SOLAR RADIO BURSTS WITH SPECTRAL FINE STRUCTURES IN PREFLARES

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ABSTRACT

Good observations of preflare activities are important for us to understand the origin and triggering mechanism of solar flares, and to predict the occurrence of solar flares. This work presents the characteristics of microwave spectral fine structures as preflare activities of four solar flares observed by the Ondřejov radio spectrograph in the frequency range of 0.8–2.0 GHz. We found that these microwave bursts which occurred 1–4 minutes before the onset of flares have spectral fine structures with relatively weak intensities and very short timescales. They include microwave quasi-periodic pulsations with very short periods of 0.1–0.3 s and dot bursts with millisecond timescales and narrow frequency bandwidths. Accompanying these microwave bursts are filament motions, plasma ejection or loop brightening in the EUV imaging observations, and non-thermal hard X-ray emission enhancements observed by RHESSI. These facts may reveal certain independent, non-thermal energy releasing processes and particle acceleration before the onset of solar flares. They may help us to understand the nature of solar flares and to predict their occurrence.

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

1. INTRODUCTION

As early as 1959, Bumba \& Křivský found a small flare (or luminosity increase) preceding a main solar flare and introduced the term preflare to address the weak effects on the solar atmosphere that they produce. Early studies have been reviewed by Martin (1980) and Gaizauskas (1989). Thanks to the development of recent advanced observing techniques to obtain high spatial and temporal resolution data, preflare activities are frequently identified. Common preflare activities include the formation of a sigmoid in soft X-rays (Liu et al. 2010); filament activities, such as rise, oscillation, and eruption (Chifor et al. 2006; Isobe \& Tripathi 2006; Vemareddy et al. 2012); and transient brightening in multi-wavelengths (Hz (Contarino et al. 2003), UV and EUV (Cheng et al. 1985), 1600 A continuum emission (Warren \& Warshall 2001), soft X-ray (Fárník \& Savy 1998), and hard X-ray (Harrison et al. 1985; Tappin 1991; Asai et al. 2005; Chifor et al. 2007)). These multi-wavelength studies deal with questions concerning the geometry of the magnetic field, the changing physical properties of the plasma trapped in those fields, particle accelerations, and the relationship between the preflare and the main activities.

It is imperative that we improve our knowledge of the magnetic field and plasma conditions in current sheets during the preflare phase in order to resolve the flare problems. Such studies can be guided by radio observations, which often provide details concerning dynamical plasma processes not visible at other wavelengths. Especially in the microwave frequency range, radio signatures are always regarded as direct signals of the flaring primary energy-releasing and particle accelerations. Preflare activities in the microwave range were long ago discovered to consist of changes in the intensity and/or polarization of the microwaves emitted from an active region some tens of minutes before the onset of a flare (Hurford \& Zirin 1982; Kai et al. 1983; Xie et al. 1994). Recently, many fine structures with narrow bandwidth and short duration, which are usually superimposed on smooth background continuum emission, were recorded frequently in order to develop broadband radio spectrometers with high temporal and frequency resolution (Fu et al. 2004a, 2004b; Huang et al. 2008; Huang \& Tan 2012; Tan 2013). These are important signatures to understand energy release and particle acceleration in solar flares. Most detailed analyses of microwave fine structures reported in the literature mainly focus on the impulsive or decay phase of the flare, paying little attention to the preflare phase. Successful observations studying the preflare phase require a high sensitivity and signal-to-noise ratio for their data, and simultaneous image observations to determine the host region.

Microwave emission (especially at centimeter and decimeter wavelengths) originates in the lower corona and the chromosphere, which provides an independent means of exploring the solar atmosphere. A good observational understanding of preflare activities, based on high-sensitivity spectrograms with broadband microwaves, and high spatial and temporal resolution filtergrams in multi-wavelengths will certainly help us to understand the nature of solar flares. After a recent advanced upgrade, the Ondřejov radio spectrographs (ORSC) are able to observe solar microwave emission with high frequency resolution, high temporal resolution, and high sensitivity. Additionally, with the launch of the Solar Dynamics Observatory (SDO), we can daily obtain full disk filtergrams of the Sun from the chromosphere to the corona up to 0.5 $R_\odot$ above the solar limb with 0.6 arc-second spatial resolution and 12 second temporal resolution at EUV wavelengths with the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012). Preflare activities that are recorded by ORSC and AIA simultaneously will provide a unique opportunity to reveal some key flare processes, such as the causality consequence, the actual trigger mechanism, and the primary energy release region. Moreover, despite the differences in size, energy, and morphology, solar eruptions in the solar atmosphere, such as flares, filament eruptions, and coronal mass ejections (CMEs), may be different aspects of a common physical
process involving plasma ejection and magnetic reconnection (e.g., Shibata, 1999; Priest & Forbes 2002). Therefore, the preflare activities are important not only for the initiation of flares, but also for all accompanying eruptive phenomena. Studying the distinct preflare phenomena could shed new light on one of the most important puzzles of space weather, that is, understanding why flares, filaments, and CMEs erupt.

From a theoretical point of view (for understanding the flare phenomenon) and a practical point of view (for forecasting where and when a flare will occur), it is essential to make a closer study of the preflare conditions in active regions. In this work, we report observations of preflare activities in the form of the microwave fine structure of four solar flares. Here, preflare activity is defined as a transient event preceding the GOES flare at the site of the flare region for which direct physical associations with the flare are implied. The observations and sample are presented in Section 2. The main results are addressed in Section 3. Conclusions and discussions will be provided in Section 4.

2. OBSERVATIONS AND SAMPLE

2.1. Observations

In this work, the preflare microwave fine structures were recorded by ORSC, which are broadband spectrometers located at Ondřejov, the Czech Republic (Jiřička et al. 1993). ORSC includes two dedicated spectrographs, RT4 and RT5. The frequency ranges of RT4 and RT5 are from 2.0 to 5.0 GHz and 0.8 to 2.0 GHz, respectively. Following an advanced upgrade in 2006, ORSC now has high spectral and temporal resolution, and high sensitivity in the broadband microwave frequency range. The spectral resolution is 5 MHz and the temporal resolution is 10 ms.4

In order to obtain a comprehensive understanding of the preflares, we also use other multi-wavelength observations from several instruments, including the following.

1. Phoenix-4 at Bleien Observatory. Since all preflare activity in our sample occurred on the low frequency side of RT5, we adopt radio observations in the low frequency range of 200–800 MHz recorded by a seven meter dish with a crossed logarithmic periodic antenna (Phoenix-4) at Bleien observatory (east) to obtain the full information on the spectral properties of radio bursts in preflares. Its frequency resolution is several MHz and its temporal resolution is 5–32 (164 MHz) and 2–125 (432 MHz). NRH observations will help to determine the source region of the radio emission.

2. Atmospheric Imaging Assembly on Solar Dynamics Observatory (AIA/SDO). AIA/SDO provides multiple simultaneous high-resolution full-disk images of the corona and transition region up to 0.5 R⊙ above the solar limb with 1.5 arcsecond spatial resolution and 12 s temporal resolution. Seven narrow EUV bandpasses centered on specific lines have been employed: Fe xviii (94 Å), Fe viii, X xi (131 Å), Fe ix (171 Å), Fe xii, X xiv (193 Å), Fe xiv (211 Å), He ii (304 Å), and Fe xvi (335 Å). The temperature diagnostics of the EUV emissions cover the range from 6 × 10⁷ K to 2 × 10⁷ K. AIA observations provide topological evolution information for the related source regions associated with the preflare activities. We choose four wavelengths of 1600 Å, 304 Å, 171 Å, and 193 Å, which contain the emission from the solar photosphere, chromosphere, corona, and hot flare plasma.

3. Nancay Radioheliograph (NRH). NRH is operated by the Observatoire de Paris at 10 frequencies between 150 and 450 MHz. This instrument consists of 44 antennas with sizes ranging from 2 to 10 m spread over two arms (EW and NS) with respective lengths of 3200 m and 2440 m. The resolution of the two-dimensional (2D) images depends on the frequency and the season. Roughly speaking, the resolutions are approximately 5–3:2 (164 MHz) and 2:2–1:25 (432 MHz). NRH observations will help to determine the source region of the radio emission.

4. The RHESSI. RHESSI is a NASA Small Explorer Mission, launched on 2002 February 5. It images solar flares from soft X-rays (3 keV) to gamma-rays (up to 17 MeV) and provides high-resolution spectroscopy up to gamma-ray energies of 17 MeV. Furthermore, it is able to obtain spatially resolved spectroscopy with high spectral resolution. From RHESSI observation, we may determine information about the non-thermal processes associated with the preflares. (Lin et al. 2002).

5. Soft X-ray (SXR) telescope on Geostationary Operational Environmental Satellites (GOES). SXR/GOES provides continuous monitoring of the full-disk solar SXR intensity in the 0.5–4 Å and 1–8 Å channels with a minimum cadence of 2 s. This is the most important indicator showing the whole process of solar flares.

2.2. Sample

The sample of radio bursts that we studied in this work was obtained during the time period from 2010 April (after the launch of SDO) to 2013 June. During this time period, 2996 flares (including C-, M, and X-class flares) were recorded by GOES and 240 radio bursts were recorded by ORSC. Out of the 240 radio bursts, 156 radio bursts were associated with GOES flares. Out of the 156 flares associated with radio bursts, 18 radio bursts started prior to the associated GOES flares. In order to determine the spatial correlation between radio bursts and flares without corresponding image observations, we deleted events that occurred on the solar surface with numerous active regions at first. After this step, 14 events remained. For these 14 events, the following steps were used to confirm the spatial correlation between radio bursts and the corresponding flare events. (1) Radio images from the Nancay Radioheliograph (NRH) were used if the preflare radio bursts occurred at NRH observational frequencies. Even though the spatial resolution of NRH is approximately several arcminutes, it is sufficient to determine whether or not a radio burst has the same host region as the flare. (2) The flare host region is an isolated active region on the solar disk and there are no other activities that can be identified from SDO observations at wavelengths of 304 Å and 193 Å. Finally, four flares remained. We show the event list in Table 1. Out of the four events, three events (the C3.2 flare event on 2010 August 14, the C5.5 flare event on 2011 December 25, and the M1.9 flare on 2012 May 07) can be confirmed by both criteria. The C4.4 flare on 2010 August 1 is confirmed by SDO data.

4 The quick look images can be obtained online at http://www.asu.cas.cz/~radio/info.htm.
Figure 1. (a) Line-of-sight magnetograph observed by HMI with NRH contours (228 MHz); (b) running difference image of 304 Å observed by AIA with NRH contours (228 MHz); (c) time profile of the radio flux in the flare host region at 228 MHz observed by NRH. The yellow and green shading outlines the integration time of the NRH contours in panels (a) and (b).

Table 1

| Date       | Position | GOES Flare | Radio Burst | HXR |
|------------|----------|------------|-------------|-----|
|            |          | Class      | Start (UT) | Peak (UT) | End (UT) | Type | Start (s) | $t_{\text{high}}$ (s) | $f_{\text{low}}$ (GHz) | $f_{\text{high}}$ (GHz) | $P$ (s) | 12–25 KeV | EUV |
| 2010 Aug 1 | N20E36   | C3.2       | 07:56      | 08:26     | 09:46    | dot   | 07:53:50 | 0.9                     | <0.8                  | I         | LB      |     |
| 2010 Aug 14| N17W52   | C4.4       | 09:41      | 09:59     | 11:10    | dot   | 09:37:12 | 40                      | 0.9                   | 0.5       | I       | FE, LB |
| 2010 Aug 14| N17W52   | C4.4       | 09:41      | 09:59     | 11:10    | dot   | 09:40:00 | >2.0                    | 0.35                  | I         |         |     |
| 2011 Dec 25| S32W16   | C5.5       | 08:49      | 08:55     | 09:01    | QPP   | 08:48:35 | 3.5                     | 1.35                  | 1.035     | 0.2     | I       | FE, LB |
| 2011 Dec 25| S32W16   | C5.5       | 08:49      | 08:55     | 09:01    | QPP   | 08:48:35 | 2.3                     | 1.00                  | 0.6       | 0.2     | I       |     |
| 2011 Dec 25| S32W16   | C5.5       | 08:49      | 08:55     | 09:01    | QPP   | 08:48:35 | 0.5                     | 1.00                  | 0.6       | 0.1     | I       |     |
| 2011 Dec 25| S32W16   | C5.5       | 08:49      | 08:55     | 09:01    | QPP   | 08:48:35 | 1.2                     | 1.00                  | <0.8      | 0.1     | I       |     |
| 2011 Dec 25| S32W16   | C5.5       | 08:49      | 08:55     | 09:01    | QPP   | 08:48:35 | 1.4                     | 1.10                  | <0.8      | 0.3     | I       |     |
| 2011 Dec 25| S32W16   | C5.5       | 08:49      | 08:55     | 09:01    | QPP   | 08:48:35 | 0.5                     | 1.00                  | <0.72     | 0.1     | I       |     |
| 2011 Dec 25| S32W16   | C5.5       | 08:49      | 08:55     | 09:01    | QPP   | 08:48:35 | 1.05                    | <0.8                  | 0.3       | I       |     |
| 2012 May 7 | S19W46   | M1.9       | 14:03      | 14:31     | 14:52    | dot   | 14:02:09 | 10.4                    | 1.45                  | 0.5      | 1/      | FE, LB |
| 2012 May 7 | S19W46   | M1.9       | 14:03      | 14:31     | 14:52    | dot   | 14:02:24 | 18.4                    | 1.45                  | 0.55      | /       |     |

Note. $\Delta t$: duration of the burst group; \(/\): no RHESSI data; I: RHESSI flux (12–25 keV energy band) increases associated with the preflare radio bursts; FE: filament eruption; LB: loop brightening.

3. ANALYSIS RESULTS

3.1. The Properties of the Preflare in a C5.5 Event on 2011 December 25

On 2011 December 25, a C5.5 flare occurred in a newly emerging active region NOAA 11387 (S32W16). According to the GOES record, the flare started at 08:49 UT, peaked at 08:55 UT, and ended at 09:01 UT. It is an impulsive flare with an impulsive phase lasting about six minutes. According to ORSC records, the main radio burst associated with the GOES flare appeared around 08:48:35 UT. Meanwhile, there are some impulsive radio bursts with relatively weak intensity and very short duration that occurred prior to the main radio burst. Figure 1(a) is the line-of-sight magnetic field observed by HMI with the flare host region outlined by the white square. This figure shows that the active regions on the solar surface at that time are few and far apart. Figure 1(b) is a 304 Å running difference image observed by AIA at 08:47:20 UT. Its base image was taken at 08:46:40 UT. It shows that the initial brightening, which occurred in the flare host region and was temporally correlated with the microwave burst, is a unique activity on the solar surface at that time. This event was observed by NRH at several frequencies. The blue contours in Figures 1(a) and (b) show the source regions of the microwave observed by NRH at 228 MHz. They are set at 50% and 80% of the maximum brightness. The NRH contours shown in Figure 1 were integrated during the time periods from 08:47:12 to 08:47:22 UT (Figure 1(a)) and from 08:47:32 to 08:47:42 UT (Figure 1(b)).
These time periods were also outlined with yellow and green shading in Figure 1(c), respectively. Contours in Figure 1(b) show a unique source region that is persistent and slowly varying during NRH observations. Even during the flaring phase, this source region can be identified from time to time. The contours in Figure 1(a) show two additional transient source regions. The source region located on the south side is co-spatial with the flare host region. The time profile of the flare host region recorded by NRH at 228 MHz was shown in Figure 1(c). In plotting this time profile, we counted only those pixels whose flux is greater than 50% of the maximum. This time profile shows that the emission from the source region changes very rapidly during the preflare phase and then is maintained at a high level during the flare. It is known that active regions can emit radio signals without a flare at 228 MHz, possibly through the thermal bremsstrahlung mechanism, but it varies very slowly. Therefore, we suggest that the rapidly varying emission that is emitted from the flare source region is related to the preflare activity.

3.1.1. Microwave Spectral Structures in the Preflare

Figure 2(a) shows the dynamic microwave spectrum during the preflare and impulsive phases in the frequency range from 0.2 to 1.4 GHz. The black vertical line indicates the starting time of the flare. The microwave spectrum shows that several independent radio bursts appear about 2 minutes before the GOES flare, i.e., around 08:47:04 UT. They have relatively weak intensity with very short durations (several seconds). Around 08:48 UT, less than one minute before the flare, the main radio burst begins to appear. The main burst is a slow drifting structure with a long duration (more than six minutes) and strong intensity. The spectrum shows that the preflare microwave bursts are in the form of individual bursts. Meanwhile, the early phase of the main burst begins prior to the flare and lasts throughout the entire impulsive phase.

The temporal profile of the radio bursts at 0.85 GHz recorded by ORSC and at 0.7 GHz recorded by Phoenix-4 are shown in Figure 2(b). The former profile shows an abundance of substructures while the latter does not. Moreover, the flux of the preflare is only about 7% of the maximum intensity of the main burst.

The detailed dynamic spectra of the independent radio bursts recorded by ORSC during the period from 08:47:16 to 08:47:39 UT are expanded in Figure 3(a). Based on the spectrum, six groups of drifting structures can be identified. The frequency bandwidth of the bursts were calculated using following steps. First, we integrated the radio burst throughout its frequency bandwidth of the bursts were calculated using following steps. First, we integrated the radio burst throughout its frequency bandwidth. The spectra are defined as the frequencies at which the flux is greater than the background flux. Meanwhile, the duration is defined as the time interval wherein the radio flux is greater than the background flux. The middle panel shows the first group burst with fully temporal resolution. The radio flux at 1.2 GHz were overlapped in Figure 3. The transverse line indicates the background flux at that frequency. Stars represent the start and end of the burst. The time profile of the radio burst group occurred around 08:47:16 UT with a duration of about 3.5 s and a frequency range from 1.035 GHz to 1.35 GHz. The properties of the other burst groups are listed in Table 1.

Meanwhile, Figure 3(b) shows that the radio burst is composed of many drifting pulsations. These pulsations scatter over the image along the temporal axis with different time intervals during the early stage and then overlap with each other. Careful examination of the first few pulses revealed that they first occur at low frequencies and then shift to high frequencies rapidly. The magnitude of the frequency drifting rate is about $-10$ GHz s$^{-1}$. For a single pulse, the duration is approximately several tens of milliseconds and the bandwidth is about 0.3 GHz. To study the periodic nature of the pulsating structure, we adopt a wavelet analysis for the observational data. The wavelet power spectrum shown in Figure 3(c) was computed from time series at a frequency of 1.15 GHz. The solid black contour is the 95% confidence level for the red noise. Areas outside the contour are regions of the wavelet spectrum where edge effects become important, i.e., the so-called cone of influence. The wavelet power spectra show that there is a strong periodic component at 0.2 s. This periodicity is relatively stable. There is another periodic component within the 95% confidence level that occurs at 0.4 s. Two seconds later, these two periodic components shift slightly from a period near 0.4 s to a period closer to 0.7 s, and from a period near 0.4 s to a period closer to 0.3 s, respectively.

3.1.2. The Properties of the Source Region in the Preflare

In order to obtain information on the source region in the preflare, here we adopt multi-wavelength observations. Figure 4 shows the dynamic evolution of the preflare activities in the UV and EUV imaging observations recorded by AIA/SDO. The magnetic field obtained by Helioseismic and Magnetic Imager on board SDO (HMI/SDO) was overlaid on the 1600 Å and 171 Å images around 08:44 UT, with blue representing negative polarities and red representing positive polarities. The most distinctive feature of the host region is that there is an S-shaped filament (positive magnetic helicity) crossing over the neutral line with ends near (260, −340) and (310, −330) in the solar disk coordinate system. The presence of an S-shaped filament is regarded as evidence for current-carrying twisted or sheared magnetic fields that possess magnetic helicity. Active regions with this kind of morphology are more likely to erupt than others (Canfield et al. 1999).

The beginning of the eruption is marked by a very gradual but noticeable rise in the right part of the S-shaped filament as early as 08:42 UT. The displacement of the filament was traced along a slice as indicated by the white vertical line in the 193 Å image at 08:44:43 UT. A time-distance diagram of the filament along the slice was shown in Figure 2(c). This diagram shows that the slow rise of the filament can be best observed between 08:42–08:47 UT with the steady upward motion of the filament. Its speed is around 20 km s$^{-1}$. The initial intensity enhancements of the flare can be found easily from the 1600 Å image, which is situated under the middle of the filament around 08:44:43 UT. The EUV brightening propagated in the direction along the polarity inverse line from the initial brightening area and extended away from the polarity inverse line. The
development of two flare ribbons can be seen clearly in 1600 Å images. Brightenings extended in the 171 Å and 193 Å images associated with the two ribbons are the dynamic evolution loops in the low atmosphere which are located under the filament. The microwave bursts associated with the flaring process occurred around 08:47 UT. The filament speed was found to increase around the same time and to reach a maximum of 200 km s\(^{-1}\) around 08:51 UT.

We analyzed the X-ray spectrum of the preflare brightening observed with RHESSI by means of imaging spectroscopy with the Object Spectral Executive (Dere et al. 1997; Landi et al. 2006). Figure 5 shows the spectrum of thermal and non-thermal X-ray emission associated with the individual bursts during the period from 08:47 to 08:48 UT. The thermal (low-energy) portion is fitted with the variable thermal component, while the non-thermal (high-energy) portion is fitted with a single power

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**Figure 2.** (a) Dynamic radio spectrum of the 2011 December 25 event at 0.2–1.6 GHz; the vertical lines in all panels represent the start of the GOES flare. (b) Temporal profiles of radio bursts at 0.7 and 0.85 GHz. (c) Red line: time derivative of the GOES X-ray intensity profile at wavelength of 1–8 Å; black line: RHESSI time profile in the 12–25 KeV energy band. (d) Temporal profile of filament displacements (black stars) and velocity (red stars).
law. Figure 5 shows that at energies above \( \sim 9 \) KeV, the non-thermal contribution dominates over the thermal component. The temporal profile of non-thermal emission recorded by RHESSI in the 12–25 KeV energy band is shown in Figure 1(c). Meanwhile, the red curve shows the time derivative of the GOES 1–8 Å flux. Both curves show an obvious increase immediately after the first group of microwave bursts. The RHESSI flux increase in the preflare phase is small, and so the integration time of the flux curve in Figure 2(d) is 4 s. The integration time of RHESSI is too long to find a counterpart of the QPP in RHESSI observation. However, the microwave QPPs, which occurred just before the maximum of an X6.9 class flare, accompanying hard X-ray QPPs were studied by Tan & Tan (2012).

The X-ray brightening between 08:47–08:48 UT, observed at energies of 3–6 keV (red), 6–12 keV (blue), and 12–25 keV (green), are overlaid on 304 Å, 171 Å, and 193 Å images around 08:47 UT. Contour levels are set at 60% and 80% of the maximum brightness of each energy band. These images reveal the presence of a single source in 3–6 keV and 6–12 keV. The single source at a difference energy band was found located on the polarity inversion line and spatially coincident with the initial brightening. The HXR emission in the 12–25 keV energy band has two sources. One source is spatially consistent with the low-energy sources, which covers the initial brightening at the preflare phase and located on top of the two ribbons. The figure indicates that the maximums of X-ray sources at softer energies (3–6 keV and 6–12 keV) and harder energies (12–25 keV) are at the tops of loops (which may be formed below the rising filament). The other source in the 12–25 keV energy band encircles the foot of the other loops. Meanwhile, no intensity enhancement at EUV wavelengths (1600 Å, 171 Å, and 193 Å) was identified to be spatially corrected with this source.

These X-ray sources remained at the same place throughout the entire flaring process.

Briefly, in the preflare phase of the C5.5 event on 2011 December 25, microwave QPPs with periods of subsecond appeared in the 0.6 GHz–1.35 GHz frequency range. Accompanying these microwave QPPs was nonthermal hard X-ray emission, and the motion of a sigmoid filament was observed by multiple wavelength imaging observations.

3.2. Properties of Preflares in the Other Three Events

Here, we present the other three flare events that are also discerned to have microwave spectral fine structures in their preflare phases.

3.2.1. C3.2 Event on 2010 August 1

The C3.2 flare on 2010 August 1 occurred at the heliographic location 20N 36E. The flare started at 07:56 UT, peaked at 08:26 UT, and ended at 09:46 UT. This was a long duration flare with an impulsive phase lasting for 30 minutes. Figure 6(a) shows the dynamic microwave spectrum during its preflare and impulsive phases in the frequency range from 0.2 GHz to 2.0 GHz. Since the microwave flux varies greatly during the flare period and the sensitivity of two instruments is different, the spectrum is shown in different contrasts to show the fine structures of the microwave bursts in difference phase. The figure indicates that the maximums of X-ray sources at softer energies (3–6 keV and 6–12 keV) and harder energies (12–25 keV) are at the tops of loops (which may be formed below the rising filament). The other source in the 12–25 keV energy band encircles the foot of the other loops.

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Figure 4. Dynamic activities observed by AIA/SDO at wavelengths of 1600 Å, 171 Å, and 193 Å in the preflare phase of the event on 2011 December 25. The magnetic field observed by HMI/SDO was overlaid on 1600 Å and 171 Å images at 08:44:36 UT. Snapshots of AIA 171 Å and 193 Å around 08:47 UT were overlaid by contours indicating RHESSI emission at 3–6 keV (red), 6–12 keV (blue), and 12–25 keV (green). Contour levels are set at 60% and 80% of the maximum brightness for each individual image. The vertical line in the 193 Å image at 08:44:36 UT represents the slice along which the displacement of the filament was calculated.
burst that extends to the main burst. Meanwhile, the radio burst in ORSC first appears on the low frequency side and is confined to a narrow frequency band for several minutes. Its counterpart with the development of the flare, the intensity of the radio burst increases and the frequency band is extended.

The simultaneous hard X-ray flux recorded by RHESSI in the 12–25 KeV energy band was shown in Figure 6(b) as a blue curve. This figure shows that the hard X-ray flux begins to increase at 07:55 UT. The black curve shows the time derivative of the GOES 1–8 Å flux.

The fully temporal resolution dynamic spectrum during the time period from 07:55:20 to 07:55:23 is shown in Figure 6(c). The vertical black line in Figures 6(a) and (b) indicates the time point shown in Figure 6(c). The radio flux at 0.83 GHz overlaps with the spectrum and the horizontal line shows the background flux. From the spectrum, it is easy to find the microwave spectral fine structures in the form of dots scattering in the frequency range of 0.8–0.9 GHz. The dot bursts appear as a group of individual bursts with short durations and narrow frequency bandwidths. The figure shows that for the single dot burst, the time period is approximately several tens of milliseconds and the frequency range is several tenths of MHz. In association with the development of the flare, these dots occurred more frequently and were brighter, and they extended from the low frequency side to the high frequency side. Figures 6(d)–(f) show the initial brightening at EUV wavelengths in the preflare phase and the bright flare loops in the impulsive phase of the flare observed by AIA/SDO.

### 3.2.2. C4.4 Event on 2010 August 14

The C4.4 flare event on 2010 August 14 appeared near the western limb of the solar disk (N17W52) and was associated with a filament eruption. It is a long duration flare with an impulsive phase as long as 18 minutes. The erupting filament is located along the boundary of two active regions as a sigmoid shape observed by EUV images from AIA/SDO. The beginning of the activity can be marked as the slow rise of the filament, which occurred about 40 minutes before the GOES flare. Figure 7(a) shows the dynamic microwave spectrum during the preflare and impulsive phases in the frequency range from 0.2 GHz to 2.0 GHz. The black line marks a weak, short duration radio burst that occurred about four minutes before the flare. The GOES flux in the 1–8 Å energy band is shown by the black curve. The blue line indicates the beginning of the flare. Figure 7(b) shows the time derivative of the GOES flux in 1–8 Å (black curve) and the RHESSI flux in the 12–25 KeV energy band (blue curve). Both curves show the slow increase of the flux in the preflare phase. The microwave fine structure in the preflare phase was shown in Figure 7(c). The radio flux at 0.87 GHz is overlapped on the spectrum and the horizontal line shows the background flux. The figure shows a group of dot bursts near a frequency of 0.8 GHz. The frequency bandwidth for each single dot is approximately several tenths of MHz, and the duration is approximately several tens of millisecond. Figure 7(d) shows the morphology of the filament at its initial activities. Figure 7(e) shows the filament eruption during the preflare microwave bursts.

#### 3.2.3. M1.9 Event on 2012 May 7

The M1.9 flare event on 2012 May 7 was also a long duration event with an impulsive phase lasting 28 minutes. Figure 8(a) shows the dynamic microwave spectrum of the flare from the very beginning to its peak. The figure shows that some weak and independent radio bursts occurred just one minute before the flare in the frequency range 0.55–1.4 GHz. The fine structures of the preflare microwave burst are shown by the expanded fully temporal resolution spectrum in Figure 8(b). The figure shows fine structures in the form of dots crowded in a narrow band. For a single dot, the bandwidth is approximately several tenths of MHz, and the duration is approximately several tens of millisecond. Figures 8(c)–(e) show that the eruption begins as the activity of a small filament located along the margin of the host region, as indicated by the arrows. The filament cannot be identified in 193 Å before its eruption, but it can be identified in 193 Å as some brightening fiber with obvious twisting during the eruption.

### 3.3. Brief Summary of Observational Results

We have studied the properties of microwave fine structures in the preflare phase and associated activities in the source regions observed at multiple wavelengths (such as the hard X-rays of RHESSI, the UV and EUV of AIA/SDO, etc.). The results derived from our analysis of the four sampled events are summarized in Table 1. The main observational results are as follows.

1. There are some microwave bursts with spectral fine structures occurring in the preflare phase of the mentioned flare events. These fine structures appeared about one to four minutes before the start of the GOES flares in the flare host region, for which direct physical associations with flares are implied. Among the four events, very short period QPPs occurred in one short duration flare (C5.5 flare on 2011 December 25), while small-scale bursts, like dot burst groups, occurred in the other three long duration flares (the C4.4 flare on 2010 August 1, the C3.2 flare event on 2010 August 14, and the M1.9 flare on 2012 May 7).
2. There is only one type of microwave spectral fine structure that was identified in the preflare phase for each flare. The microwave QPPs appeared about two minutes before the flare. Their durations are in the time period from several tenths of a second to several seconds, and their frequency bandwidths are in the range of several hundred MHz. Their periods are of several tenths of a second, which belong to very short period QPPs. Meanwhile, the microwave dot bursts appeared about one to four minutes before the flare. They are all in a great cluster with a duration longer than 10 s. Meanwhile, the duration and frequency range for each dot is approximately several tens of milliseconds and several tenths of MHz.

3. All four events, except for one that occurred in the RHESSI night time, have an obvious HXR flux enhancement. As for the C5.5 flare on 2011 December 25 accompanying the microwave QPPs in the preflare, the RHESSI HXR images were obtained in 3–6 keV, 6–12 keV, and 12–25 keV. It shows the presence of a single source in 3–6 keV and 6–12 keV and double sources in 12–25 keV. The RHESSI sources were located on the polarity inverse line and near the initial brightening in the UV/EUV images.

Figure 6. Flare event on 2010 August 1. (a) The dynamic radio spectrum. The black curve is the GOES flux in the 1–8 Å energy band. The blue vertical line indicates the start of the GOES flare. (b) The blue curve is the RHESSI counts at the energy band of 12–25 KeV and the black curve is the derivative of the GOES soft X-ray flux in the 1–8 Å energy band. (c) The dynamic radio spectrum with fully temporal resolution during the period indicated by the black vertical line in panels (a) and (b). (c)–(e) Dynamic evolution of the event observed by AIA.
4. From SDO observations, we found that for all events, the beginning of the flare can be marked by a filament rise or plasma ejection, simultaneously associated with loop brightening or loop interactions.

4. CONCLUSIONS AND DISCUSSIONS

This work investigated a series of solar flares and confirmed the relationships between the preflare radio bursts and the flare activity in four flares. Based on our investigation, we find that there are several observational activities occurring several minutes before the beginning of the flare. These activities include the following.

1. Microwave bursts with spectral fine structures at relatively weak intensity and very short timescales. These fine structures occurred in the frequency range 0.3 GHz–1.5 GHz, including microwave QPPs with very short periods of 0.1–0.3 s and dot bursts with millisecond timescales and narrow frequency bandwidths.
2. Filament motions, especially those which behaved as a sigmoid filament ascending, plasma ejections, and plasma loop brightening. These motions can be observed by the EUV images of AIA/SDO.

3. Non-thermal processes, such as the HXR enhancement in the energy channel of 12–25 keV observed by RHESSI or the rapid growth of the temporal derivative of the GOES soft X-ray flux.

In fact, these three different observational activities are essentially closely related to each other. Both the subsecond microwave spectral fine structures and the HXR enhancements indicate electron acceleration and primary energy release. Consequently, these releases of energy and the energetic electrons may trigger plasma motion in the source region and result in the ascending sigmoid filament, plasma ejections, and plasma loop brightening that can be observed by EUV imaging observations.

Previous literature showed that microwave bursts with spectral fine structures frequently occurred in the impulsive and decay phases of solar flares (Chernov 2006; Huang et al. 2008; Huang & Tan 2012). In this work, we find that microwave bursts with spectral fine structures also occur in the preflare phase, especially in the microwave QPP on subsecond timescales and dot bursts on millisecond timescales, which have similar properties as observed in previous works. Many people have pointed out that it is very difficult to adopt the general MHD oscillation mechanism to explain the formation of microwave QPP with subsecond timescales (see review of Aschwanden 1987; Nakariakov & Milnikov 2009). Tan et al. (2007) proposed that the resistive tearing-mode oscillations in current-carrying flare loops may modulate the nonthermal microwave emission and form QPP at subsecond periods. In this new mechanism, the plasma loops carry electric currents with finite resistivity, which may excite resistive tearing-mode instability and produce a series of magnetic islands. Electrons can be accelerated near the X points between each of two adjacent islands and form energetic electron beams. The plasma may produce coherent emission when the energetic electron beams interact with the adjacent plasmas. When acceleration from X points is modulated by the tearing-mode oscillation, microwave QPP can occur (Tan et al. 2007). The occurrence of subsecond microwave QPP implies that the electron acceleration is quasi-periodic. When acceleration from X-points is stochastic, microwave dot bursts may occur with a random distribution in the spectrogram (Tan 2013). Because the acceleration site is located around each X point, it

![Figure 8. Same figure as Figure 6, but for the event on 2012 May 7.](image-url)
lasts for a very short period and occurs in a small region. The microwave QPPs with s of 0.1–0.3 s and dot bursts in the preflare reveal the following information concerning the flare source region: the flare loops carry electric currents, and therefore there is a considerable accumulation of non-potential free energy that may consequently trigger magnetic reconnection and electron acceleration in the flare source region. Therefore, energy release may take place in the preflare as well as the impulsive phase of the flares, although their intensities are relatively weaker than the latter.

When we investigate the preflare microwave signature in order to understand and predict the solar flare, we always meet two critical problems. The first is the definition of the start time of a flare, and the other is whether the preflare microwave signatures are rare or general. In this work, the start times of flares were extracted from the GOES list. The GOES satellites provide continuous monitoring of the integrated full disk solar X-ray intensity in a hard (0.5–4 Å) channel and a soft (1–8 Å) channel. The flare start defined by SXR/GOES is when four consecutive 1 minute SXR values meet all of the following three conditions: (1) all four values are above the background threshold; (2) all four values are strictly increasing; and (3) the last value is greater than 1.4 times the first value that occurred 3 minutes earlier. Meanwhile, the start time is defined as the first minute in the sequence of 4 minutes. According to this definition, it is quite natural that some small, gradual, or impulsive flux enhancements associated with small activities do exist before the GOES flare.

As for the second problem, preflare activity in the microwave was discovered as early as the 1950s by Bumba & Křivský (1959). They found that about 20% of the flares in their sample are preceded by much smaller bursts on wavelengths of 130 cm (1959). They found that about 20% of the flares in their sample were associated with the preflare microwave activities related to the subsequent main energy release. Xie et al. (1994) studied the microwave flux variation of flares at four frequencies (1.42, 2.13, 2.84, 4.26 GHz) and found that approximately 30% of flares are preceded by narrow band preflare activity. Meanwhile, they found that the preflare activity occurs at low frequencies more frequently than at high frequencies. Rare previous studies show that radio preflare activity does not occur in a majority of cases. Hurford et al. (1984) have shown that preflare bursts may occur in such narrow spectral bands that they can easily be missed by instruments responding to a single frequency. In the present work, we found that out of the 156 flare-associated radio bursts, 12% (18 events) were preceded by microwave fine structures. For the lack of corresponding image observations, only four events are confirmed to be located in the same host region as the main flare. Such preflare activities appear to be as a narrow band (not greater than 1 GHz), short duration (the longest duration is 40 s for impulsive radio burst), and weak intensity (about 10% of the maximum flux of the main flare). Therefore, they can easily be missed by narrow band spectrometers.

Preflare activity that appeared in multiple wavelengths have been considered as a potential clue to understanding the physical conditions in the solar atmosphere that lead to a flare eruption. Especially for the spectral fine structures in microwave bursts, the preflare activity can provide insight into the magnetic fields, plasma condition, initial motion and interaction of the plasma loops, and the primary magnetic reconnection process in the flare cradle regions. In addition, as the microwave signals are much more sensitive than the other wavelength observations, a systematic summary of the preflare characteristics can help us to predict the catastrophic solar eruptive events. However, since there are no corresponding imaging observations at the related frequencies in our study, some important parameters of the source regions, such as the spatial scale, height, and configurations of the source region, are not clear. Without the polarization information, the parameters of the magnetic field and plasma in the source region cannot be deduced either. This information is very important for us to establish the direct connections between the microwave bursts and multi-wavelength activity. The forthcoming snapshot imaging observations at broad frequency bandwidths of the next generation of radio telescopes (CSRH, 0.4–15 GHz, Yan et al. 2009; FASR, 0.05–20 GHz, Bastian 2003) will provide much more abundant and confirmable information concerning the preflares. We will conduct further investigations on this topic and obtain further insight on the flare triggering mechanism.

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