SMALL-SCALE MICROWAVE BURSTS IN LONG-DURATION SOLAR FLARES

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ABSTRACT

Solar small-scale microwave bursts (SMBs), including microwave dot, spike, and narrow-band type III bursts, are characterized by very short timescales, narrow frequency bandwidth, and very high brightness temperatures. Based on observations of the Chinese Solar Broadband Radio Spectrometer at Huairou with superhigh cadence and frequency resolution, this work presents an intensive investigation of SMBs in several flares that occurred in active region NOAA 10720 during 2005 January 14–21. Especially for long-duration flares, the SMBs occurred not only in the early rising and impulsive phase, but also in the flare decay phase and even after the end of the flare. These SMBs are strong bursts with inferred brightness temperatures of at least $8.18 \times 10^{11}$–$1.92 \times 10^{13} \text{ K}$, very short lifetimes of 5–18 ms, relative frequency bandwidths of 0.7%–3.5%, and superhigh frequency drifting rates. Together with their obviously different polarizations from background emission (the quiet Sun, and the underlying flaring broadband continuum), such SMBs should be individual, independent strong coherent bursts related to some non-thermal energy release and the production of energetic particles in a small-scale source region. These facts show the existence of small-scale strong non-thermal energy releasing activities after the flare maxima, which is meaningful for predicting space weather. Physical analysis indicates that a plasma mechanism may be the most favorable candidate for the formation of SMBs. From the plasma mechanism, the velocities and kinetic energy of fast electrons can be deduced and the region of electron acceleration can also be tracked.

Key words: Sun: activity – Sun: flares – Sun: particle emission – Sun: radio radiation

Online-only material: color figures

1. INTRODUCTION

In solar broadband spectral observations at the microwave frequency range, especially at decimeter and centimeter wavelengths, it has long been known that there are many isolated short-timescale strong bursts, such as microwave spike bursts (Benz 1986; Huang & Nakajima 2005; Rozhansky et al. 2008; Dabrowski et al. 2011), dot bursts (Karishan et al. 2003), and narrow-bandwidth type III bursts (Huang & Tan 2012), that are frequently associated with solar flares. The main features of these bursts include very short timescales (lifetime < 0.1 s), very high brightness temperature ($T_b > 10^{12} \text{ K}$), and very high brightness temperatures ($T_b > 10^{12} \text{ K}$), and they always occur in large clusters. Practically, there are never obvious differences among these three types of bursts, and we may call them by a joint name such as solar small-scale microwave bursts (SMBs), which possibly associates them with similar strong non-thermal energy releasing processes. SMBs are always superposed on underlying broadband flaring continuum emission (Malville et al. 1967) and frequently occur in the rising and maximum phases of solar impulsive flares (Benz 1986; Csillaghy & Benz 1993). However, recent observations indicate that they also occur in the flare decay phase and even after the end of the flare (Benz et al. 2002; Huang & Tan 2012).

The obvious differences of SMBs from underlying broadband flaring continuum emissions indicate that they may have entirely different generation mechanisms. Actually, SMBs are possibly related to some strong non-thermal processes with very short timescales and very small flaring magnetic energy release regions. These processes may possibly be elementary in solar flares, which should be fragmented (Benz 1985; Messmer & Benz 2000). However, thus far, there is no perfect model for explaining the formation of flaring fragmentation and the generation of SMBs. As for the source locations of SMBs, there are two different theoretical viewpoints. The electron cyclotron maser emission mechanism (ECME) predicts that SMB emission would be expected to originate from some loss-cone instabilities in some regions close to the footpoints of a magnetic loop with strong magnetic field: $\omega_{\text{ce}} \gg \omega_{\text{pe}}$ (Melrose & Dulk 1982). Here, $\omega_{\text{ce}}$ is the electron gyrofrequency and $\omega_{\text{pe}}$ is the electron plasma frequency. Other theories propose that SMBs are produced by acceleration processes and therefore would be expected to originate in the location of acceleration sites. Tan & Tan (2012) found that each pulse of a microwave quasi-periodic pulsation at a frequency of 2.60–3.80 GHz is composed of a group of SMBs, and the concomitant zebra pattern (ZP) indicates that the corresponding magnetic field strength is only 147–210 Gs, which is too weak to meet the ECME conditions. Therefore, they proposed that SMBs are triggered by plasma emission, another coherent emission mechanism, which is triggered by Langmuir turbulence produced from non-thermal energetic electrons (Zheleznyakov & Zlotnik 1975; Chernov et al. 2003). In this case, the formation of SMBs is closely related to electron accelerations and the evolution of plasma instability. Benz et al. (2002) find that decimetric spikes are produced from a single source, occurring in the flare decay phase and located about 200″–400″ away from the flare site in hard X-ray and soft X-ray (SXR) bursts. This fact brings into question whether decimetric spikes are related to main flare electron acceleration, but raises the possibility that they are related to some coronal post-flare acceleration processes. Therefore, a much more detailed investigation of SMBs will provide insight into the elementary processes taking place in flaring regions and reveal the intrinsic properties of accelerations of non-thermal particles.

In order to recognize SMBs clearly, telescopes need high spectral resolutions and high cadence. The Gudel–Benz law indicates that the lifetime of SMBs is largely a function of emission frequency in the frequency range 237–2695 MHz:
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SBRS by using the broadband spectral observations obtained by range. to recognize that SMBs occur in the corresponding frequency of 1.25 ms and spectral resolution of 4 MHz. It is sufficient in Huairou (SBRS a frequency bandwidth of about 13 MHz at a frequency of around function of emission frequency: (1993) found that the bandwidth of an individual SMB is also a lifetime around 1.20 GHz is about 12 ms. Csillaghy & Benz conclusions are summarized in Section 4.

2. OBSERVATIONS AND ANALYSIS

2.1. The Flare Events

The solar active region NOAA 10720 is flare productive and was the most impressive region of the visible solar disk in 2005 January. It appeared on the solar disk as a simple beta-type magnetic region on January 10, grew rapidly, and fully developed on January 15, ending as a complex sunspot region on January 23. There have been 5 X-class flares, 17 M-class flares, and more than 60 C-class flares produced in this active region and recorded by the GOES satellites in 14 days of tracking across the solar disk (from 2005 January 10 to January 23). Cheng et al. (2011) investigated the properties of these flares and their relationships to coronal mass ejections (CMEs). Zhao & Wang (2006) investigated the non-potentiality and free energy transportation in this active region.

SBRS/Huairou observed 13 events perfectly at frequencies of 1.10–1.34 GHz and 2.60–3.80 GHz around the flaring in the active region NOAA 10720 during 2005 January 14–21, including three X-class flares, five M-class flares, and five C-class flares. Table 1 lists the main parameters of these 13 flare events. Three events are long-duration flares (duration \( \geq 50 \) minutes) including two M-class flares (E5, E10) and one X7.1 flare (E13); seven events are short-duration (duration \( \leq 30 \) min) flares including three M-class (E3, E4, E6) and four C-class flares (E7, E8, E9, E12). Cheng et al. (2011) reported that E1 (X1.2 flare), E4 (M8.4 flare), and E6 (M2.6 flare) are confined flares without CMEs, while the long-duration events E5, E10, and E13 are impulsive flares with strong CMEs.

2.2. Observational Data

Here, the observational data was obtained by SBRS/Huairou, which is a group of advanced high-performance solar radio spectrometers with high cadence, broad frequency bandwidth, and high frequency resolution (Fu et al. 1995, 2004; Yan et al. 2002). SBRS/Huairou includes three parts: 1.10–2.06 GHz (the antenna diameter is 7.0 m, cadence is 5 ms, and frequency resolution is 4 MHz. When it works at 1.10–1.34 GHz, the cadence is 1.25 ms, 2.60–3.80 GHz (the antenna diameter is 3.2 m, cadence is 8 ms and frequency resolution is 10 MHz), and 5.20–7.60 GHz (sharing the same antenna as the second part, and the cadence is 5 ms and frequency resolution is 20 MHz). Antennas point to the center of solar disk, automatically controlled by computers. The spectrometer can receive the total flux of solar radio emission with dual circular polarization (left- and right-handed circular polarization (LCP and RCP)), and the dynamic range is 10 dB above the quiet solar background emission. The observation sensitivity is \( \delta F \leq 2\% S_\odot \); here, \( S_\odot \) is the standard flux of the quiet Sun. From the Solar Geophysical Data (SGD) we can obtain \( S_\odot \) at frequencies of 610, 1415, 2695, 2800, and 4995 MHz, and perform the calibration of the observational data following the method reported by Tanaka et al. (1973). As for the strong burst, the receiver may work beyond its linear range and a nonlinear calibration method is then replaced (Yan et al. 2002). Similar to other congeneric instruments, such as Phoenix (100–4000 MHz; Benz et al. 1991), Ondrejov (800–4500 MHz; Jiricka et al. 1993) and the Brazilian Broadband Spectrometer (200–2500 MHz; Sawant et al. 2001), SBRS/Huairou has no spatial resolution. However, as the Sun is a strong radio emission source, a great deal of research (e.g., Dulk 1985) indicates that the microwave bursts obtained by spectrometers are always coming from the solar active region.
when the antenna points to the Sun. Specialized software based on the IDL program has also been developed for analyzing the spectrograms, which can clearly display the spectral fine structures. In order to corroborate the results obtained by SBRS/Huairou, we also scrutinize the observational data obtained by the Nobeyama Radio Polarimeters (NorP). We found that NorP also obtained the completed observations during the several interesting flare events, such as E1, E4, E5, E6, E12, and E13. This work focuses on studying these flare events.

In order to present a receivable statistical analysis of SMBs, it is necessary to confirm practical definitions of the parameters for describing SMBs. Here, we follow the definitions mainly from Tarnstrom & Philip (1972) to obtain the parameters.

1. **Burst strength** ($F$). Defined as the maximum emission intensity subtracting the background emission intensity before and after the corresponding SMB. A flux enhancement $F$ that obviously exceeds the quiet Sun emission may be regarded as a microwave burst. A universally accepted criterion is $5\sigma$; here, $\sigma$ is the standard deviation of the background emission, and when a flux enhancement exceeds $F \geq 5\sigma$ with respect to the background emission, we may call it an isolated burst event. For example, from the SGD record during 2005 January 15–20, we may obtain the standard flux value of the quiet Sun $S_0 \simeq 30–32$ sfu at frequencies of 1.10–1.34 GHz. The corresponding sensitivity is about $\delta F \sim 0.60–0.64$ sfu.

Because the signal of an SMB has a much shorter timescale and a much narrower bandwidth than that of the underlying flare continuum emission, it is easily affected by other factors, such as instrument perturbations. Here, we adopt the similar criteria of high-energy physical experiments of $5\sigma$ to produce a real observation result ($3\sigma–5\sigma$ to produce evidence, and $<3\sigma$ only reflects a hint or clue). Naturally, this criteria will leave out some SMBs with relatively weak intensities. However, such high criteria can help us to avoid the influence of other factors and increase the confidence level of our analysis.

2. **Lifetime** ($\tau$). Can be measured from the time interval of the SMB temporal profile with half the maximum of emission intensity.

3. **Frequency bandwidth** ($\Delta f$). Can be measured from the frequency width of the SMB spectral profile with half the emission intensity maximum.

In the above three parameters, the key step is to determine the time or frequency at the maximum value and half the maximum value. Here, we use an IDL GAUSSFIT function fitting method to compute the nonlinear least-squares fit to a function,

$$F(t) = a_0 + a_1 e^{-b(t-t_0)^2}.$$  

Then, the burst intensity is $F = a_1$, the averaged emission intensity of the background is $a_0$, the time of maximum intensity is at $t_0$, and the SMB lifetime is $\tau = 2\sqrt{\ln 2/b_f} \simeq (1.665/\sqrt{b_f})$. The left panel of Figure 1 is an example of this method applied to the temporal profile of an SMB. Here, the burst strength $F \simeq 35$ sfu and the lifetime $\tau \simeq 13.1$ ms.

As the averaged emission intensity of the background increases with frequency, we may use another function to fit the spectral profile of SMB:

$$F(f) = a_0 + a_1 e^{-b(f-f_0)^2} + a_2 f.$$  

Here, $f$ is the emission frequency and $a_0 + a_2 f$ presents the averaged emission intensity of the background at different frequencies. The frequency bandwidth of the SMB can be obtained: $\Delta f = 2\sqrt{\ln 2/b_f} \simeq (1.665/\sqrt{b_f})$. The right panel of Figure 1 is an example applied to the spectral profile of an SMB. Here, the frequency bandwidth of the SMB is $\Delta f \approx 14.9$ MHz.

Sometimes, SMBs become so crowded that we cannot distinguish them from each other. In order to make the result believable, here we only analyze isolated SMBs, while neglecting crowded SMBs that cannot be distinguished clearly from each other. An isolated SMB is defined as the quenching time between two SMBs being longer than its lifetime and the frequency gap between two SMBs being wider than its frequency bandwidth.

4. **Frequency drifting rate** ($R_{\text{drift}}$). Defined as the slope of an SMB on the time–frequency plane.

5. **Polarization degree**, $r = (F_L - F_R)/(F_L + F_R) \times 100\%$. Here, $F_L$ and $F_R$ are the burst strength of an SMB at LCP.
and RCP, subtracting background emissions, respectively. \( r > 0 \) indicates the left polarization, and \( r < 0 \) indicates the right polarization.

6. SMB occurrence rate \( (N_{smb}) \). Because almost all SMBs in this work occur only at frequencies of 1.10–1.34 GHz, we therefore define \( N_{smb} \) as the number of SMBs per second at frequencies of 1.10–1.34 GHz.

Table 1 lists the solar flares observed by SBRS/Huairou in NOAA 10720 during 2005 January 14–21. The following sections present the comprehensive analysis results based on the above definitions.

2.3. Analysis Results

From the SBRS/Huairou observation at frequencies of 1.10–1.34 GHz and 2.60–3.80 GHz, we found the following.

1. There are six flares occurring in isolated SMBs, and all isolated SMBs only appeared at frequencies of 1.10–1.34 GHz. The observations at frequencies of 2.60–3.80 GHz obtained by SBRS/Huairou were also inspected carefully, and it was found that there were no SMBs occurring in the above flares, except some quasi-periodic pulsations (in E4, E5, E9, and E11) and ZP structures (E1 and E5 on January 15). This fact implies that all SMBs occurred only in the frequency band below 2.60 GHz in the active region NOAA 10720, which is different from other cases, such as the flare occurring in active region NOAA 10930 on 2006 December 13 (Wang et al. 2008).

2. The eighth column of Table 1 lists the number of isolated SMBs occurring in each flare at frequencies of 1.10–1.34 GHz. Here, we find that different flares have different manifestations of SMBs: (1) the most abundant SMBs occurred in two long-duration flares: E5, an M8.6 flare that occurred on 2005 January 15 with a duration of 83 minutes and about 6000 SMBs at frequencies 1.10–1.34 GHz; and E13, an X7.1 flare that occurred on 2005 January 20 with a duration of 50 minutes and about 12,600 SMBs; (2) some sporadic SMBs occurred in four other flares, including E1, E10, E11, and E12; (3) the short-duration flares tend to have a lack of SMBs, such as E2, E3, E4, E6, E7, E8, and E9.

The following paragraphs present the detailed properties of the SMBs that appeared in these flares.

2.3.1. Abundant SMBs in a Long-duration M8.6 Flare on 2005 January 15

The GOES SXR emission indicates that the M8.6 flare starts at 05:54 UT, reaches maximum at 06:37 UT, and ends at 07:17 UT on 2005 January 15 with a duration of 83 minutes. It is a long-duration flare accompanied by a powerful CME with a speed of up to more than 2000 km s\(^{-1}\) and abundant SMBs. SMBs appear not only in the early rising and impulsive peak phases of the flare, but also occur in the flare decay phase. Figure 2 presents two segments of SMBs that occurred in the rising and decay phases, respectively, of the long-duration M8.6 flare (E5) on 2005 January 15. The left panels show a segment of SMB spectrograms during 06:02:05.0–06:02:06.0 UT in the flare rising phase with LCP (upper left) and RCP (bottom left). The small bright patches represent SMBs that show very strong left polarization and are distributed randomly. The frequency bandwidth of the individual SMBs is in the range of 8–32 MHz, and the lifetime is about 5–21 ms. As a comparison, the quenching time between each adjacent pair of SMBs is
in the range of 50–100 ms, which is much longer than the SMB lifetime. The frequency gap between each adjacent pair of SMBs is in the range of 24–64 MHz, which is wider than the frequency bandwidth of each individual SMB. The right panels of Figure 2 present another segment of SMBs during 06:38:22.0–06:38:23.0 UT in the flare decay phase. These show that almost all SMBs appeared in RCP with strong polarization. Most of the lifetimes are shorter and the frequency bandwidths are narrower than those occurring in the flare rising phase. In both of the above two cases, the frequency drifting rates of some SMBs can be measured, and the values of \( R_{\text{drift}} \) are in the range of 1500–6000 MHz s\(^{-1}\). At the same time, most SMBs are perpendicular to the time axis, such that we cannot detect their \( R_{\text{drift}} \). This is possibly because their frequency drifting rates are so high that we cannot detect them due to the restrictions of limited spectral and temporal resolutions. For example, when the bandwidth is 12 MHz, the detectable maximum \( R_{\text{drift}} \) is 9600 MHz s\(^{-1}\) for a cadence 1.25 ms, etc.

Figure 3 presents the temporal profiles of the emission intensities of two segments of SMBs with LCP and RCP, respectively. As a comparison, the emission intensity of the quiet Sun recorded during 05:45:00.0–05:45:00.6 UT (before the onset of the flare) is also overplotted on the same figure. It is obvious that the microwave emission can be decomposed into three components. The first component is the quiet Sun emission (\( F_{\text{quiet}} \)), which can be represented by the record before the solar flare (e.g., during 05:45–05:50 UT); the second one is the underlying broadband flaring continuum emission (\( F_{\text{flare}} \)), which can be defined as the emission during the gap between two SMBs; and the last one is the emission of SMBs (\( F_{\text{SMB}} \)) that exceeds \( F_{\text{flare}} \) significantly. Around the M8.6 flare, \( F_{\text{quiet}} \sim 29–30 \) sfu at LCP and RCP without significant polarization. The left panel of Figure 3 shows that \( F_{\text{flare}} \sim 107.4 \) sfu (the standard deviation \( \sigma = 5.09 \) sfu) at LCP and 87.7 sfu (\( \sigma = 2.74 \) sfu) at RCP, and \( F_{\text{SMB}} \) at LCP is in the range of 43–85 sfu, which exceeds \( 5\sigma \) with respect to \( F_{\text{flare}} \) and far surpasses the instrument sensitivity \( \delta F \). The right panel of Figure 3 indicates that \( F_{\text{flare}} \sim 153.7 \) sfu (\( \sigma = 4.85 \) sfu) at LCP and 157.8 sfu (\( \sigma = 3.26 \) sfu) at RCP, \( F_{\text{SMB}} \sim 42–145 \) sfu at RCP, which also exceeds \( 5\sigma \) with respect to \( F_{\text{flare}} \) and far surpasses the instrument sensitivity \( \delta F \). We may suppose that each SMB is an independent burst, which is different from the underlying broadband flaring continuum and the quiet Sun emissions.

The spectrogram in Figure 2 implies that the distribution of SMBs is random, either in the flare rising phase or in the decay phase. Actually, from the onset of the long-duration M8.6 flare to its decay phase, numerous SMBs occurred. The left panel of Figure 4 presents the distribution of the SMB occurrence rate in the flare and a comparison between the GOES SXR emission and the microwave emission intensity at LCP and RCP. The plus signs (+) indicate the SMB occurrence rate. The solid curves are the radio emission intensity at 1.20 GHz. The positive and negative values indicate the presence at LCP and RCP, respectively. The comparison between the GOES SXR and the microwave emission intensity at LCP and RCP indicates that there are time differences between their maxima. The GOES SXR maximum occurred at about 06:37 UT, LCP the maximum occurred at about 06:25 UT, and the RCP maximum occurred at about 06:16 UT. A rough estimation indicates that there are about 6000 SMBs associated with the flare. Among them, about 94% LCP SMBs occurred before the LCP maximum, and about 91% RCP SMBs occurred after the LCP maximum.

Polarization is another important parameter reflecting the nature of SMBs. The right panel of Figure 4 plots the temporal distribution of the polarization degree of SMBs averaged over the time interval of 1 s (marked as \( \Delta \)) associated with the M8.6 flare. In order to investigate the relationships between SMBs and the underlying flare broadband emission, the polarization degrees of \( F_{\text{quiet}} \) (during 05:45–05:57 UT) and \( F_{\text{flare}} \) (during 05:57–07:15 UT) are also overplotted on the same figure. Here, we find that \( F_{\text{quiet}} \) has no obvious polarization with \( r < 10\% \); \( F_{\text{flare}} \) has a moderate LCP increasing slowly from the rising phase to the decay phase and in the range of \( r \sim 10\%–55\% \), and then decreasing rapidly to below 10% after the end of the flare. Different from the above two components, almost all SMBs have strong circular polarization with degrees of polarization exceeding 55%; they are mainly strong LCP before LCP maximum (06:25 UT) and strong RCP after LCP maximum. There is no obvious correlation between the polarizations of SMBs and background emission (\( F_{\text{quiet}} \) and \( F_{\text{flare}} \)). This fact...
implies that SMBs are independent bursts overlapping the underlying background emission.

According to the SMB occurrence rates in the spectrograms, we may partition them into three groups: group A occurred in the flare early rising phase and mainly at LCP during 05:57–06:25 UT; group B occurred around the impulsive peak phase at RCP during 06:13–07:10 UT; and group C occurred in the flare decaying phase at LCP after 07:10 UT.

Among the 6000 SMBs, there are about 25% SMBs whose frequency drifting rate can be obviously measured; the value of $R_{\text{drift}}$ is in the range of 1200–9600 MHz s$^{-1}$. Table 2 lists the averaged burst strength, lifetime, frequency bandwidth, and the frequency drifting rate in each group of SMBs. Actually, the other SMBs also possibly have frequency drifting rates that are not detected because of the restrictions of the limited temporal and spectral resolutions of the instruments, which implies that the frequency drifting rates of SMBs may be beyond 9600 MHz s$^{-1}$.

Sometimes, SMBs occur in pairs with reversed frequency drifting rates at nearly the same time and different frequency range; we call these reversed-drifting SMB pairs. Figure 5 presents two examples of such reversed-drifting SMB pairs that occurred at 06:02:35.65–06:02:35.92 UT (in the flare rising phase) and 06:38:25.60–06:38:25.82 UT (in the flare decay phase). The crossing point of the extension lines (the dashed lines in Figure 5) of each SMB of the reversed-drifting SMB pairs can present a reversed time ($\Delta t$) and a reversed frequency ($f_r$). Here, $\Delta t$ is defined as the time difference between the crossing point (C) and the corresponding SMB (approximate average of the two SMBs), and $f_r$ is defined as the frequency with which the crossing point occurs. In the left panel of Figure 5, the reversed-drifting SMB pair occurs at the LCP, the reversed frequency $f_r \sim 1.150–1.175$ GHz, and the low-frequency SMB is from 1.100 GHz to 1.150 GHz, with a frequency drifting rate of about $-800$ MHz s$^{-1}$, while the high-frequency SMB is from 1.250 GHz to 1.280 GHz, with a frequency drifting rate of 1170 MHz s$^{-1}$. The reversed time is 75–80 ms ahead of the corresponding SMBs. Among all the reversed-drifting SMB pairs, the reversed frequency $f_r \sim 1.15–1.19$ GHz, and the negative frequency drifting rate is in range from $-500$ MHz s$^{-1}$ to $-3500$ MHz s$^{-1}$, while the positive frequency drifting rate is in the range from 1400 MHz s$^{-1}$ to 4000 MHz s$^{-1}$. Obviously, the reversed-drifting SMB pairs in the flare rising phase have slightly lower reversed frequencies and much longer reversed time than those in the flare decay phase. Supposing that an SMB is associated with some energetic electron beams in the ambient plasma, then the reversed-drifting SMBs may imply some local magnetic reconnections in small-scale regions, and the crossing points may indicate the electron acceleration site where the electrons accelerated and propagated upward and downward, and then triggered the formation of reversed-drifting SMBs. Therefore, the reversed frequency may reflect the region where magnetic reconnections take place, and the reversed time may reflect the propagating process of energetic electrons from the acceleration site to its emission source region.

Figure 4. Left panel is the distribution of the SMB occurrence rate in the M8.6 flare (E5) on 2005 January 15. The plus signs (+) indicate the SMB occurrence rate. The solid curves are the radio emission intensity at 1.20 GHz. The positive and negative values indicate the presence of LCP and RCP, respectively. The dashed line is the soft X-ray emission at 1–8 Å observed by GOES. The right panel is a comparison of the polarization degrees between the quiet Sun (during 05:45–05:57 UT), flare (during 05:57–07:15 UT), and SMBs (Δ).

2.3.2. Abundant SMBs in a Long-duration X7.1 Flare on 2005 January 20

E13 is another SMB abundant long-duration flare. GOES SXR observations show that it starts at 06:36 UT, reaches maximum at 07:01 UT, and ends at 07:26 UT on 2005 January 20 with a duration of 50 minutes. It is an X7.1/2B flare, the most extremely powerful flare event occurring in the deep descending phase of solar cycle 23. It has attracted great attention from the solar and solar-terrestrial community for its strong fast halo CME, strong gamma-ray bursts with energy up to 200 MeV, the strongest solar energetic particle flux, and the strongest microwave bursts (Grechnev et al. 2008; Bombardieri et al. 2008; Wang et al. 2009). The most important point is that E13 is an SMB abundant event. From the SBR/Hzaiou observation at 1.10–1.34 GHz, about 12,600 isolated SMBs have been distinguished. Different from E5, no isolated SMBs occurred
Figure 5. Spectrograms of the reversed-drifting SMB pairs occurring in the rising (left, 06:02:35.65–06:02:35.92 UT) and decay (right, 06:38:25.60–06:38:25.82 UT) phases of the M8.6 flare (E5) on 2005 January 15. The crossing point (C) of the dashed lines indicates the reversed time ($t_r$) and a reversed frequency ($f_r$).

(A color version of this figure is available in the online journal.)

Table 2

| Event | Distribution | $F$ (sfu) | $\tau$ (ms) | $\Delta f$ (%) | $R_{\text{drift}}$ (MHz s$^{-1}$) | $N_{\text{smb}}$ (s) | $L$ (km) | $T_b$ (K) |
|-------|--------------|-----------|-------------|-------------|-----------------|---------------------|--------|--------|
| E1    | Rising phase | 44.3      | 71.6        | 35.5        | 3.0             | 820.5               | 90     | 600    | 1.28 $\times 10^{12}$ |
| E5-A  | Rising phase | 52.8      | 15.1        | 23.6        | 2.0             | 3150                | 4600   | 400    | 3.46 $\times 10^{12}$ |
| E5-B  | Around peak  | 52.7      | 9.3         | 10.0        | 0.8             | 2120                | 1240   | 160    | 1.92 $\times 10^{13}$ |
| E5-C  | Decay phase  | 43.0      | 5.0         | 14.8        | 1.2             | 4110                | 1520   | 240    | 7.16 $\times 10^{12}$ |
| E10   | Decay phase  | 39.0      | 221.1       | 41.7        | 3.5             | 152.9               | 45     | 700    | 8.18 $\times 10^{11}$ |
| E11   | Rising phase | 40.1      | 49.7        | 24.8        | 2.1             | 736.3               | 92     | 420    | 2.38 $\times 10^{12}$ |
| E12   | Rising phase | 40.6      | 69.5        | 32.6        | 2.7             | 965.0               | 17     | 540    | 1.58 $\times 10^{12}$ |
| E13   | Decay phase  | 55.9      | 10.3        | 20.0        | 1.7             | 3006                | 12600  | 340    | 5.10 $\times 10^{12}$ |

Notes. $\tau$ is lifetime, $\Delta f$ is frequency bandwidth (MHz), $R_{\text{drift}}$ is the frequency drifting rate (MHz s$^{-1}$). $N_{\text{smb}}$ is the SMB occurrence rate, and $L$ and $T_b$ are the estimated upper limited width and lower limited brightness temperature of the source region, respectively.

in the early rising and impulsive peak phase of the E13 flare. All SMBs occurred after 07:10 UT, the decay phase of the flare.

Figure 6 presents two segment spectrograms of SMBs at LCP and RCP observed by SBRS/Huairou in the decay phase and after the ending of the X7.1 flare (E13) on 2005 January 20. The left panels show one-second-segment spectrograms of SMBs during 07:13:06–07:13:07 UT in the flare decay phase. There are about 30 SMBs with strong LCP distributed randomly in this segment. The frequency bandwidth of the SMBs is in the range of 12–40 MHz, and the lifetime is about 5–40 ms with an average value of 14 ms. Some SMBs show frequency drifting, and $R_{\text{drift}}$ is in the range from $-2000$ MHz s$^{-1}$ to $3840$ MHz s$^{-1}$. The underlying broadband flaring continuum emission $F_{\text{flare}}$ is about 145 sfu with $\sigma \approx 6.4$ sfu at LCP and 151 sfu with $\sigma \approx 6.1$ sfu at RCP. The burst strength of SMBs, $F_{\text{smb}}$, is in the range of 16–32 MHz with an average value of 24 MHz, and the averaged lifetime is about 9 ms. Some SMBs show the frequency drifting rate $R_{\text{drift}}$ from 2100 MHz s$^{-1}$ to $-3600$ MHz s$^{-1}$. In this case, the underlying broadband flaring continuum emission $F_{\text{flare}}$ is about 103 sfu with $\sigma \approx 4.7$ sfu at LCP and 101 sfu with $\sigma \approx 4.1$ sfu at RCP. The burst strength of SMBs, $F_{\text{smb}}$, is in the range of 41–105 sfu with an average value of 59.5 sfu. The average polarization degree is about 99%. Similar to the SMBs occurring in E5, there are also some SMBs occurring in E13 that have reversed frequency drifting rates. The reversed frequency is about 1.180 GHz, and the reversed time is about 90–105 ms ahead of the corresponding SMBs.

From the spectrograms during the X7.1 flare, there are about 12,600 isolated SMBs recognized at frequencies of 1.10–1.34 GHz. The left panel of Figure 7 presents the distribution of the SMB occurrence rate in the flare and comparisons between GOES solar X-ray emission and the underlying microwave emission intensity at LCP and RCP. Here, we find that all SMBs occurred during 07:10–07:45 UT, after second segment. The frequency bandwidth of the SMBs is in the range of 16–32 MHz with an average value of 24 MHz, and the averaged lifetime is about 9 ms. Some SMBs show the frequency drifting rate $R_{\text{drift}}$ from 2100 MHz s$^{-1}$ to $-3600$ MHz s$^{-1}$. In this case, the underlying broadband flaring continuum emission $F_{\text{flare}}$ is about 103 sfu with $\sigma \approx 4.7$ sfu at LCP and 101 sfu with $\sigma \approx 4.1$ sfu at RCP. The burst strength of SMBs, $F_{\text{smb}}$, is in the range of 41–105 sfu with an average value of 59.5 sfu. The average polarization degree is about 99%. Similar to the SMBs occurring in E5, there are also some SMBs occurring in E13 that have reversed frequency drifting rates. The reversed frequency is about 1.180 GHz, and the reversed time is about 90–105 ms ahead of the corresponding SMBs.

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Figure 6. Two segment spectrograms of SMBs at LCP and RCP observed by SBRS/Huairou in the decay phase and after the end of the X7.1 flare (E13) on 2005 January 20. (A color version of this figure is available in the online journal.)

Figure 7. Left panel is the distribution of the SMB occurrence rate in the X7.1 flare (E13) on 2005 January 20. The plus signs (+) indicate the SMB occurrence rate. The solid curves are the radio emission intensity at 1.20 GHz. The positive and negative values indicate the presence of LCP and RCP, respectively. The dashed line is the soft X-ray emission at 1–8 Å observed by GOES. The right panel is a comparison of polarization degrees between the quiet Sun (before 06:36 UT), flare (during 06:36–07:26 UT), and SMBs (△). or far away from the maxima of the GOES solar X-ray emission and the underlying microwave emission intensity at LCP and RCP. The SMB distribution is very crowded together, and some of the SMB occurrence rates ($N_{smb}$) exceed 100, which is much higher than that occurring in the above M8.6 flare event. The right panel of Figure 7 presents a comparison of polarization degrees between the quiet Sun (before 06:36 UT), flare broadband continuum microwave emission (during 06:36–07:26 UT), and SMBs. Here, we also find that the polarization degree of the quiet Sun emission is very close to zero; the underlying flare broadband continuum emission is weakly left-handed circular polarized with $r \leq 20\%$, while most SMBs are strongly left-handed circular polarized with $r > 60\%$. We also find that a few SMBs have strongly RCP during 07:27 and 07:45 UT, far way from the flare maximum. Here, once again, we find that SMBs have obviously different polarization degrees from the quiet Sun and the underlying flaring broadband continuum microwave emission. The range of SMB frequency bandwidth is 8–28 MHz, and the lifetime is 5–18 ms. There are also some SMBs that can be detected with obvious frequency drifting rates, and the value is in the range of 1400–8800 MHz s$^{-1}$. 

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Table 2 lists the averaged burst strength, lifetime, frequency bandwidth, and the frequency drifting rate of SMBs associated with the X7.1 flare event.

2.3.3. Sporadic SMBs in Some Flares

Besides the above two SMB-abundant flares, there are an additional four flares having sporadic SMBs, including E1 (X1.2 flare, duration of 40 minutes), E10 (M6.7 flare, duration of 57 minutes), E11 (X1.3 flare, duration of 37 minutes), and E12 (C4.8 flare, duration of 15 minutes) in active region NOAA 10720. Tables 1 and 2 list the main parameters of these events. The left panels of Figure 8 present 3.0 s segments of a spectrogram of a group of SMBs with LCP and RCP occurring in the early rising phase of an X1.3 flare during 08:06:31–08:06:34 UT on 2005 January 19 (E11), which shows that SMBs are strongly right-handed circular polarized with an average $\widetilde{\tau} \simeq 77\%$. There are a total of 92 SMBs associated with the X1.3 flare, most of them having frequency drifting rates in the range from $-205$ to $-3200$ MHz s$^{-1}$ with an average value of $-736.3$ MHz s$^{-1}$ and no positive frequency drifting rate. The burst strength is in the range of 29–72 sfu with an average value of 40.1 sfu. The lifetime is in the range of 20–76 ms, the average lifetime is 49.7 ms, and the average frequency bandwidth is 24.8 MHz.

The right panels show a 2.3 s segment spectrogram of a few isolated SMBs occurring during 07:43:19.7–07:43:22.0 UT in the decay phase of another long-duration M6.7 flare (E10) on 2005 January 19. There are a total of 45 isolated SMBs associated with the flare. Some of them have frequency drifting rates in the range from $-61.3$ to $-253.7$ MHz s$^{-1}$. Here, SMBs are weakly right polarized with $\widetilde{\tau} \simeq 31\%$, the average lifetime is 221.1 ms, the average burst strength $\widetilde{F} \simeq 39.0$ sfu, and the average frequency bandwidth is 41.7 MHz, which is much wider than that occurring in the SMB-abundant long-duration flares.

Actually, Table 2 indicates that in the four flare events with sporadic SMBs, the SMB lifetime is much longer, the frequency bandwidths are wider, the frequency drifting rates are much slower, and the SMB burst strengths are a bit smaller than those in the long-duration flares with a large number of SMBs.

2.3.4. Brief Summary

The above analysis shows that there are six flares in active region NOAA 10720 having isolated SMBs at frequencies of 1.10–1.34 GHz, and some of them are abundant with SMBs, while others only have sporadic SMBs.

1. Among the six flare events, there are three events having SMBs in their decay phase, and they are only the long-duration flares. This fact implies that long-duration flares tend to produce more SMBs in the decay phase.

2. Most SMBs, especially the SMBs occurring abundantly in the decay phase of long-duration flares, have strong circular polarization that is extremely different from the background emission ($F_{\text{quiet}}$ and $F_{\text{flare}}$), very short timescales ($\sim 5$–15 ms), and narrow frequency bands (around 0.8%–2.0%).

3. In the long-duration flares, some SMBs occur in the deep decay phase far away from the flare maxima, even after the end of the flare and they still have similar burst strengths and strong polarizations. Some of SMBs have reversed frequency drifting rates; the reversed frequency is about 1.15–1.19 GHz, and the reversed time is about 20–80 ms ahead of the corresponding SMBs.

4. There is no obvious correlation between the burst strength, lifetime, frequency bandwidth, frequency drifting rates, or polarization degrees between SMBs and background emission ($F_{\text{quiet}}$ and $F_{\text{flare}}$). This fact implies that SMBs are independent bursts overlapping on the underlying background emission.

3. PHYSICAL DISCUSSIONS

From the relative frequency bandwidth of SMBs, we may estimate the upper limited spatial scales of the source region: $l \approx H_f \cdot (\Delta f / f)$. Here, $H_f = |(f \sqrt{\n})|$ is the scale length of emission frequency around the source region. The highly circular polarization of SMBs indicates that the emission mechanism is possibly the fundamental plasma emission, and the emission frequency can be expressed: $f = 9.2 \rho n_e$, $n_e$ is the electron plasma density. Then, $H_f = 2H_{\rho n}$. Here, $H_{\rho n} = |(n \sqrt{\n})|$ is the scale length of the plasma density ($n$), which depends on the plasma thermal temperature ($T_p$). Supposing that the thermal temperature around the source region is about 1 MK, $H_{\rho n} \sim 10^5$ km, and the source region is near the lower part of the corona. Then the upper limited spatial width of the SMB source regions can be obtained. The eighth column of Table 2 presents the estimated upper limited width of the SMB source regions, which is in the range of 160–700 km. This result is consistent with the very long baseline interferometry imaging observations that show the diameter of the spike source region to be about 50 km at 1663 MHz (Tapping et al. 1983). Furthermore, the lower limit of the SMBs’ emission brightness temperature ($T_b$) can be deduced (Smerd 1951; Tan et al. 2009):

$$T_b \simeq 3.6 \times 10^{25} \frac{F_{\text{amb}}}{(\Delta f / f)^2} \text{(K)}.$$ (1)

Here, units of $F_{\text{amb}}$ and $\Delta f$ are in sfu and Hz, respectively. The last column of Table 2 lists the estimated lower limited brightness temperatures of the SMBs, which are in the range of $8.1 \times 10^{11}$–$1.92 \times 10^{13}$ K. As a comparison, the image observation indicates that the length of active region AR10720 is about 200” at 17 GHz (obtained from Nobeyama Radio Heliograph), and we may suppose that the source region of the flaring radio emission will be larger than 200”. As an upper limit, the emission brightness temperature of the flare radio emission at 1.20 GHz is about $4.5 \times 10^{12}$ K, which is several orders lower than that of SMBs. The emission brightness temperature of the quiet Sun can also be estimated to be $6.3 \times 10^{12}$ K, which is two orders lower than that of the flaring broadband emissions.

The very high brightness temperatures of SMBs indicate that the emission mechanism should be some coherent emissions, which may reflect the presence of non-thermal energetic electrons in the source region. Considering that they occur not only in the flare rising and impulsive phases, but also in the flare decay phase and even far away from the impulsive phase, they possibly reflect the existence of similar small-scale nonthermal energy releasing in the flare decay phase.

The most frequently mentioned coherent mechanism is ECME, which is supposed by many to be the formation mechanism of solar radio spike bursts (Fleishman et al. 2003). However, ECME occurs only when the following conditions are satisfied (Melrose & Dulk 1982):

$$\omega - \frac{s_0 \omega_0}{\gamma} - k_3 v_1 = 0$$ (2)

and

$$\omega_0 \gg \omega_{pe}.$$ (3)
Here, $\omega$ is the emission frequency, $s$ is the harmonic number, $\gamma$ is the Lorentz factor of the energetic electrons, and $k_{\parallel}$ and $v_{\parallel}$ are the parallel components of the wave number and electron velocity, respectively. The most favorable regime for producing ECME is the loss-cone instabilities occurring near the footpoint of flare loops. If the mechanism is ECME, then from Equation (3), the magnetic field strength in the SMB source region should be $\gg 430$ Gs.

So far, we have no direct measurement of the magnetic field in the solar corona. Microwave ZPs may be a useful tool for
microwave source regions (Tan et al. 2012). It is fortunate that providing information on the magnetic field associated with the microwave quasi-periodic pulsation with millisecond bursts (Tan & Tan 2012), here we may also adopt the same model to interpret the formation of SMBs. We may suppose that the post-flaring loops are current-carrying plasma loops, where the resistive tearing mode instability can be triggered, and causes the formation of many small-scale magnetic islands along each rational surface in the plasma loops. Each X-point between the adjacent magnetic islands will be a small reconnection site and will produce secondary acceleration in the ambient electrons, similar to the regime in the current sheet (Shen et al. 2011). These accelerated electrons impact the adjacent plasmas around the small X-point, trigger the Langmuir turbulence and plasma waves, and produce microwave bursts by a plasma emission mechanism. Such microwave bursts are simply SMBs. As there are many magnetic X-points in the current-carrying plasma loops, each X-point will be a small reconnection site, and the region around each X-point will be the source of an SMB. As a result, SMBs can arise in huge clusters. However, as we lack imaging observations, it is a big challenge to set up a more self-consistent structure of the SMB source region.

The above analysis indicates that non-thermal energy releasing and high inhomogeneity in the source region are necessary for the formation of SMBs in the frame of plasma emissions.

As the frequency of plasma emission depends on the plasma density $f = s f_{pe} \simeq 9 n_{H}^{1/2}$, when the fast electrons move in the inhomogeneous ambient plasma, the frequency will drift: $(df/dt) = (9s/2n_{H}^{1/2}) (dn_{H}/d\tau) (d\tau/dt) = (f/2H_{s}) v_{e}$. Here, $f_{pe} = (\omega_{pe}/2\pi)$, $s$ is the harmonics, $s = 1$ is the fundamental emission, and $s = 2$ is the second harmonic emission. Then, the velocity of fast electrons can be estimated:

$$v_{e} \simeq 2H_{s} \cdot \frac{1}{f} \frac{df}{dt}.$$ (6)

Then, from the frequency drifting rates of SMBs, we may estimate the velocity of the fast electrons. For example, in the long-duration flare E5, the frequency drifting rates are in the range of 1200–9600 MHz s$^{-1}$, the corresponding velocities of fast electrons are in range of 0.07–0.53 c, and the kinetic energy is 3–80 keV. Here, c is speed of the light. In another long-duration flare E13, the frequency drifting rates are in the range of 1400–8800 MHz s$^{-1}$, the corresponding velocities of fast electrons are in range of 0.08–0.49 c, and the kinetic energy is 3–75 keV. When $(df/dt) > 0$, the exciter moves from a tenuous plasma region to a dense plasma region, such as the downward motion in the corona; when $(df/dt) < 0$, the exciter moves from a dense plasma region to a tenuous plasma region, such as the upward motion in the corona. The reversed-drifting SMB pairs may track the position of the acceleration region. From the reversed time we may estimate the distance between the acceleration region and the SMB source region: $D \simeq v_{e} t_{r}$. Supposing $v_{e} \sim 0.07–0.53$ c, and $t_{r} \sim 20–80$ ms, then $D$ is about 400–38,000 km. This agrees with the theoretical requirement that the Langmuir wave can be triggered in place at some distance from the acceleration region. These facts are also consistent with a similar recent result from EUV and hard X-ray observations (Liu et al. 2013).

However, in flares with only sporadic SMBs (E1, E10, E11, and E12), the frequency drifting rates of some SMBs

where Equation (5) does not agree, it will quench. The very short lifetime of an SMB requires that the source region must be highly inhomogeneous, filled with great numbers of small-scale structures. Similar to the regime of microwave quasi-periodic pulsation with millisecond bursts (Tan & Tan 2012), here we may also adopt the same model to interpret the formation of SMBs. We may suppose that the post-flaring loops are current-carrying plasma loops, where the resistive tearing mode instability can be triggered, and causes the formation of many small-scale magnetic islands along each rational surface in the plasma loops. Each X-point between the adjacent magnetic islands will be a small reconnection site and will produce secondary acceleration in the ambient electrons, similar to the regime in the current sheet (Shen et al. 2011). These accelerated electrons impact the adjacent plasmas around the small X-point, trigger the Langmuir turbulence and plasma waves, and produce microwave bursts by a plasma emission mechanism. Such microwave bursts are simply SMBs. As there are many magnetic X-points in the current-carrying plasma loops, each X-point will be a small reconnection site, and the region around each X-point will be the source of an SMB. As a result, SMBs can arise in huge clusters. However, as we lack imaging observations, it is a big challenge to set up a more self-consistent structure of the SMB source region.

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However, in flares with only sporadic SMBs (E1, E10, E11, and E12), the frequency drifting rates of some SMBs
being as slow as 60–900 MHz s\(^{-1}\), the above method presents the velocities as being only in the range of 0.003–0.05 c. Considering their relatively longer lifetimes, wider frequency bandwidth, moderate circular polarizations, and occurrence mainly in the early rising phase of mid- or short-duration flares, they are possibly associated with some small-scale plasma jets. However, this is just a guess for lack of corresponding imaging observations.

4. CONCLUSIONS

In the previous work (Benz 1986), since most SMBs (mainly indicated spike bursts) appear during the primary energy release in solar flares, they are regarded as being fragmented into about 10,000 more or less single elementary flare bursts. Also, at least part of the flaring energy is carried by fast electrons released in these elementary flare bursts. However, this work presents a comprehensive analysis of a series of solar flares occurring in active region NOAA 10720 during 2005 January 15–20, and indicates that long-duration flares can produce abundant independent isolated SMBs in the flare decay phase as well as in the flare rising phase, some of which occurred even in the deep decay phase far after the flare peak, and even after the end of the flare. These SMBs have strong circular polarization that is extremely different from the background emission \((F_{\text{quiet}} \text{ and } F_{\text{flare}})\), very short timescales (around 5–15 ms), and narrow frequency bands (around 0.8%–2.0%). They are possibly independent bursts overlapping the underlying background broadband continuum emission. The inferred brightness temperature is at least \(8.18 \times 10^{11}–1.92 \times 10^{13}\) K, and the obviously different polarizations of the SMBs from background emission (the quiet Sun and flare emission) indicates that each SMB should be an individual independent strong coherent emission burst related to some non-thermal energy releasing and the production of energetic particles. These facts imply the existence of energetic particles and strong nonthermal energy releasing processes with small scales in the decay phase of long-duration flares. This is meaningful for the prediction of space weather events.

As for the formation of SMBs, because the magnetic field strength deduced from ZPs and nonlinear force-free field extrapolation around the source region is too weak, ECME seems unlikely to be the formation mechanism of SMBs, while the plasma emission mechanism may become the favorable candidate for the formation of SMBs at fundamental Langmuir frequencies, although this also has some unresolved problems, such as the pattern of high inhomogeneity in source regions. From the plasma mechanism, we may deduce the velocities and kinetic energy of fast electrons associated with SMBs. Using the observations of reversed-drifting SMBs, we may track the region of the electron acceleration and estimate the distance between the acceleration region and the SMB source regions, etc.

Energetic electrons coming from solar flares may have a severe impact on the environment of solar-terrestrial space. The activity of nonthermal processes and energetic electrons in the decay phases of long-duration flares indicates that it is also important to pay close attention to the impact of post-flare activities of long-duration flares on space weather events. The study of SMBs may reveal some new principles of the energetic non-thermal processes associated with solar flares, such as particles accelerations, the detailed structure of the source region, and the mechanism of energy conversions, etc.

Because of instrument limitations, this work only presents the behaviors of SMBs in a relatively small frequency range (1.10–1.34 GHz). Figure 6 and other spectrograms show that it is most possible to exceed the frequency range of 1.10–1.34 GHz. It is necessary to extend the observational frequency greatly to below 1.10 GHz and above 1.34 GHz with superhigh cadence and high frequency resolutions. Additionally, the imaging observations at the corresponding frequencies are also most important for its ability to provide directly the locations, geometrical structures, and magnetic fields in the source region (Yan et al. 2009). These will help us to set up a much more self-consistent theoretical model of solar SMBs.

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