MICROWAVE QUASI-PERIODIC PULSATION WITH MILLISECOND BURSTS IN A SOLAR FLARE ON 2011 AUGUST 9

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Received 2011 December 10; accepted 2012 February 1; published 2012 March 19

ABSTRACT
A peculiar microwave quasi-periodic pulsation (QPP) accompanying a hard X-ray (HXR) QPP of about 20 s duration occurred just before the maximum of an X6.9 solar flare on 2011 August 9. The most interesting aspect is that the microwave QPP consists of millisecond timescale superfine structures. Each microwave QPP pulse is made up of clusters of millisecond spike bursts or narrowband type III bursts. There are three different frequency drift rates: the global frequency drift rate of the microwave QPP pulse group, the frequency drift rate of the microwave QPP pulse, and the frequency drift rate of individual millisecond spikes or type III bursts. The physical analysis indicates that the energetic electrons accelerating from a large-scale highly dynamic magnetic reconnecting current sheet above the flaring loop propagate downward, impact the flaring plasma loop, and produce HXR bursts. The tearing-mode (TM) oscillations in the current sheet modulate HXR emission and generate HXR QPP; the energetic electrons propagating downward produce Langmuir turbulence and plasma waves, resulting in plasma emission. The modulation of TM oscillation on the plasma emission in the current-carrying plasma loop may generate microwave QPP. The TM instability produces magnetic islands in the loop. Each X-point will be a small reconnection site and will accelerate the ambient electrons. These accelerated electrons impact the ambient plasma and trigger the millisecond spike clusters or the group of type III bursts. Possibly, each millisecond spike burst or type III burst is one of the elementary bursts (EBs). A large number of such EB clusters form an intense flaring microwave burst.

Key words: magnetic fields – Sun: flares – Sun: radio radiation

Online-only material: color figure

1. INTRODUCTION
On 2011 August 9, a powerful X6.9 solar flare took place in active region NOAA 11263 near the west limb on the solar disk (left panel of Figure 1, observed at an EUV wavelength of 171 Å by the Atmospheric Imaging Assembly on Solar Dynamics Observatory, AIA/SDO). The X6.9 flare event starts at 08:00 UT, reaches maximum at 08:04 UT, and ends at 08:14 UT (top-right panel in Figure 1). It is the largest flare event in the current solar Schwabe cycle, and it resulted in a coronal mass ejection. A strong microwave burst (right panels of Figure 1) that accompanied this flare was observed at a frequency of 2.60–3.80 GHz by the Chinese Solar Broadband Radio Spectrometer in Huairou (SBRS/Huairou). The microwave burst starts at 08:01 UT and ends at 08:07 UT, lasting only about 6 minutes. For comparison, we know that the microwave burst associated with other X-class flare events always has a long duration of several tens of minutes or 1–2 hr; for example, the X3.4 flare event on 2006 December 13 has a duration of 110 minutes (Tan et al. 2010). In the peculiar short duration of the microwave burst in the X6.9 flare event, the most prominent feature is the quasi-periodic pulsation (QPP) and its accompanied superfine structures of millisecond timescales. The main task of this work is to investigate the peculiar features of the microwave QPP and its related physical processes in detail.

It is well known that the flare-related QPP, especially at the microwave frequency range, can be a valuable diagnostic tool for in situ conditions in the flaring source region, and the investigations can provide unique insight into coronal plasma dynamic processes. For example, the duration of a QPP can be a measure of the plasma density inhomogeneity in the source region, the periodicity can be a measure of the diameter or the width of the inhomogeneity, and so on (Roberts et al. 1984). Many authors have studied the features and physical mechanisms from observations and theoretical models (Young et al. 1961, Gotwols 1972, Fu et al. 1990, Kliem et al. 2000, Nakariakov et al. 2003, Tan et al. 2007, etc.). Aschwanden (1987) presented an extensive review of QPP models and classified them into three groups: (1) MHD oscillations that modulate the microwave emissivity with standing or propagating waves (Roberts et al. 1984; Nakariakov & Melnikov 2009), (2) periodic self-organizing systems of plasma instability, and (3) the periodic particle accelerations. Different kinds of models can explain different timescales of QPP. Recently, a series of microwave QPPs with multi-timescales forming a broad hierarchy have also been reported; it is proposed that different timescales of QPP may have different generation mechanisms. The broad hierarchy of timescales of QPP that occurred in the same flare event may imply that there is a multi-scale hierarchy of sizes of the magnetic configurations and the timescales of the dynamic magnetic reconnection processes in the flaring region (Tan et al. 2010).

On the spectrogram of broadband microwave observations, the QPP behaves as a train of approximated almost equidistant vertical bright stripes. Each bright stripe is a QPP pulse. Generally, the previous works regarded the pulse as a relatively isolated element. So far, there have been very few works investigating whether there are some further superfine structures in each QPP pulse. Chernov et al. (2008) reported a flare event in which some pulses of the weakly rapid microwave QPP consisted completely of several small-scale narrowband drifting millisecond fibers, and the frequency drift rate of the fibers was in the range of $-160$ to $-270$ MHz s$^{-1}$. In this work, we find that each individual pulse of the rapid microwave QPP is made...
up of clusters of millisecond spike bursts or narrowband type III bursts with frequency drift rates of about 20 GHz s\(^{-1}\). We will introduce the peculiar features of the superfine structures in the QPP in Section 2 and present a physical analysis in Section 3. Finally, some conclusions are drawn in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Observational Data and Analysis Method

In this work, we mainly apply the microwave observations obtained from SBRS/Huairou to investigate the detailed peculiar features of the microwave QPP. SBRS/Huairou is an advanced solar radio telescope with super-high cadence, broad frequency bandwidth, and high frequency resolution, which can distinguish the superfine structures of microwave bursts from the spectrogram (Fu et al. 1995, 2004; Yan et al. 2002). It includes three parts: 1. 1.10–2.06 GHz (with an antenna diameter of 7.0 m, a cadence of 5 ms, and a frequency resolution of 4 MHz), 2. 2.60–3.80 GHz (with an antenna diameter of 3.2 m, a cadence of 8 ms, and a frequency resolution of 10 MHz), and 3. 5.20–7.60 GHz (which shares the same antenna as the second part, a cadence of 5 ms, and a frequency resolution of 20 MHz). Automatically controlled by a computer, the antenna points to the center of the solar disk. The spectrometer can receive the total flux of solar radio emission with dual circular polarization (left- and right-handed circular polarizations), and the dynamic range is 10 dB above quiet solar background emission. The observation sensitivity is \( S/S_\odot \leq 2\% \), where \( S_\odot \) is the standard flux value of the quiet Sun. From the Solar Geophysical Data, we can obtain the data at frequencies of 1415 MHz, 2695 MHz, 2800 MHz, and 4995 MHz, and make 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 will be used instead (Yan et al. 2002).

Similar to other congeneric instruments, such as Phoenix (100–4000 MHz; Benz et al. 1991), Ondřejov (800–4500 MHz; Jiricka et al. 1993), and Brazilian Broadband Spectrometer (200–2500 MHz; Sawant et al. 2001), SBRS/Huairou has no spatial resolution. However, as the Sun is a strong source of radio emission, a great deal of work (e.g., Dulk 1985, etc.) shows that the microwave bursts received by spectrometers are always coming from the solar active region when the antenna points to the Sun.

In order to make the QPP clearer and more reliable, we adopt the analysis method described in detail by Tan et al. (2010). With this method, we can easily obtain the microwave QPP’s related parameters, such as the period, duration, polarization degree, global frequency drifting rates (GFDR), and single-pulse frequency drifting rates (SPFDR), etc. These parameters are explained by Tan (2008). Because of the close relationships between the hard X-ray (HXR) emission and the microwave bursts (Dennis 1988), we also adopt the HXR observations obtained by the Reuven Ramaty High Energy Solar Spectroscopic Imaging (RHESSI) to make a complementary comparison.

2.2. Observational Results

During the X6.9 flare, SBRS/Huairou obtained high-quality observations at a frequency of 2.60–3.80 GHz. The right panels of Figure 1 present the profiles of the microwave flux at a frequency of 2.80 GHz with left- and right-handed circular polarizations around the flaring event. As a comparison, the profiles of GOES soft X-ray (SXR) intensities at wavelengths of 1–8 Å (GOES8) and 0.5–4 Å (GOES4) are also plotted in Figure 1. Here, we find that the main part of the microwave burst occurred in the flare rising and peak phase, and decays rapidly after the flare peak. The microwave intensity profile has two obvious enhancements; the first one is at about 08:02:04 UT and the second one is at about 08:03:56 UT. An obvious QPP occurred during 08:03:09–08:03:30 UT, in the midst of the two enhancements (marked with a thick bidirectional arrow in the right panel of Figure 1), very close to the maximum of the SXR GOES flare (08:04 UT).

A careful inspection of the RHESSI HXR observations displays that HXR emission also shows QPP features at an energy of 12–100 keV. The wavelet analysis indicates that evidence of HXR QPP is most obvious at an energy of 25–50 keV. Figure 2 presents the light curve of HXR at an energy of 25–50 keV.
RHESSI Count Flux vs Time

**Figure 2.** Light curve of hard X-ray at an energy of 25–50 keV observed by RHESSI during the QPP occurrence, which also has a feature of quasi-periodic pulsations.

during the microwave QPP occurrence, which shows that the intensity of HXR emission also has an obvious feature of QPP, and the average period is about 2.46 s, which belongs to short-period pulsation (SPP).

Figure 3 presents the microwave QPP observed by SBRS/Huairou at a frequency of 2.60–3.80 GHz. The top-left panels show the spectrum of the QPP at left- and right-handed circular polarizations, and the QPP behaves as a series of bright pulses, which indicates that the QPP can be divided into three different pulse groups: the first pulse group begins at 08:03:09 UT, ends at 08:03:17 UT, and lasts for 8 s (marked as group A); the second begins at 08:03:18, ends at 08:03:22 UT, and lasts for 4 s (marked as group B); and the third begins at 08:03:23, ends at 08:03:29 UT, and lasts for 6 s (marked as group C).

The frequency bandwidth of each pulse is in the range of 400–1100 MHz. The comparison between the left- and right-handed circular polarizations shows that the QPP is strongly right-handed circular polarized with a polarization degree of about 70%. The measurement of the time intervals between each adjacent vertical bright stripe indicates that the period of the QPP is about 0.70 s, 0.86 s, and 0.42 s at the first, second, and third pulse groups, respectively. All of them belong to broadband very short period pulsation (VSP; Wang & Xie 2000; Tan et al. 2007). Comparing the microwave and HXR, we find that the period of the microwave QPP is much shorter than that of the HXR QPP. The top-right panels of Figure 3 show the profiles of the flux intensities of the microwave QPP at left- and right-handed circular polarizations at a frequency of 2.84 GHz (upper and middle panels). This indicates that the emission enhancement at each QPP pulse with respect to the background emission is about 100–250 sfu, which demonstrates that the QPP is very obvious and strong.

The arranged patterns of microwave QPP pulse groups indicate that there are frequency drifts in each pulse group (GFDR). In order to obtain the frequency drift rate, we define the central frequency of each pulse at its central time as follows:

\[
f_{cp} = \frac{\sum (f_i \times F_i)}{\sum F_i}.
\]  

Here, the central time of the pulse is when the flux intensity approaches the maximum around the pulse. \(f_i\) is the frequency and \(F_i\) is the corresponding flux intensity which subtracts the background emission around the occurrence of the microwave QPP. The bottom of the top-right panel of Figure 3 presents the distribution of the central frequency (\(f_{cp}\)) at each QPP pulse. The dotted lines are fitted by linear least-squares methods. In QPP group A, the central frequency of QPP pulses can be fitted by a single line; the slopes of the fitted lines give an average GFDR of 53.3 MHz s\(^{-1}\). In QPP group B, the central frequency of QPP pulses can also be fitted by a single line with a GFDR of \(-78.9\) MHz s\(^{-1}\). In QPP group C, the central frequency of QPP pulses decreases slowly in the first half with a GFDR of \(-98.2\) MHz s\(^{-1}\), and then increases slowly with a GFDR of 129.5 MHz s\(^{-1}\) in the second half. It seems that some dynamic processes that occurred in the emission source region.

The bottom panels of Figure 3 present the expanded spectrograms of QPP pulse groups A (left), B (middle), and C (right) at the left- and right-handed circular polarizations, respectively, which can present the details of the superfine structures on each QPP pulse. With a careful inspection, we find that the frequency drifts also occur at each QPP pulse (SPFDR). We apply a similar method, as described in Tan et al. (2010), to determine the SPFDR. The top-left panel of Figure 4 presents examples of the method; the SPFDR can be calculated by the slope rate of the fitted lines. The top-right panel of Figure 4 plots the calculated results of the SPFDR in the whole QPP. Here, we find that all of the SPFDRs of QPP pulse group A are negative, their absolute values are in the range of 3.51–13.84 GHz s\(^{-1}\), and their average value is 7.73 GHz s\(^{-1}\). However, the SPFDRs in QPP pulse groups B and C change rapidly from negative to positive, the absolute values are from 4.38 GHz s\(^{-1}\) to 14.61 GHz s\(^{-1}\) in group B and 2.91 GHz s\(^{-1}\) to 26.25 GHz s\(^{-1}\) in group C, and their average value is about 7.78 GHz s\(^{-1}\) in group B and 15.88 GHz s\(^{-1}\) in group C. In addition, almost all of the SPFDRs are at least two orders higher than that of GFDR in the QPP pulse groups.

At the same time, a careful inspection of each individual QPP pulse presents another important feature: each pulse has a superfine structure in shorter timescales. The expanded spectrograms (the bottom panels of Figure 3) present the details of the millisecond superfine structures in each QPP pulse. Here, we find that almost all of the microwave QPP pulses are structured with clusters of millisecond spike bursts. The bandwidth of the spike bursts is in the range of 20–60 MHz, the duration is in the range of 8–24 ms (however, being restricted by the 8 ms cadence of the telescope, we cannot know if there are any spike bursts with durations shorter than 8 ms; in fact, some spike bursts are only observed by a single data point, and this evidence is enough to lead us to believe that some spike bursts may have a lifetime shorter than 8 ms), the flux intensity is in the range of 50–100 sfu, and the polarization degree is close to 100% (bottom-left panel of Figure 4). In addition, part of the millisecond spikes shows obvious evidence of a fast negative frequency drifting rate with values ranging from \(-18\) GHz s\(^{-1}\) to \(-25\) GHz s\(^{-1}\), with an average of \(-20\) GHz s\(^{-1}\).

The bottom-right panel of Figure 4 shows the expanded profile at a frequency of 3.23 GHz of a QPP pulse, which shows that the QPP pulse is structured with a cluster of type III bursts. The type III bursts form a drifting pulsating structure with a local GFDR of about 2.91 GHz s\(^{-1}\) and a pulsating period of about 0.16 s. As for each individual type III burst, the instantaneous duration is about 8–24 ms, the frequency bandwidth is about 500–1000 MHz, the polarization degree is above 85%, the frequency drift rate ranges from \(-14.58\) GHz s\(^{-1}\) to \(-20\) GHz s\(^{-1}\), and the average value is about \(-17.30\) GHz s\(^{-1}\).
Top-left panels show the spectrograms at left- and right-handed circular polarizations of the microwave quasi-periodic pulsation (QPP) observed at 2.60–3.80 GHz by the Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou). The top-right panels show the emission flux profiles at left- and right-handed circular polarizations (upper and middle) of the QPP at a frequency of 2.60–3.80 GHz, and the central frequency distribution of QPP pulses (below). The bottom panels show the expanded spectrograms of microwave QPP pulse groups A (left), B (middle), and C (right), respectively, which present the details of the superfine structures of QPP pulses.

From the bottom-right panel of Figure 3, several segments of strong zebra pattern (ZP) structures can be found at a frequency of 2.60–2.75 GHz at 08:03:24–08:03:27 UT accompanying the microwave QPP pulses. Three zebra stripes can be seen in the extended spectrogram in Figure 5 around 08:03:26 UT; the flux intensities on individual stripes are degressive from low frequency to high frequency (about 1100–1300 sfu on the low-frequency stripe, 700–1000 sfu on the middle stripe, and 200–600 sfu on the high-frequency stripe above the adjacent background emission). This shows strong right-handed circular polarization. The frequency separation between the adjacent zebra stripes is about 70–100 MHz. Generally, the ZP structure is always regarded as one of the most important microwave fine structures that can be used to diagnose magnetic field strength in the coronal source regions (Zlotnik 2009; Chernov 2010). Adopting a similar method of magnetic field estimation from ZP structure with a double plasma resonance model in the same frequency range used in the work of Tan et al. (2012), we may obtain that the magnetic field strength in the coronal source region of the ZP structure is about 147–210 G, and the average value is about 178 G.

In brief, the RHESSI HXR observation at an energy of 25–50 keV implies the existence of an HXR QPP with a period of 2.46 s. At the same time, the microwave observation at a frequency of 2.60–3.80 GHz indicates the occurrence of a much faster QPP with an average period of 0.705 s. Each pulse of
3. PHYSICAL DISCUSSIONS
What physical implications are hinted in the millisecond superfine structures of each individual microwave QPP pulse, and how do we understand the three different kinds of frequency drift rates?

First, we need to determine the mechanism of the QPP. Here, we are only interested in the HXR QPP with a period of 2–3 s and the microwave VSP with a period of subseconds. It is well known that propagating MHD oscillation modes or the standing fast sausage modes in dense magnetic traps may produce a QPP with a period of the above values (Roberts et al. 1984; Aschwanden 1987; Tan et al. 2010). Zaitsev et al. (1984) demonstrated that the variation of plasma density in a magnetic loop by fast magnetosonic waves excited by energetic protons in Cherenkov or bounce resonance might produce a QPP with a period of seconds. Zaitsev et al. (1998, 2000) proposed another model in which a current-carrying plasma loop should be an LRC-circuit resonator, which might cause periodic modulation of the loop magnetic field, energy release rate, and energetic electron production; therefore, the microwave emission, and the corresponding period, should be dependent on the longitudinal electric current \( P_{\text{LRC}} \sim 10^{12}/I_\phi \), \( I_\phi \) is the longitudinal electric current in the loop. In order to produce VSP in this work, the longitudinal electric current in the loop should be in the range of \((1.16–2.38) \times 10^{12} \) A. Such a value is very popular in a general flaring plasma loop (Gary & Demoulin 1995, Tan 2007, etc.). It seems that the above models are the possible candidates for the QPP with periods as given in this work. However, these models have a bit of difficulty in explaining the frequency drifting rates and the superfine structures with clusters of millisecond spike bursts or type III bursts. Here, we need a model that can explain the properties including the rapid QPP and the superfine spiky structures.

Kliem et al. (2000) and Karlicky (2004) proposed that microwave QPP can be caused by quasi-periodic particle acceleration from a highly dynamic regime of magnetic reconnection in an extended large-scale current sheet above the flaring loop. The reconnection is dominated by repeated formation and subsequent coalescence of magnetic islands, known as secondary tearing modes (TMs). This model can explain the QPP with a
and their evolutions. From the bandwidth of the emission we may estimate the perturbation of the plasma density. The frequency drifting rate can reflect the motion of the plasma loop and the energetic particles. Combining all these observable parameters, we may probe many physical conditions in the cross section of the loop. The pulsating emission is localized in some regions of small size, for example, around magnetic islands in flaring plasma loops. From the bandwidth of the emission we may estimate the perturbation of the plasma density. The frequency drifting rate can reflect the motion of the plasma loop and the energetic particles. Combining all these observable parameters, we may probe many physical conditions and their evolutions.

As for the mechanism of the millisecond spike bursts or narrowband type III bursts, Benz (1986) proposed that decimeter narrowband millisecond spikes are coherent emission as a signature of electron acceleration in the flare, and that flare energy release must be fragmented with each spike indicating a single energy release episode in the shortest time and space scale originating from magnetic reconnection sites (Huang & Nakajima 2005; Wang et al. 2008). Fleishman & Melnikov (1999) made a detailed comparison of the observed spike properties with various theoretical models and found that the electron cyclotron maser emission (ECME) driven by nonthermal electrons can explain almost all the observed properties. Fleishman et al. (2003) proposed that the source of the spike cluster should be a coronal loop filled by fast electrons and relatively tenuous background plasma. Each spike is generated by ECME in a local small source inside the loop. ECME takes place only when the following conditions are satisfied (Melrose & Dulk 1982):

$$\omega - \frac{s \omega_{pe}}{\gamma} - k_{||} v_1 = 0$$  \hspace{1cm} (2)

and

$$\omega_{ce} \gg \omega_{pe}.$$  \hspace{1cm} (3)

Here, $\omega$ is the emission frequency, $\omega_{ce}$ is the electron gyrofrequency, $\omega_{pe}$ is the electron plasma frequency, $s$ is the harmonic number, $\gamma$ is the Lorentz factor of the energetic electrons, and $k_{||}$ and $v_1$ are the parallel components of the wave number and particle velocity, respectively. Equation (3) implies that the source region of ECME must have a relatively strong magnetic field. Because of the accompanying ZP and microwave QPP structures, we may suppose that their source regions are close to each other, and the magnetic field strengths are also similar to each other. However, the estimation of ZP structures indicates that the magnetic field strength is about 147–210 G, and the corresponding gyrofrequency $f_{ce}$ is about 412–588 MHz, which is much lower than the observed frequency ($\sim$ 3.00 GHz). This fact implies that ECME seems not to be the formation mechanism of the millisecond spiky bursts observed in this work.

It is well known that there is another kind of coherent emission: plasma emission, which is always generated from the coupling of two excited plasma waves with frequency of about $2f_{pe}$ and weak polarizations, or the coupling of an excited plasma wave and a low-frequency electrostatic wave with frequency of about $f_{pe}$ and strong polarizations (Zheleznyakov & Zlotnik 1975; Chernov et al. 2003). Generally, the plasma emission is triggered by some Langmuir turbulence produced from nonthermal energetic electrons.

Combining the above analysis, we may qualitatively plot the physical processes associated with the QPP as in Figure 6:

1. From the idea of Kliem et al. (2000), we may propose that the energetic electrons accelerating from a highly dynamic magnetic reconnection in an extended large-scale current sheet above the flaring loop propagate downward, interact with the plasma in the flaring loop, and produce HXR bursts by the bremsstrahlung mechanism. The TM oscillation in the current sheet may modulate the HXR emission and form the HXR QPP (the big red arrow in Figure 6).

2. The energetic electrons propagating downward may impact the flaring loop and trigger the Langmuir turbulence and plasma waves in the loop. The coupling between the plasma wave and the low-frequency electrostatic wave emits microwave radiation by the mechanism of plasma emission. From the idea of Tan et al. (2007), the modulation
3. Each magnetic X-point is an energy releasing site in the current-carrying plasma loop. Each X-point will be a small reconnection site and will make a secondary acceleration on the ambient electrons. As a result, the spike bursts or type III bursts can arise in huge clusters. Because the plasma density always has a negative gradient from the X-point to the space between two adjacent rational surfaces (Furth et al. 1973; Drake et al. 2006), the frequency drifting rates of spike bursts or type III bursts are negative. Because the scale length of the density inhomogeneity \( H_n \) around the X-point is shorter than that in the ambient plasma of the loop, from Equation (4) we may conclude that the frequency drifting rates of spike bursts or type III bursts are higher than those of the microwave QPP pulses.

4. CONCLUSIONS

Based on the above observations and physical analysis, we derive the following conclusions:

1. Just before the flare maximum, there are HXR QPPs and microwave QPPs with durations of about 20 s. The HXR QPP belongs to an SPP, and the microwave QPP belongs to a VSP. Each individual microwave QPP pulse is structured with clusters of millisecond bursts; most of the millisecond bursts are clusters of spike bursts, and the rest are type III bursts. There are three different frequency drifting rates: GFDR of the microwave QPP pulse group, SPFDR of the microwave QPP pulse, and SPFDR of millisecond spike bursts or narrowband type III bursts.

2. The physical processes associated with the QPP can be described as follows: the energetic electrons accelerating from a highly dynamic magnetic reconnection in an extended large-scale current sheet above the flaring loop propagate downward, interact with the plasma of the flaring loop, and produce HXR bursts by bremsstrahlung mechanism. The TM oscillation in the current sheet may modulate the HXR emission and form HXR QPP; the energetic electrons propagating downward may produce the Langmuir turbulence and plasma waves in the loop and trigger the plasma emission. The modulation of the TM oscillations in the current-carrying plasma loop may lead to the formation of microwave QPP. The TM instability causes the formation of magnetic islands in the current-carrying plasma loop. Each magnetic X-point between the adjacent two magnetic islands will be a small reconnection site and will make a secondary acceleration on the ambient electrons. These accelerated electrons may impact the ambient plasma and trigger the millisecond spike clusters or the group of type III bursts by plasma mechanism.

3. Each magnetic X-point is an energy releasing site in the current-carrying plasma loop, and each millisecond spike burst or type III burst is possibly one of the elementary bursts (EBs). A large number of EB clusters form an intense flaring microwave burst.

4. We may apply the above conclusions to analyze the conditions of the source regions, e.g., the GFDR of the microwave QPP pulse group can be adopted to estimate the motion of the flaring loop, the SPFDR of the microwave QPP pulse can be adopted to estimate the velocity of the energetic electrons and the corresponding energies, and the SPFDR of millisecond spike bursts or type III bursts.
can be applied to estimate the density inhomogeneity ($H_n$) around the X-point in the flaring plasma loops.

However, as we lack imaging observations with spatial resolutions in the corresponding frequency range, there are many unresolved problems of the QPPs, for example, the spatial behaviors, the spatial scales of the source region, etc. To overcome these problems, some new instruments are needed, for example, the Chinese Spectral Radioheliograph (0.4–15 GHz) in the decimeter- to centimeter-wave range, currently being constructed (Yan et al. 2009), and the proposed American Frequency Agile Solar Radiotelescope (50 MHz–20 GHz; Bastian 2003). Perhaps, when these instruments begin to work, we will obtain further cognitions of the solar activities.

The authors thank the referee for helpful and valuable comments on this paper. Thanks are also due to the GOES, RHESSI, SDO/AIA, and SBR/S/Huairou teams for the observational data. This work is mainly supported by NSFC grant nos. 11103044 and 10921303, MOST grant no. 2011CB811401, and the National Major Scientific Equipment R&D Project ZDYZ2009-3.

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