the fastest frequency-drifting rates, and the ND and PD spikes are randomly distributed on the spectrogram, which differs from the type III pair bursts and spike-like bursts. Both normal type III bursts and ND spike-like bursts are mainly distributed on the lower-frequency sides, while the RS type III bursts and PD spike-like bursts are distributed mainly on the high-frequency sides. In brief, there are three kinds of FDRBs: type III pair bursts, spike bursts, and spike-like bursts, which should be intrinsically related to the flare but have different physical processes.

### Table 1

| Burst type | Type III Pair Burst | Spike Burst | Spike-like Burst |
|------------|---------------------|-------------|-----------------|
| Frequency bandwidth (MHz) | 45–120 (85) | 2.6–14.0 (6.6) | 7–25 (12) |
| Relative frequency bandwidth $f_u$ | 0.25–0.55 (0.42) | 0.01–0.04 (0.03) | 0.04–0.12 (0.07) |
| Lifetime (ms) | 200–700 (430) | 10–90 (37.6) | 30–60 (42) |
| Negative relative-drifting rate (s$^{-1}$) | 0.85–1.25 (1.03) | 0.13–0.39 (0.29) | 0.37–0.71 (0.56) |
| Positive relative-drifting rate (s$^{-1}$) | 0.70–1.29 (1.01) | 0.11–0.26 (0.19) | 0.41–0.67 (0.53) |

**Note.** The number in the brackets is the average value of the corresponding parameter.

As we have no imaging observations at the corresponding radio frequency, it is difficult to determine the location of the source regions of radio bursts. However, because the flare is a limb event, we can obtain an estimation of the source region indirectly from multi-wavelength observations.

Figure 6 shows three consecutive snapshots (every 1 minute) at three EUV (171 Å, 131 Å, 94 Å) channels observed by AIA/SDO that present the evolutionary processes during the flare impulsive phase. The overlaid contours are microwave emission at 17 GHz observed by NoRH (white) and HXR emissions observed by RHESSI in the selected time at energies of 6–12 keV (blue), 12–25 keV (yellow), 25–50 keV (red), and 50–100 keV (pink), respectively.

Figure 6 shows that there is a small compact upper-HXR source and a large lower-HXR source at energies of 50–100 keV that are located very close to a cusp-shaped structure on the EUV images; these images brighten sequentially at high-temperature emission of 131 Å, delineating the newly reconnected field lines around 00:20 UT. The HXR sources are indicate a strong energy release that could be either the flare footpoints or the site where the magnetic reconnection took place. Two neighboring loop systems (north and south) are involved and the HXR sources are situated between them. At the same time, a microwave burst is almost superimposed on the large lower-HXR source. A systematical investigation of the flare and the following CME was demonstrated by Chen et al. (2016), who suggested that the eruption could be caused by breakout magnetic reconnection around the multi-polarity regions.

We propose that the small, compact, upper-HXR source is responsible for the normal type III bursts, while the large lower-HXR source is responsible for the RS type III bursts. The mid-position between the upper and lower sources could be responsible for the reconnection and acceleration site where the height is about 65″ ($H = 4.7 \times 10^4$ km) above the solar surface, and the corresponding radio emission occurred near a separate frequency (about 30 MHz). Because the spike bursts occurred very close and around a separation frequency, their source region must be near the above acceleration site. The spike-like bursts on the type II bursts should be above the upper-HXR source beyond 70″ above the solar surface, $H > 5.1 \times 10^4$ km.

Using the mechanism of plasma emission, the plasma density around the reconnection and acceleration site (near the separate frequency) can be estimated as about $1.2 \times 10^{15}$ m$^{-3}$. The frequency range of the spike bursts is 170–410 MHz and their corresponding plasma density is from $3.6 \times 10^{14}$ m$^{-3}$ to $2.1 \times 10^{15}$ m$^{-3}$. The frequency range of spike-like bursts is 100–286 MHz, with a plasma density from $1.2 \times 10^{14}$ to $1.1 \times 10^{15}$ m$^{-3}$.

Another parameter is the magnetic field in the source region. The flare event is very close to the solar limb, so we have no reliable measurement of the magnetic field. We may indirectly
estimate it from the fitted method of Dulk & McLean (1978):

\[
B = 0.5 \left( \frac{r}{R_c} - 1 \right)^{-\frac{1}{2}} = 0.5 \left( \frac{H}{R_c} \right)^{-\frac{1}{2}}. 
\]  

(2)

The unit of magnetic field \((B)\) is Gs and \(R_c\) is the solar photospheric radius. \(r\) is the distance from the source region to the solar center. \(H\) is the height above the solar photospheric surface. We can obtain the magnetic field at about 28 Gs around the acceleration site. As the radio type II burst occurred above the upper-HXR source region, the related magnetic field should be a bit weaker than 25 Gs. Considering the uncertainty of Equation (1), it is reasonable to assume the magnetic field strength is in the range of 15–40 Gs.

With the above results, we can estimate the Alfvén speed around the acceleration site and the source region of a type II

Figure 6. Flare consecutive snapshots in every minute at 171 Å, 131 Å, and 94 Å in the impulsive phase of the X1.3 flare on 2014 April 25. The overlaid contours are microwave emission at 17 GHz observed by NoRH (white) and hard X-ray emission observed by RHESSI in the selected time at energies of 6–12 keV (blue), 12–25 keV (yellow), 25–50 keV (red), and 50–100 keV (pink), respectively.
burst as $v_A = 1650$–4900 km s$^{-1}$ (0.005–0.016$c$). Considering the uncertainty of the estimated magnetic field strength, the Alfvén speed is at least of the order of $v_A > 1000$ km s$^{-1}$. This is much faster than the CME’s velocity (about 600 km s$^{-1}$). This point is very important for understanding the physical processes underlying the above FDRBs.

3. Physical Analysis

Now that there are three different kinds of solar FDRBs, type III pair bursts, spike bursts, and spike-like bursts, what are the physical processes underlying these bursts?

3.1. Energy Estimation of the Nonthermal Electrons

In order to understand the physical processes underlying the solar radio bursts, we must first uncover the related emission mechanism and kinetic energy of the emitting electrons. The short lifetime, narrow frequency bandwidth, and high brightness temperature indicate that all of the type III pairs, spikes, and spike-like bursts should be produced by coherent emission processes. One possible candidate is electron cyclotron maser emission (ECME), a coherent process that is related to magnetized plasma instabilities in relatively strong magnetic fields, such as the loss-cone instability, etc. (Melrose & Dulk 1982; Robinson 1991; Fleishman et al. 2003; Tang et al. 2012). However, ECME requires a relatively strong magnetic field that would exceed 35–146 Gs at 100–410 MHz. As we mentioned in the above section, the magnetic field is only about 28 Gs around the acceleration site and below 25 Gs along the path of the type II burst. This indicates that it would be very difficult to trigger ECME in this event.

Another candidate is coherent plasma emission (Zheleznyakov & Zlotnik 1975). With plasma emission and the observed $D$, the speed of the emission source (Equation (3) in Tan 2013) can be estimated using

$$v_i \approx 2H_\parallel D.$$  

Here, $H_\parallel$ is the plasma barometric scale length. Generally, $H_\parallel$ increases with the height of the emission source above the solar surface (Benz et al. 1983; Stahli & Benz 1987; Achwenden et al. 1995, etc.). However, as we do not know the exact height of the source region at certain frequencies directly, it is still difficult to obtain the exact value of $H_\parallel$. Here, we try to obtain an indirect estimation of $H_\parallel$. Figure 1 shows that radio type III pairs occur around the peak time of HXR emission flux at energies of 50–100 keV, thus we may assume that the type III pair-related energetic electrons have kinetic energies of about 50–100 keV, and the corresponding velocities are in the range of 0.42–0.57$c$.

Substituting this velocity and the observed $D$ into Equation (2), we obtain an estimation $H_\parallel \approx 7.6 \times 10^4$ km. This value is compatible with other estimations at the frequency range of metric waves (Benz et al. 1983; Tan et al. 2016).

Using the above estimated $H_\parallel$ and the observed $D$ of radio spike bursts, we can obtain an estimation of the velocities of the emitting sources: $(1.7–4.0) \times 10^4$ km s$^{-1}$ (about 0.06–0.13$c$) for the PD spikes and $-(2.0–5.9) \times 10^4$ km s$^{-1}$ (about 0.07–0.2$c$) for ND spikes. These velocities are too fast to demonstrate the motions of CMEs or any solar plasma jets. They are possibly responsible for the movement of emitting nonthermal electron beams, and the corresponding kinetic energies are in the range of 0.8–4.4 keV for PD spikes and 1.1–10.0 keV for ND spikes, respectively.

Using the same method, we may estimate the velocities and kinetic energies of the emitting electrons associated with the spike-like bursts in the type II bursts. As for the PD spike-like bursts, the corresponding velocities and kinetic energies are $(5.6–10.8) \times 10^4$ km s$^{-1}$ (about 0.19–0.36$c$) and 9.1–35.6 keV, respectively. For PD spike-like bursts, the corresponding velocities and kinetic energies are $(6.2–10.2) \times 10^4$ km s$^{-1}$ (about 0.21–0.34$c$) and 11.5–33.5 keV, respectively.

Although the above velocities of the nonthermal electrons are slower than those of the electron beams related to type III pair bursts, they are still much higher than those of the thermal elections in the background plasma and much higher than the Alfvén speed in the background plasma. These nonthermal electrons are enough to trigger Langmuir waves and the related coherent plasma emission (Robinson & Benz 2000).

3.2. Acceleration Processes of the Nonthermal Electrons

The electron acceleration is crucial for converting magnetic energy into kinetic energy in solar eruptions. However, so far, it still remains uncertain which mechanism accelerates electrons and other charged particles. The existing competing mechanisms include acceleration by magnetic reconnection, turbulence, and shock waves (Miller et al. 1997; Tsuneta & Naito 1998; Drake et al. 2006; Zharkova & Siversky 2011). Thus, how do we accelerate the nonthermal electrons related to the different kinds of FDRBs?

Figure 7 shows our proposed physical explanation for the related electron accelerations and the generations of radio type III pairs (normal and RS type III), spikes, and spike-like bursts in front of CMEs, respectively.

1. Type III pair bursts. It is natural to suppose that the nonthermal electrons related to type III pair bursts are accelerated by the flaring magnetic reconnection, which...
produces the upward nonthermal electron beams that generate the normal type III bursts and the downward nonthermal electron beams that generate the RS type III bursts. Therefore, the type III pair bursts can be explained as being produced by bidirectional electron beams from the flaring magnetic reconnection site (showing (1) in Figure 7) and the separation frequency \( f_s \) may pinpoint the flare primary energy-release site where the magnetic reconnection and particle accelerations take place (Li et al. 2011; Tan et al. 2016). In this event, the separate frequency \( f_s \) is around 310 MHz and the corresponding plasma density is about \( 1.2 \times 10^{15} \) m\(^{-3}\). This separate frequency is relatively lower than that in most of the other flares (Achwanden & Benz 1997; Tan et al. 2016), and the corresponding height of the reconnecting site is around \( H = 4.7 \times 10^4 \) km above the solar surface. As reported by Chen et al. (2016), the reconnection is classified as breakout type magnetic reconnection.

(2) Spike bursts. Considering the random distributions of the PD and ND spike bursts in large clusters, it is very possible that the related nonthermal electrons are accelerated by shock waves. Although there is a CME, it occurred after the spike bursts, which implies that the CME has no relationship to the formation of the spike bursts. Additionally, the overall spike bursts have no obvious frequency-drifting rate, which is distinct from the type II bursts with slow drifting rates. The spike bursts follow the type III pair bursts around the separation frequency, indicating that they should be related to the flaring magnetic reconnection. Thus, we suppose that the spike bursts are produced by a group of nonthermal electrons accelerated by a shock wave that is likely generated when the reconnecting fast outflows or downward high-energy electron stream interact on the flaring loop top, similar to the flaring termination shock reported by Chen et al. (2015) and shown in Figure 7.

(3) Spike-like bursts. The formation of spike-like bursts should be related to the motion of the CME. According to the traditional view, a fast CME triggers a shock wave that accelerates the electrons to produce a type II radio burst and the spike-like bursts (Mann et al. 1995; Cane & Erickson 2005). However, by adopting the estimation of \( H_n \) and the observed frequency-drifting rate of type II burst, we found that the speed of the emission source region is in the range of \( 300–460 \) km s\(^{-1}\). This speed is a bit slower than that measured with EUV images (about 600 km s\(^{-1}\), Chen et al. 2016), but still at the same order of magnitude. The speed is much slower than the Alfvén speed around the acceleration site and the source region of type II bursts, \( V_A = 1650–4900 \) km s\(^{-1}\) (0.005–0.014c). The related CME is only a slow one, which could not trigger a shock wave. What triggered these spike-like bursts, then? It is known that a CME is a cloud of moving magnetized plasma, and the background coronal plasma is also permeated with a magnetic field. Considering that the distribution of the ND and PD spike-like bursts is very similar to the type III pair bursts produced from magnetic reconnection, we propose that the interaction between the CME and the background magnetized coronal plasma generates moving magnetic reconnection (showing (3) in Figure 7), and accelerate electrons to produce nonthermal energetic electrons, which triggered the formation of type II radio bursts and spike-like bursts. The upward accelerated electrons from the moving magnetic reconnection generate the ND spike-like bursts, while the downward accelerated electrons from the moving magnetic reconnection generate the PD spike-like bursts. The moving magnetic reconnection following a slow CME naturally explains the formation of the spike-like bursts superimposed on the type II radio burst.

4. Summary and Discussion

Generally, it is thought that there is no obvious difference between solar radio spikes and spike-like bursts superimposed on type II bursts, for they should be generated from similar physical processes and mechanisms. However, based on the careful parameter scrutinizing in this work, we find that they are actually distinct. We find that there are three kinds of FDRBs in an X-class flare. They are generated by nonthermal energetic electrons accelerated by different physical processes as follows:

(1) Type III pair bursts. Broad bandwidth, fast frequency-drifting rate, and ND bursts occurred in the frequency below the separation frequency, while PD bursts occurred above the separation frequency. They are generated from nonthermal electrons accelerated by flaring magnetic reconnection.

(2) Spike bursts following type III pair bursts. Very short lifetimes, very narrow bandwidths, and ND and PD bursts are distributed randomly following the type III pairs around the separation frequency. They are generated from the energetic electrons possibly accelerated by a termination shock wave above the flaring loop top. The shock wave possibly formed when the reconnecting fast outflows or high-energy electron stream impact the flaring loop top.

(3) Spike-like bursts superimposed on the type II burst. With a very short lifetime and narrow bandwidth, about two times the bandwidth and nearly two times the frequency-drifting rates of spike bursts, the ND and PD bursts are distributed separately on two sides of the central ridges of the type II burst. They are generated from the energetic electrons possibly accelerated by a moving magnetic reconnection when the CME interacts with the background magnetized coronal plasma.

The above explanation is reasonable. However, it requires more observations to demonstrate its feasibility. Particularly, the termination shock wave acceleration necessary to produce spike bursts and the moving magnetic reconnection required to produce spike-like bursts need more multiple observations to demonstrate the existence of special plasma loops, magnetic field configurations, and radio bursts at the corresponding frequencies. These multiple observations should include EUV images with high spatial resolution, broadband radio spectrometers with high temporal and frequency resolutions, and spectral radio images at the corresponding frequency, such as the MUSER observations (Yan et al. 2009; Chen et al. 2019). In the future, we plan to collect more flare events with multiple observations to investigate the relationships among radio type III pair bursts, spike bursts, spike-like bursts, and the related flare and CME processes to reveal the real origin of nonthermal electrons from solar eruptions.

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References
Achwanden, M. J., & Benz, A. O. 1997, ApJ, 480, 825
Achwanden, M. J., Benz, A. O., Dennis, B. R., & Schwartz, R. A. 1995, ApJ, 455, 347
Achwanden, M. J., Benz, A. O., & Schwartz, R. A., 1993, ApJ, 417, 790
Armatas, S., Bouratzis, C., Hillaris, A., et al. 2019, A&A, 624, A76
Bastian, T. S., Benz, A. O., & Gary, D. E. 1998, ARA&A, 36, 131
Benz, A. O., Bernold, T. E. X., & Dennis, B. R. 1983, ApJ, 271, 355
Benz, A. O., Zlobec, P., & Jaeggi, M. 1982, A&A, 109, 305
Cane, H. V., & Erickson, W. C. 2005, ApJ, 623, 1180
Chen, B., Bastian, T. S., Shen, C. C., et al. 2015, Sci, 350, 1238
Chen, X. Y., Yan, Y. H., Tan, B. L., et al. 2019, ApJ, 878, 78
Chen, Y., Du, G. H., Zhao, D., et al. 2016, ApJ, 820, L37
Chernov, G. P., Yan, Y. H., Tan, C. M., Chen, B., & Fu, Q. J. 2010, SoPh, 262, 149
Drake, J. F., Swisdak, M., Che, H., & Shay, M. A. 2006, Natur, 443, 553
Dulk, G. A. 1985, ARA&A, 23, 169
Dulk, G. A., & Altschuler, M. D. 1971, SoPh, 20, 438
Dulk, G. A., & McLean, D. J. 1978, SoPh, 57, 279
Fleishman, G. D., Gary, D. E., & Nita, G. M. 2003, ApJ, 593, 571
Iwai, K., Tsuchiya, F., Morioka, A., & Misuwa, H. 2012, SoPh, 277, 477
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Li, B., Cairns, I. H., Yan, Y. H., & Robinson, P. A. 2011, ApJL, 738, L9
Lin, R. P., Dennis, B. R., Hurford, G. J., et al. 2002, SoPh, 210, 3
Lin, R. P., & Hudson, H. S. 1971, SoPh, 17, 412
Lin, R. P., Poter, D. W., Garnett, D. A., & Scarf, F. L. 1981, ApJ, 251, 364
Mann, G., Clallen, T., & Aurass, H. 1995, A&A, 295, 775
Melrose, D. B., & Dulk, G. A. 1982, ApJ, 259, 844
Miller, J. A., Cargill, P. J., Emslie, A. G., et al. 1997, JGR, 102, 14631
Ning, Z. J., Fu, Q. J., & Lu, Q. K. 2000, SoPh, 194, 137
Reid, H. A. S., & Ratcliffe, H. 2014, RAA, 14, 773
Robinson, P. A. 1991, SoPh, 134, 299
Robinson, P. A., & Benz, A. O. 2000, SoPh, 194, 345
Stahli, M., & Benz, A. O. 1987, A&A, 175, 271
Tan, B. L. 2013, ApJ, 773, 165
Tan, B. L., Karlicky, M., Meszarosova, H., & Huang, G. L. 2016, RAA, 16, 74
Tan, B. L., Tan, C. M., Zhang, Y., Meszarosova, H., & Karlicky, M. 2014, ApJ, 780, 129
Tan, B. L., Zhang, Y., Tan, C. M., & Liu, Y. Y. 2010, ApJ, 723, 25
Tang, J. F., Wu, D. J., & Yan, Y. H. 2012, ApJ, 745, 134
Tsuneta, S., & Naito, T. 1998, ApJ, 495, L67
Yan, Y. H., Zhang, J., Wang, W., et al. 2009, EM&P, 104, 97
Zharkova, V., & Siversky, T. 2011, ApJ, 733, 33
Zheleznyakov, V. V., & Zlotnik, E. Y. 1975, SoPh, 44, 461