MICROWAVE QUASI-PERIODIC PULSATIONS IN MULTI-TIMESCALES ASSOCIATED WITH A SOLAR FLARE/CME EVENT

BaoLin Tan1, Yin Zhang, ChengMing Tan, and Yuying Liu

Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, China; bltan@nao.cas.cn

Received 2010 February 19; accepted 2010 August 18; published 2010 October 6

ABSTRACT

Microwave observations of quasi-periodic pulsations (QPPs) in multi-timescales at the Solar Broadband Radio Spectrometer in Huairou (SBRS/Huairou) on 2006 December 13 are confirmed to be associated with an X3.4 flare/coronal mass ejection (CME) event. It is most remarkable that the timescales of QPPs are distributed in a broad range from hectoseconds (very long period pulsation, VLP, \( P > 100 \) s), decaseconds (long period pulsation, LPP, \( 10 < P < 100 \) s), a few seconds (short period pulsation, SPP, \( 1 < P < 10 \) s), deciseconds (slow very short period pulsation, slow-VSP, \( 0.1 < P < 1.0 \) s), to centiseconds (fast very short period pulsation, fast-VSP, \( P < 0.1 \) s), and form a broad hierarchy. The statistical distribution of QPPs in logarithmic period–duration space indicates that all the QPPs can be classified into two groups: group I includes VLP, LPP, SPP, and some slow-VSPs distributed approximately around a line; group II includes fast-VSP and most of the slow-VSPs dispersively distributed away from the above line. This feature implies that the generation mechanism of group I is different from group II. Group I is possibly related to some MHD oscillations in magnetized plasma loops in the active region; e.g., VLPs may be generated by standing slow sausage mode coupling, resonating with the underlying photospheric 5 minute oscillation, with the modulation amplified and forming the main framework of the whole flare/CME process; LPPs, SPPs, and some slow-VSPs are most likely to be caused by standing fast modes or LRC-circuit resonance in current-carrying plasma loops. Group II is possibly generated by modulations of resistive tearing-mode oscillations in electric current-carrying flaring loops.

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

Online-only material: color figures

1. INTRODUCTION

Solar quasi-periodic pulsations (QPPs) are frequently observed in optical, EUV, radio, soft X-ray, hard X-ray, and even gamma-ray emissions (Nakariakov et al. 2010). In the same way that seismological waves can reveal the interior structure of the Earth or other celestial bodies, solar QPPs are also a very important kind of phenomena that may provide information regarding, e.g., the interior structures and the physical conditions of the source regions or the propagating media. The flare-associated QCP can provide information on solar flaring regions and give some possible insight into coronal plasma dynamic processes, such as the remote diagnosis of the microphysics of energy releasing sites, especially since QPPs occur in the microwave frequency range and are always regarded as direct signals of flaring primary energy-releasing regions. So far, we know from observations that the timescales (expressed as the period \( P \)) of QPPs range widely from a few tens of milliseconds to several minutes. Based on the summary of previous observational and theoretical investigations, according to the timescale of periods, we may extend the previous QPP classification (Wang & Xie 2000) into a much wider hierarchy.

1. Very long period pulsation (VLP), also called very low frequency oscillation. Its period is in the hectosecond or several minute range. Generally we may define VLPs as \( P > 100 \) s (e.g., 40 minutes, Kaufmann 1972; 276 s, Aschwanden et al. 1999; 8–12 minutes, Foullon et al. 2005; 10–18 minutes, Foullon et al. 2010).

2. Long period pulsation (LPP). The period is in the decasecond range, defined as \( 10 \text{ s} < P < 100 \text{ s} \) (e.g., Parks & Winckler 1969; Qin et al. 1996; Melnikov et al. 2005; Inglis & Nakariakov 2009, etc.).

3. Short period pulsation (SPP). This kind of QPP is very common, and its period is in the seconds, \( 1 \text{ s} < P < 10 \text{ s} \) (e.g., Abrami 1970; Rosenberg 1970; Trottet et al. 1981; Zaitsev & Stepanov 1982; Qin et al. 1996, etc.).

4. Very short period pulsation (VSP). Its period is in the subsecond range, frequently down to tens of milliseconds (e.g., Young et al. 1961; Gotwols 1972; Fleishman et al. 2002; Tan et al. 2007; Tan 2008; Jiricka & Karlicky 2008; Karlicky et al. 2010, etc), and so we may classify VSPs into two sub-classes (Tan et al. 2007):

   (a) slow-VSP, where the period is in the decisecond range, \( 0.1 \text{ s} < P < 1.0 \text{ s} \);
   (b) fast-VSP, where the period is in the centisecond range, \( P < 0.1 \text{ s} \); usually, it is only several tens of milliseconds.

Intrinsically, there is no distinct borderline between the different classes of QPPs. So far, because of instrumental limitations, we have not reliably distinguished any QPPs with a period shorter than 10 ms.

In previous studies, there has been always only one or two classes of QPPs reported in one flare event. Even the multi-periodic pulsations observed in some cases also have only one or two classes of QPPs. For example, in the work of Qin et al. (1996), the periods of the two pulsating components are 1.5 s and 40 s, which belong to SPPs and LPPs, respectively; in the work of Melnikov et al. (2005), the periods of the two pulsating components are 14–17 s and 8–11 s, respectively, which rank both in the same class of QPP; in the work of Inglis & Nakariakov (2009), the periods of the three pulsating...
components are 28 s, 18 s, and 12 s, respectively, and all of them belong to the class of LPPs. Karlicky et al. (2005) reported the timescales of slowly drifting pulsating structures (DPS) with a period of 0.9–7.5 s, and the short periods present as a power-law distribution, especially in the range of 0.06–0.2 s, where the power-law index is in the range of 1.3–1.6. So far we have no literature to show the coexistence of more than two different classes of QPPs in the same flaring event. We do not know what the relationship is among the different classes of QPPs. At the same time, we have plenty of reason to suppose that such relationships may imply some physical information regarding the solar active region or the flaring mechanisms.

It is very fortunate that an X3.4 flare/coronal mass ejection (CME) event occurred in the solar active region of AR 10930 on 2006 December 13. This event has many unusual features: (1) AR 10930 is an isolated active region on the solar disk (the left panel of Figure 1); (2) the flare is a long-duration event; the GOES soft X-ray bursts start at 02:14 UT and end at 02:57 UT, and the radio bursts start at 02:20 UT and last after 04:50 UT; and (3) the eruption is repetitious, and from broadband microwave observations, we find that this event clearly has many big bursts. Many people studied this flare/CME event from different points of view (Kosovichev & Sekii 2007; Yan et al. 2007; Ning 2008; Kuznetsov 2008; Zhang et al. 2008, etc.). Minoshima et al. (2009) especially presented multi-wavelength observations of electron acceleration in the flare. In Figure 1 of their paper, the light curves of the microwave radio emission observed at the Nobeyama Radio Polarimeter (NoRP; 9.4 GHz, 17 GHz, and 34 GHz) and the hard X-ray obtained at the Reuven Ramaty High Energy Spectroscopic Imager (RHESSI) in 25–40 keV, 40–60 keV demonstrate QPPs with very long periods. Together with the great number of very short period pulsations (VSPs) observed in the Chinese Solar Broadband Radio Spectrometer in Huairou (SBRS/Huairou; Tan et al. 2007; Tan 2008), it is reasonable to analyze the observations of QPPs in multi-timescales, their mutual relationships, and the possible physical implications in detail. From these investigations, we find that the most remarkable feature in this flare event is the coexistence of several classes of QPPs, including VLPs, LPPs, SPPs, slow-VSPs, and fast-VSPs; these QPPs form a broad hierarchy of timescales.

In this work, based on the observations at frequencies of 2.60–3.80 GHz at SBRS/Huairou, we present the observations and analysis of multi-timescales in QPPs associated with the flare event on 2006 December 13. Section 2 introduces the observation data and analysis methods. Section 3 presents the main features of QPPs. In Section 4, we give a detailed discussion of the physical mechanisms of QPPs with multi-timescales. Finally, we summarize and give some deductions in Section 5.

2. OBSERVATIONS DATA AND ANALYSIS

2.1. Observation Data

The X3.4 flare/CME event in AR 10930 on 2006 December 13 was observed by RHESSI, Hinode, NoRH, NoRP, SOHO/MDI, TRACE, and SBRS/Huairou (Kubo et al. 2007; Su et al. 2007). We select mainly the observations of SBRS/Huairou because of its high cadence, broad frequency bandwidth, and high-frequency resolution to investigate the multi-timescale pulsating phenomena associated with the flare/CME event. SBRS/Huairou includes three parts: 1.10–2.06 GHz, 2.60–3.80 GHz, and 5.20–7.60 GHz (Fu et al. 1995; Fu et al. 2004; Yan et al. 2002). However, only the spectrometer of 2.60–3.80 GHz was operating well around the above flare/CME event. The diameter of the antenna of the spectrometer is 3.2 m. The antenna points to the center of the solar disk and is automatically controlled by a computer. The spectrometer can receive the total flux of solar radio emission with dual circular polarization (left- and right-circular polarizations), and the dynamic range is 10 dB above quiet solar background emission. The observation sensitivity is $S/S_0 \leq 2\%$, where $S_0$ is the quiet solar background emission. Similar to several other spectrometers,
Figure 2. Spectrogram of the solar radio emission at a frequency of 2.60–3.80 GHz at 01:30–05:30 UT, 2006 December 13.

Such as Phoenix (100–4000 MHz; Benz et al. 1991), Ondřejov (800–4500 MHz; Jiricka et al. 1993), and BBS (200–2500 MHz; Sawant et al. 2001), SBRS/Huairou has no spatial resolution. However, a great number of works (e.g., Dulk 1985, etc.) have shown that the radio bursts received by spectrometers are always coming from the solar active region when the antenna points to the Sun. In this present work, because AR 10930 is an isolated active region around the X3.4 flare/CME event (shown in the left panel of Figure 1), we believe that the microwave bursts are only coming from the same active region associated with the event. In the frequency range of 2.60–3.80 GHz, there are 120 channels with a frequency resolution of 10 MHz, and a temporal resolution of 8 ms, and left- and right-circular polarization components with an accuracy of polarization degree 5%–10%. The data were analyzed by using software that was developed with the IDL algorithm. In order to identify weak burst structures, some wavelet methods have been developed for data processing. The calibration of the observation data followed the method proposed by Tanaka et al. (1973). The standard flux values of the quiet Sun is adopted from the data published by the Solar Geophysical Data (SGD) at frequencies 4995 MHz, 2800 MHz, 2695 MHz, and 1415 MHz. As for strong bursts, the receiver may work beyond its linear range and a nonlinear calibration method will be used instead (Yan et al. 2002).

In order to confirm that the observations of SBRS/Huairou are not artificial, we make comparisons among SBRS/Huairou, NoRPs, and the soft X-ray intensity obtained at the GOES satellite. Here, NoRP observes the Sun with multiple frequencies 1.0, 2.0, 3.75, 9.4, and 80 GHz. It is capable of obtaining total solar flux and circular polarization degree with a temporal resolution of 0.2 s. The right panel of Figure 1 presents the observed results of the GOES soft X-ray intensity (a), radio emission intensities obtained at NoRP (b), and SBRS/Huairou (c) at the same frequency of 3.75 GHz at 01:30–05:30 UT, 2006 December 13. We find that these radio results obtained from the two different telescopes (one is in China and the other is in Japan) are almost exactly the same in profile shape and intensity. Figure 2 presents the dynamic spectrogram of solar radio emission at a frequency of 2.60–3.80 GHz at 01:30–05:30 UT, 2006 December 13. Radio bursts start (02:20 UT) after the flare onset (02:14 UT) and end at 04:50 UT. They are consistent with the enhancement of the GOES soft X-ray intensity. These facts confirm again that radio observations of SBRS/Huairou are coming from the solar flaring processes.

The biggest advantage of SBRS/Huairou is that it makes it possible to synchronously obtain more particular information, such as the polarization degree, pulsating frequency bandwidth, frequency drifting rate, and fine structures of microwave emission spectrograms, with much higher temporal and frequency resolutions than most other instruments.

2.2. Analysis Method

As a rule, we can use Fourier analysis (fast Fourier transformation (FFT)) or wavelet analysis to investigate pulsating structures in observation data. Generally, QPP always behaves as a train of approximately parallel vertical and equidistant stripes in broadband dynamic spectrograms. Each stripe represents one pulse. The time interval between two adjacent stripes represents the pulsating period. By scrutinizing the observed dynamic spectrograms, we can also distinguish and confirm the existence of QPPs clearly and pick up their parameters easily, such as central emission frequencies ($f_0$), frequency bandwidth ($b_w$), period ($P$), duration ($D$), global frequency drifting rate ($R_{gfd}$), signal pulse frequency drifting rate ($R_{spfd}$), and polarization degree ($r$). In a QPP, the parameters of $P$, $f_0$, $b_w$, $r$, $R_{gfd}$, and $R_{spfd}$ may have
similar values. In different QPPs, the above parameters will obviously have different values. We can easily distinguish one QPP from another. We then need to decompose pulsating components from the observed data. In our observations, the data have two synchronous modes: one is with a cadence of 0.2 s, and the other has a cadence of 8 ms. From observations with a cadence of 0.2 s, we may investigate features of VLPs, LPPs, and some SPPs; from the observations with a cadence of 8 ms, we may investigate VSPs and most of the SPPs.

In order to make the pulsating component clearer and more reliable, we adopt two methods to investigate QPPs. These two methods can be mutually cross-examined. When their results are consistent with each other, a QPP is identified. The first method is a kind of statistical method, which directly counts the temporal intervals between adjacent pulse peaks in the pulsating structures from the broadband radio dynamic spectrogram. This method is very straightforward, and the details are presented as follows.

1. Identify solar microwave bursts. The instrument sensitivity is \(S/S_0 \leq 2\%\). From SGD data, we may get the microwave flux intensity of the quiet solar background emission at frequencies 1.415 GHz, 2.695 GHz, 2.800 GHz, and 4.995 GHz, which are 52 sfu, 88 sfu, 90.7 sfu, and 158 sfu, respectively, on 2006 December 13. Then, we may obtain that the microwave flux intensity of the quiet solar background emission at frequencies 2.60–3.80 GHz is 85.3–121.4 sfu by linear extrapolation, and the instrument sensitivity is about 1.70–2.40 sfu. Generally, the background emission during the flare/CME event is much greater than the quiet-Sun emission (before the event, i.e., before 02:20 UT), and it equals the quiet-Sun emission before the flare event.

2. Identify the pulsating structure by scrutinizing the observed spectrograms directly. Here, the microwave flux intensity at each pulse in the pulsating structure will be 5.0 sfu higher than the quiet solar background emission, so it is very clear in the dynamic spectrogram.

3. Obtain the timescale of the pulsating structure approximately by directly counting the temporal intervals between adjacent pulse peaks from the spectrogram. Such estimation can roughly give values of the period \(P\), duration \(D\), central emission frequency \(f_0\), and the bandwidth \(b_w\) of the QPP.

4. Smooth the observing flux curves to filter out the high-frequency noise components by using a sliding window narrower than the pulsating period; the result may be expressed as \(F\). The width of the smoothing window should be experientially \(\frac{1}{4}P\).

5. Smooth the flux curves \(F\) in a wide sliding window to filter out the pulsating component and obtain the background emission of the QPP. The width of the smoothing window should be experientially \(2P\). The result can be expressed as \(F_b\). Generally, the background emission during the flare/CME event is much greater than the quiet-Sun emission (before the event, i.e., before 02:20 UT), and it equals the quiet-Sun emission before the flare event.

Usually, the smoothing method will generate some additional boundary effects. In order to suppress such effects, we need to extend the range of the analyzed data. That is to say, if the duration of the QPP is \(D\), and the QPP starts from \(t_1\) and ends at \(t_2\), \(D = t_2 - t_1\), then we select the analyzing data from \(t_1 - \frac{D}{2}\) to \(t_2 + \frac{D}{2}\) before smoothing processing. After smoothing processing, we investigate the pulsating features only within the data fragment from \(t_1\) to \(t_2\).

6. Subtract the background emission \(F_b\) from the result \(F\) of step (4) and obtain the pulsating component \(F_p\), \(F_p = F - F_b\). The pulsating component is a quantity relative to the background emission \(F_b\); it will oscillate from positive to negative values around \(F_b\).

7. Investigate the dynamic features of QPPs by analyzing \(F_p\). Such features may include more exact period \(P\), modulation degree \(M\), polarization degree \(r\), single pulse frequency drifting rates \(R_{\text{spd}}\), and global frequency drifting rate \(R_{\text{gfd}}\). These parameters are defined and explained in Tan (2008).

Figure 3 presents an example of the above QPP extraction procedure. Here, we note that the existence of saturation effects at several segments may affect the analysis results. Such saturation effects exist at 02:25–02:25:30, 02:41:30–02:43, 02:52–02:54, 03:01:40–03:05, and 03:32–03:36. Additionally, from the above method, the pulsating component \(F_p\) is a...
quantity relative to the background emission ($F_b$), and $F_b$ is an average level obtained by smoothing the flux curves ($F$) in a wide sliding window. From the left panel of Figure 3 we know that $F_b$ is much greater in the flare/CME event than in the quiet-Sun emission (before the event, i.e., before 02:20 UT); it possibly may be mainly associated with thermal plasmas in the flaring region. So, the actual radiation flux in QPP is always positive. The negative $F_p$ is only a relative result with respect to $F_b$.

3. MAIN FEATURES OF QPPs

Based on the above observation data and analysis methods, we find that there are five classes of QPPs, including VLPs, LPPs, SPPs, and slow- and fast-VSPs, coexisting and associated with the flare/CME event on 2006 December 13. They form a broad hierarchy of QPPs with different timescales. All the QPPs occurred during the enhancement of the soft X-ray obtained by the GOES satellite. From the right panel of Figure 1 we find that no radio burst occurred before 02:20 UT and after 04:50 UT, and the dynamic spectrogram in Figure 2 is almost a uniform pattern during these two time sections. We also use Fourier analysis in these two sections of observation data, and find no pulsating evidence. These facts indicate that there are no detected pulsating structures before and after the flare/CME event. All the QPPs are associated with the abovementioned flare/CME event.

3.1. Very Long Period Pulsation (VLP)

The most remarkable implication of Figures 1–3 may be the QPPs with very long periods. According to the profile, the radio bursts can be plotted into four graphs of QPP which are marked as A, B, C, D, and separated by vertical dash-dotted lines in Figure 3, respectively.

The left panel of Figure 4 shows pulsating components at different frequencies of the VLP including graphs A and B occurring at 02:20–03:50 UT, 2006 December 13 at a frequency of 2.60–3.80 GHz, which indicates that the VLP is a broadband pulsation and goes beyond the possible frequency range of the telescope. The solid and dotted curves represent the right- and left-circular polarized components, respectively. Values of the pulsating components are relative to the background emission $F_b$. In the right panel, (a) shows a profile of radio emission at frequency 2.95 GHz and (b) shows a result of Fourier analysis (FFT) at the corresponding frequency, which indicates that the period of the LPP is 258 s.

Figure 4. VLP occurred at 02:20–03:50 UT, 2006 December 13 at a frequency of 2.60–3.80 GHz observed at SBRS/Huairou. Left panel shows pulsating components at different frequencies. The solid and dotted curves represent the right- and left-circular polarized components, respectively. Values of pulsating components are relative to the background emission $F_b$. In the right panel, (a) shows a profile of radio emission at frequency 2.95 GHz and (b) shows a result of Fourier analysis (FFT) at the corresponding frequency, which indicates that the period of the LPP is 258 s.
The main difference between the two graphs is the evolution of the polarization degree. The left panel of Figure 4 gives some evidence that there is a circular polarization reversion from right-circular polarization to left-circular polarization around the frequency 3.40 GHz in graph A. However, in graph B, there are no such reversions, and the polarization degree remains positive. However, because of saturation effects on both graphs A and B, we have no strict proof to distinguish graph A from graph B.

Figure 3 presents two other graphs of the VLP after 03:50 UT: graph C starts at 03:56 and ends at 04:22 UT, the period is about 260 s (4.3 minutes), and the averaged magnitude of the pulsating emission flux is about 200 sfu; graph D starts at 04:28 and ends at 04:47, the period is about 220 s (3.7 minutes), and the averaged magnitude is about 90 sfu, and strongly behaves as right-circular polarization. This graph has no saturation effect. The right panel of Figure 3 presents its magnitude evolution; the dashed curve is a Gaussian-fitted result. It shows that the pulsating process increases gradually, reaches a maximum, and then decreases.

As a whole, from graphs A, B, C to D, the averaged magnitude of the pulsating emission flux decreases from 350 sfu to 90 sfu gradually. The period reaches the maximum (270 s) at graph B, and then decreases gradually to a minimum (220 s) at graph D.

In addition, there is obvious frequency drifting at each pulse in the VLP ($R_{\text{pdf}}$). Figure 6 presents an example of a method to calculate the single pulse frequency drifting rate of QPPs. The dot-dashed line denotes the time of the maximum flux intensity at each frequency; its slope indicates the frequency drift rate at the corresponding pulse. The other LPPs occurred at 02:38:50–02:40:00 with a mean period of 16 s (this LPP has some superfine structures we will discuss in the following sections; see Figure 11), at 02:52–02:55 UT with a mean period of 35 s, and at 03:23:35–03:24:50 with a mean period of 15 s. Q-factors of these four LPPs are around 5–7, which is approximately a constant.

Using the same method presented in Figure 6, we also find that the single pulse frequency drifting rates of graphs C and D are in the range of $-50\text{ to }190\text{ MHz s}^{-1}$ and $-135\text{ to }265\text{ MHz s}^{-1}$, respectively. The main properties of the VLPs are summarized in Table 1.
3.3. Short-period Pulsation (SPP)

During the flare/CME event, we identified three segments of SPP. They are also listed in Table 1. Figure 8 presents an example of an SPP that occurred at 02:59:20–03:00:20 UT, 2006 December 13. The left panel of Figure 8 is the dynamic spectrogram which indicates that the period (the time interval between adjacent pulse stripes) is in the range of 4.7–7.2 s, with an average of 6.2 s. In the right panel of Figure 8, (a) shows the profile of the radio emission at frequency 2.95 GHz, the dashed curve is the Gaussian-fitted result which shows the magnitude evolution that also increases to a peak and then decreases; (b) is a result of the Fourier analysis (FFT) at the corresponding frequency, which indicates that the period of the SPP is 6 s, consistent with the result of the dynamic spectrogram. The emission frequency bandwidth is about 600–900 MHz, which is narrower than that of the VLP and LPP. The magnitude of pulsating emission flux at each pulse is in the range of 40–115 sfu with right-circular polarization, while there is almost no pulsating component in the left-circular polarization. From the dynamic spectrogram, we may also find that the SPP has a strong right-circular polarization. Additionally, there are obvious frequency drifts at each pulse of the SPP; their values are in the range of −4.0 GHz s$^{-1}$ to 3.5 GHz s$^{-1}$. This frequency drift rate is very close to the drifts of type III bursts (Ma et al. 2006). However, the work of Aschwanden & Benz (1986) indicates that the frequency drift rates of QPPs are considerably different from type III bursts in a similar frequency range, and...
these two kinds of microwave fine structures are intrinsically different from each other.

In fact, from the dynamic spectrogram of Figure 7 we find that there is an SPP superposed on the LPP at 02:27:50–02:28:20 UT in the frequency range of 2.60–3.00 GHz with bandwidth 400 MHz; its period is about 8.0 s, and the polarization degree is about 65%–85%. The magnitude of the pulsating emission flux at each pulse is in the range of 50–120 sfu. The single pulse frequency drift rate is from about $-1.5 \text{ GHz s}^{-1}$ to $2.5 \text{ GHz s}^{-1}$. Another SPP occurred at 02:24:35–02:24:47 UT with an average period of about 1.2 s at a frequency of 2.60–2.95 GHz; the bandwidth is about 350 MHz, and the single pulse frequency drift rate is about $5.0 \text{ GHz s}^{-1}$. From these we may find that the SPP is completely different from the VLP and LPP in terms of the parameters of polarization degree, frequency drift rate, and frequency bandwidth, etc. These differences imply that SPPs may have a different generation mechanism from VLPs or LPPs.

3.4. Very Short-period Pulsation (VSP)

More than 40 cases of VSPs with periods $P < 1.0 \text{ s}$ in the frequency range of 2.60–3.80 GHz associated with the flare/CME event on 2006 December 13 were reported in the work of Tan et al. (2007) and Tan (2008). These VSPs are quasi-periodic, broad bandwidth, and ubiquitous in all phases of the flare/CME event. In these VSPs, the right-circular polarization is very strong. Table 2 of Tan (2008) lists all their observable features. From that list we may classify them into two subclasses.

1. Slow-VSP: the period is in deciseconds, $0.1 \text{ s} < P < 1.0 \text{ s}$.
   The left panel of Figure 9 is an example of a slow-VSP that occurred at 03:25:40–03:25:47 UT, 2006 December 13 at a frequency of 2.60–2.90 GHz. There are 10 slow-VSP cases in total distinguished from the observations, which are associated with the flare event. All of them occurred after the flare peak. The period of slow-VSPs is in the range of 110–416 ms. The duration of each slow-VSP is in the range of 2.2–23 s, the single pulse frequency drift rate is in the range of 6.5–20 GHz s$^{-1}$ and is always positive, and the emission frequency bandwidth is in 250–700 MHz. The polarization is very strong, similar to that of the SPP. The magnitude of the pulsating emission flux is in the range of 20–95 sfu. We may also obtain the global frequency drift rate of slow-VSPs, and the value is from $-31.4 \text{ MHz s}^{-1}$ to $32.5 \text{ MHz s}^{-1}$.

   The left panel of Figure 9 shows that the magnitude of pulses increases gradually, and the period decreases from 480 ms to 310 ms slowly. However, the spectrogram becomes a continuum after 03:25:47 UT. One possible reason is that it becomes mixed with some other emissions. The left panel of Figure 9 is only a partial section of the slow-VSP. By scrutinizing other slow-VSPs, we find that some of them have increasing magnitudes and decreasing periods, and the others have decreasing magnitudes and increasing periods.

   Jiřička & Karlický (2008) also found a similar slow-VSP with a period of about 150 ms and a single pulse drift rate of about $-17 \text{ GHz s}^{-1}$ associated with another solar flare event.

2. Fast-VSP: the period is in centiseconds, $P < 0.1 \text{ s}$.
   The right panel of Figure 9 is an example of a fast-VSP that occurred at 03:25:25–03:25:29 UT, 2006 December 13 at a frequency of 2.60–2.90 GHz. There are more than 30 fast-VSPs distinguished from observations associated with the flare event, and they occurred in all phases of the flare (including the rising, peak, vale, and decaying phases). The period of fast-VSPs is in the range of 31–90 ms. The duration of each fast-VSP is in the range of 2.3–16 s; the single pulse frequency drift rate is from 8.33 GHz s$^{-1}$ to
Figure 9. Examples of a slow-VSP (extraordinary VSP) and a fast-VSP (ordinary VSP). In each panel, the upper and the lower parts are the left- and right-circular polarization components, respectively.

>30 GHz s\(^{-1}\); the emission bandwidth is in 220–400 MHz. The polarization degree is slightly higher than that of slow-VSPs. The magnitude of the pulsating emission flux is in the range of 15–70 sfu, slightly less than that of slow-VSPs. The global frequency drift rate of the pulsating event is from \(-86.2\) MHz s\(^{-1}\) to 34.6 MHz s\(^{-1}\), which is analogous to that of slow-VSPs.

The right panel of Figure 9 presents the magnitude of pulses which increases slowly from 160 sfu to a peak of 264 sfu, and then decreases to 145 sfu; the period increases slowly from 75 ms to 104 ms. Statistically analyzing other fast-VSPs, we find that 35% of fast-VSPs have the above evolutions, 37% of fast-VSPs evolve with increasing magnitudes and decreasing periods, and 28% of fast-VSPs evolve with decreasing magnitudes and increasing periods. This implies that most of the fast-VSPs are possibly also partially sectional.

Returning to Table 2 of Tan (2008), we find that the emission frequency bandwidths of most VSPs are narrower than those of VLPs and LPPs. Additionally, from the characteristics of the flux profiles, we find that there is another interesting feature: the VSPs can be classified into two classes by another criteria.

1. Ordinary VSPs, the width of pulses at half-maximum (\(W_p\)) is approximated as half the gap between two adjacent pulses (\(W_g\)); \(W_p \approx 0.5W_g\). Most of the fast-VSPs belong to ordinary VSPs (see the right panel of Figure 9). In a standard sinusoidal curve, \(W_p = \frac{1}{2}W_g\). The ordinary VSPs are sinusoidal-like pulsations.

2. Extraordinary VSPs, \(W_p \ll W_g\). The left panel of Figure 9 shows an example of extraordinary VSP, whose period is about 416 ms, \(W_p\) is about 35–60 ms, and \(W_g\) is about 365–380 ms.

Among 40 VSPs associated with the flare/CME event, there are only three extraordinary VSPs, which occurred at 03:25:40–03:25:47 UT, 03:28:10–03:28:15 UT, and 03:44:09–03:44:14 UT, and their periods are 416 ms, 200 ms, and 160 ms, respectively. All extraordinary VSPs belong to slow-VSPs, with a strongly right-circular polarization, and with the magnitude of the pulsating emission flux in the range of 30–70 sfu.

In fact, all of the QPPs can also be classified into ordinary QPPs and extraordinary QPPs. When we re-scrutinize the scales of \(W_p\) and \(W_g\) in other QPPs, we find that almost all the VLPs, LPPs, and SPPs belong to ordinary QPPs.

3.5. Relationships Among QPPs in Multi-timescales

Figure 10 presents a syntheitical comparison of temporal relationships of five classes of QPPs with different timescales, GOES soft X-ray fluxes, and transport rates of magnetic helicity (\(dH/dt\)). We find that all LPPs and SPPs occurred near peaks of VLPs. Additionally, from the flare impulsive phase to its decay phase, the duration of LPPs gradually decreased. However, VSPs are distributed in all phases of the flare (rising phase, peak, decay phase, or vale). This may imply that VSPs are possibly independent of other classes of QPPs. It seems to be a small additional component superposed on other classes of QPPs with longer timescales.

The period ratios between different QPPs may be meaningful. Around the first LPP shown in Figure 10, there occurred three classes of QPPs: VLPs (graph A), LPPs, and SPPs. Their average periods are 4.13 minutes, 70 s, and 8 s, respectively. Their ratios are 31.0 : 8.75 : 1. The second LPP just occurred in the gap between graphs A and B of the VLP, and during this gap we did not distinguish the other kind of QPP. During the third LPP, there occurred a VLP (graph A, \(P = 4.5\) minutes), an LPP (\(P = 15\) s), and a VSP (\(P = 90 \sim 110\) ms). The period ratio is about 2700 : 150 : 1, which is entirely different from the former ratios.

Figure 11 shows an example of concurrence of two different classes of QPPs that occurred at 02:38:50–02:40:00 UT. Higher
In the train of fast-VSPs, we find that there is obviously a 77 ms. From this figure we find that the LPP is fine structured while lower down the hierarchy is a fast-VSP with a period of 16 s, on the hierarchy of the QPP is an LPP with a period of 16 s, E-VSP indicates the extraordinary VSP.

Figure 10. Synthetical comparisons of the temporal relationships among the five classes of QPPs, GOES soft X-ray flux (GOES), and the transport rate of magnetic helicity \( \frac{dH}{dt} \). Profiles of the left- and right-circular polarization (LCP, RCP) represent the VLP, while the big, moderate, and small vertical arrows represent the LPP, SPP, and VSP, respectively. The length of the big arrow shows the duration of LPP. Here O-VSP indicates the ordinary VSP, and E-VSP indicates the extraordinary VSP.

up on the hierarchy of the QPP is an LPP with a period of 16 s, while lower down the hierarchy is a fast-VSP with a period of 77 ms. From this figure we find that the LPP is fine structured with a train of fast-VSPs, and the period ratio is more than 200. In the train of fast-VSPs, we find that there is obviously a global frequency drifting rate with a value of about 2.5 MHz s\(^{-1}\), and this drift rate is very slow compared with the single pulse frequency drifting rates. This evidence implies that there are no obvious regulations among the period ratios and the weak links between the different classes of QPPs.

Additionally, from careful investigation of the microwave observations there is no evidence of any LPP, SPP, and VSP found around the time intervals of VLP graphs C and D. It seems that all the LPPs, SPPs, and VSPs take place around the time intervals of VLP graphs A and B.

Usually, the microwave burst can be regarded as a prompt signal of non-thermal energetic particles originating from the magnetic reconnection. So, it is meaningful to search for the relationships between the magnetic field and QPPs. Here, we introduce the transport rate of magnetic helicity \( \frac{dH}{dt} \) to describe the magnetic field behavior. It can be expressed as (Berger & Field, 1984)

\[
\frac{dH}{dt} = \oint (B \cdot A_p) \nu_z dS - \oint (2(\nu \cdot A_p)B_z) dS
\]

Here, \( A_p \) is the magnetic vector potential, \( \nu \) is the fluid velocity, and \( B_z \) is the normal component of the magnetic field. In an open volume, the magnetic helicity may change by the passage of helical magnetic field lines through the surface (the first term) and by shuffling horizontal motion of field lines on the surface (the second term). In an isolated active region \( \frac{dH}{dt} \) is a nonpotential parameter that indicates the dynamic evolution of the magnetic field mainly in the flaring region (Berger & Field 1984). As the flare/CME event occurred in an isolated active region of AR 10930, we may estimate the quantity for the event by calculating from the above expression. The work of Zhang et al. (2008) shows that the temporal profile of \( \frac{dH}{dt} \) is consistent with that of the microwave burst in the flare/CME event on 2006 December 13. So, we superposed the curve of \( \frac{dH}{dt} \) on the same duration in Figure 10 (dash-dotted curve). Here, the cadence of \( \frac{dH}{dt} \) is 2 minutes, which is calculated from the observations of the Solar Optical Telescope on board Hinode (SOT/Hinode, Tsuneta et al. 2008; Kosugi et al. 2007). From the comparison of \( \frac{dH}{dt} \) and QPPs, we find that when QPPs take place \( \frac{dH}{dt} \) is positive. This fact indicates a continuous injection of magnetic helicity. This may lead to the accumulation of nonpotential energy and the magnetic reconnections in the flaring active region. There are some variations in the profile of \( \frac{dH}{dt} \) during the flaring event. However, as the cadence of \( \frac{dH}{dt} \) is only 2 minutes, we could not confirm any pulsating features in \( \frac{dH}{dt} \).

Actually, we find that VLPs, LPPs, and SPPs have a lot of similarities, such as broad emission bandwidth, almost the same level of \( Q \)-factor (\( \leq 10 \)), weakly circular polarization, and relatively slow frequency drift rates, except that they have different durations, periods, and different magnitudes of pulsating emission flux. They possibly belong to a same class of QPPs in a sense. In order to confirm such a viewpoint, we plot all the QPPs in a logarithmic period–duration space in Figure 12. We find that the VLPs, LPPs, SPPs, and some of the slow-VSPs are distributed around a line (the dot-dashed line in Figure 12). However, almost all fast-VSPs and most of the slow-VSPs are distributed far away from the above line dispersively. This fact implies that fast-VSPs and some of the slow-VSPs may be different originally from VLPs, LPPs, and SPPs. Hereby, we may classify all QPPs into two groups: group I includes VLPs, LPPs, SPPs, and some of the slow-VSPs wherein the longer duration corresponds to a longer period; group II includes fast-VSPs and most of the slow-VSPs of which the period is dispersive with respect to the duration.

Table 2 presents a brief summary of VLPs, LPPs, SPPs, slow-VSPs, and fast-VSPs.

| Hierarchy | VLP | LPP | SPP | Slow-VSP | Fast-VSP |
|-----------|-----|-----|-----|----------|----------|
| D(s)      | 1140–2640 | 90–450 | 20–80 | 2.2–23   | 2.3–16   |
| Max-F (sfu) | 90–1200 | 70–220 | 40–115 | 20–95    | 15–70    |
| \( b_p \) (MHz) | \( >1200 \) | \( >1200 \) | \( \sim 900 \) | \( 250–700 \) | \( 220–400 \) |
| Mean period (s) | 220–270 | 15–70 | 1.2–8 | 0.11–0.416 | 0.021–0.09 |
| \( \nu \) (%) | 8–45 | 10–20 | 45–65 | 45–60 | 55–75 |
| Q-factor | 6–10 | 5–7 | 4–10 | 12–209 | 30–275 |
| \( R_{\text{spdf}}(\text{MHz s}^{-1}) \) | \(-440\) to \(389\) | \(-610\) to \(78.5\) | \(-4000\) to \(3500\) | \(6500–20000\) | \(8330 \sim 30000\) |
| Cases | 4 | 4 | 3 | 10 | > 30 |

Note. Max-F indicates the magnitude of the pulsating emission flux at each pulse in the QPP.
4. DISCUSSION OF THE PHYSICAL MECHANISMS

From the above investigations, we find that there are five classes of QPPs with different timescales associated with the flare/CME event: VLPs, LPPs, SPPs, and slow- and fast-VSPs. They form a broad hierarchy of timescales from hectoseconds, decaseconds, a few seconds, deciseconds, to centiseconds. This is similar to the discovery of microwave burst timescales by Kruger et al. (1994). They classified the microwave burst timescales as tens of minutes, a few minutes, a few seconds, and sub-seconds which represent the main burst phase, main burst pulse, subpulse, and spiky burst elements, respectively. But, these bursts have no obvious periodicities. However, our investigations indicate that the most remarkable feature of QPPs is the quasi-periodicity of the repetitive pulses. What, then, is the generation mechanism of the various classes of QPPs?

It is well known that the harmonic motion of a classic mechanic oscillator is due to a restoring force proportional to the displacement, and any elastic body can be excited to oscillate in eigenmodes. When a magnetic field is present in plasma systems, the characteristic eigenfrequencies will be determined by the magnetic field, plasma density, temperature, and geometrical configurations of the magnetized plasma system. Aschwanden (1987) presented an extensive review of pulsation models and classified them into three groups.

1. MHD flux tube oscillations, which modulate the radio emissivity with standing or propagating MHD waves, e.g., slow magnetoacoustic mode, fast kink mode, fast sausage mode (Roberts et al. 1984; Nakariakov & Melnikov 2009).

2. Periodic self-organizing systems of plasma instabilities of wave–particle or wave–wave interactions interlocked by a Lotka–Volterra type of coupled equations (Aschwanden & Benz 1988).

3. Modulation of periodic acceleration (repetitive injection of particles into the emission source region) which may possibly be generated from repetitive magnetic reconnections, for example, the pulsed acceleration in solar flare (Aschwanden et al. 1994; Aschwanden 2004) or the multi-scale cascading reconnection processes in the current sheet (Kliem et al. 2000; Karlicky et al. 2005).

4.1. VLP Mechanism

At first, we investigate the generation mechanism of VLPs. From Table 1 we know that periods of VLPs are 220–270 s, which are very similar to the oscillations obtained by Aschwanden et al. (1999) from the TRACE 171 Å observations. In that case the period of oscillations is 276 s, and they interpret them as a standing fast kink mode and might be a resonant
coupling with the photospheric 5 minute $p$-mode oscillations. The period is expressed as

$$P_{\text{fast}} = \frac{2L}{sc_k} = \frac{4\pi^{1/2}L}{s} \left( \frac{\rho_o + \rho_e}{B_o^2 + B_e^2} \right)^{1/2} \approx 6.48 \times 10^{-17} L \sqrt{\frac{T_e}{B}}. \quad (1)$$

Here, the number of nodes is $s = 1$, $c_k = \left( \frac{\rho_o + \rho_e}{B_o^2 + B_e^2} \right)$ is the mean Alfvén speed for the inhomogeneous medium, $L$ is the loop length (m), $s = n_i m_i$ is the plasma density, and the subscripts $o$ and $e$ refer to the inside and outside of the loop, where $n_i \sim n_e$ (m$^{-3}$) and the magnetic field $B$ is in Tesla.

In our case, the active region AR 10930 is an isolated one on the solar disk during about 20 days before and after the flare event (Figure 13). It is structured mainly between two big sunspots, where the leading sunspot (marked as A in Figure 13) is about 50$^\circ$ (about 56,000 km), and the diameter of the following sunspot (marked as B in Figure 13) is about 15,000 km. Over these two sunspots there are many loops which connect from one sunspot to the other. We may assume that the foot-points are located near the ribbons (the thick black dotted lines in Figure 13). Then, we can estimate the lengths of the loops. The distance between two ribbons is in the range of 19.5–39$^\circ$, that is, about 14–28 Mm. Suppose the loops are semicircles; then, the loop lengths are $L = 44$–88 Mm. The plasma density and magnetic field strength of the emission source region are estimated as $n_e \sim 10^{11}$ cm$^{-3}$ and $B \sim 50$–200 G, respectively (Yan et al. 2007). Based on these parameters and Equation (1) we obtain the result that the period is in the range of 9.0–36 s. Even if we suppose that the estimation varies by a factor of 4, it would also be in the range of 2.5–144 s, too short to fit the observed periods of VLPs. Periods of the standing fast sausage mode or propagating MHD mode are shorter than that of the standing fast kink mode; it is not possible that they are candidate mechanisms of VLPs.

What about the standing slow MHD modes? We know that both the standing slow sausage mode and standing slow kink mode have periods

$$P_{\text{slow}} = \frac{2L}{sc_T} = \frac{2L}{sc_0} \left[ 1 + \left( \frac{c_0}{v_A} \right)^2 \right]^{1/2} \approx 1.30 \times 10^{-2} \frac{L}{\sqrt{T_e}}. \quad (2)$$

Here, $c_T = c_0 v_A / (c_0^2 + v_A^2)^{1/2}$ is the tube speed in magnetic flux tube, $c_0$ is the sound speed, $v_A$ is the Alfvén speed, and $T_e$ is the temperature in the plasma loop. We may use the brightness temperature to replace the plasma temperature approximately:

$$T \sim T_B = \frac{c^2 D^2 F}{k_B f^2 r^2} \approx 1.46 \times 10^{40} \frac{F}{f^2 r^2}. \quad (3)$$

Here, $c$ is the speed of light, $D$ is the distance between the Sun and the Earth, $F$ is the microwave emission flux intensity in units of sfu, and $r$ is the radius of the emission source region in units of m. As the microwave flux intensity ($F$) is from the whole Sun, it may include multiple loop sources. So, we may suppose that the emission source of $F$ will reasonably be about the size of the whole active region, i.e., the size of AR 10930, which will be about $r = 2 \times 10^5$ km. When $f = 3.2$ GHz, the mean microwave flux intensity $F = 300$ sfu, then $T \sim 1.22 \times 10^7$ K. Then we find that the period is 186.4–372.6 s, which is very close to the observed result of VLPs. So, we suggest that VLPs are possibly generated from standing slow MHD modes.

Figure 4 and Table 1 indicate that the magnitude of the pulsating emission flux of VLPs is in the range of 90–1200 sfu, which is very strong modulation. In fact, each pulse of the VLP is very much like a small eruptive process. We know that the kink mode can change the magnetic field by altering the direction. But it can change neither the magnitude of the magnetic field nor the plasma density of the loops directly. It is not clear how the kink mode produces so strong a modulation of the microwave emissions. We would believe instead that the VLP is generated by a standing slow sausage mode.

On the other hand, Kosovichev & Sekii (2007) found that the solar umbra of the leading sunspot had a 3 minute oscillation which started immediately after the hard X-ray peak (50–100 keV in RHESSI) and just before the soft X-ray maximum (GOES-12), with the amplitude exceeding that of pre-flare oscillations by a factor of 2–4. However, at the same time, Kosovichev & Sekii (2007) also pointed out that the 3 minute umbra oscillation is uncertain because of the poor observation cadence. As the periods of VLPs are 220–270 s, which are very close to the periods of the photospheric 5 minute $p$-mode oscillations ($P = 220–400$ s), we are apt to believe that Kosovichev & Sekii (2007) underestimated the periods of the umbra oscillations of the leading sunspot. The authors prefer to deduce that VLP is a result of standing slow sausage mode coupling and resonating with the underlying photospheric 5 minute $p$-mode oscillations. The modulation is amplified and constructs the main framework of the whole flare/CME eruptive processes.

4.2. LPP and SPP Mechanism

Figure 12 shows that almost all VLPs, LPPs, SPPs, and some slow-VSPs are distributed around a line in the logarithmic period–duration space; they are in the same QPP group. It is also reasonable to suppose that LPPs, SPPs, and some slow-VSPs have a generating mechanism similar to that of VLPs, in that they are at least also generated from some MHD modulations. From Equation (1) we get the period in the range of 2.5–144 s, which is consistent with the observed results of LPPs. Hence the standing fast kink mode may be the most plausible candidate mechanism of LPPs.

As for SPPs, the standing fast kink mode might not be a preferred candidate. The standing fast sausage mode should be...
the more preferred mechanism. Its period is
\[ P_{\text{sausage}}^{\text{fast}} = \frac{2\pi a}{c_t} \approx 2.02 \times 10^{-16} \frac{a \sqrt{\rho_e}}{B}, \]  
where \( a \) is the loop width (m). From Figure 13, we may estimate the loop width as about 1′′, i.e., 700–2000 km. Then, the period is 2.2–25.6 s. If the estimation varies by a factor of 4, it is in the range of 0.6–100 s, which includes the whole range of SPPs and possibly LPPs.

Actually, the propagating MHD mode has a period a factor of 0.6 shorter than that of the standing fast sausage mode. With the parameters in our case, the period is in the range of 0.4–60 s. Hence, the propagating MHD mode is also a possible mechanism of LPPs and SPPs.

Additionally, from Equations (1) and (4) we may find that the periods are most strongly dependent on the scales of the loop (length or section radius). AR 10930 is a complex active region; it is possible that there is a variety of plasma loops where the scales are smaller than the above estimation. With such smaller scale plasma loops, the periods of the standing fast kink modes or the standing fast sausage modes most likely extend to seconds and even to sub-seconds, which may explain the mechanism of LPPs, SPPs, and some slow-VSPs.

There is another alternative mechanism for QPPs with periods \( P > 1 \) s. Zaitsev et al. (1998, 2000) proposed that a coronal loop can be twisted and then carry an electric current. This current-carrying plasma loop becomes an LRC-circuit resonator, and the circuit oscillations can cause periodic modulation of loop magnetic field, energy release rate, and electron acceleration, and therefore the emission of non-thermal electrons (Khodachenko et al. 2005; Khodachenko et al. 2009). The eigenoscillation of the LRC-circuit resonator may be a possible mechanism of microwave QPPs. When the electric resistance can be neglected, the period of the circuit oscillations is
\[ P_{\text{LRC}} = \frac{2\pi}{c} \sqrt{\frac{L}{C}} \approx \frac{10^{12}}{I_p}. \]  
Here, \( L = 4l/(\log (\frac{\rho_e}{a}) - \frac{1}{2}) \) is the loop inductance and, \( C = \frac{\varepsilon_0 a^2}{2\pi l^2} \) is the effective loop capacitance. \( S = \pi a^2 \), where \( a \) is the loop section radius (m), \( l \) is the loop length (m), and \( \rho \) is the plasma mass density. \( I_p \) is the longitudinal electric current (A) in the loop. The LRC-circuit model has been used to explain microwave pulsation with periods of 0.7–17 s (Zaitsev et al. 2007, etc.); then we obtain that the oscillation period is about 200–300 s, which is much longer than the observed durations (2.2–23 s). The most reason is that there are many loops participating in the eruptive processes in the flaring region, and the pulsating structure is evident only when the contribution comes from a single flare loop. If the contribution comes from several loops, the pulsating structure will become diffuse or disappear because of superposition or interference. So, our observations of VSPs are always of fractional sections.

The duration is dominated by the current density distribution, magnetic configuration, and plasma resistivity, while the period of pulsation is dominated by the total electric current, the loop’s geometrical parameters, and the distribution of current density in the cross-section. At the same time, the pulsating emission is localized in some regions with small sizes, for example, localized around magnetic islands in flaring plasma loops. From the bandwidth of the emission we may estimate the perturbation of the plasma density. From the frequency drifting rate we may estimate the motion of the plasma loop and the motion of the energetic particles. Combining all these observable parameters, we may probe almost all the physical conditions and their evolution.

In brief, the long-period pulsation is possibly associated with a large-scale magnetized plasma loop, while the short-period pulsation is possibly associated with some small-scale configuration in the solar corona. The very short period pulsation may reflect some local information about flaring plasma loops.

On the other hand, as all extraordinary VSPs occurred essentially after the main burst of the flare/CME event, we may adopt the load/unload model (Nakariakov & Milinkov 2009) to interpret them. In the load/unload model, QPP is a side effect of transient energy releases, and the period is determined by a buildup of free energy, the mechanism of the energy release, and the energy outflow rate. We may suppose that the energy release mechanism is magnetic reconnection which is instantaneous and short-lived, and the energy outflow rate is determined by the magnetic configurations which do not change observably after the main burst of the flare/CME event. Then the period of the QPP will be determined mainly by the buildup of free energy. Naturally, immediately after the main burst of the flare/CME event, the source region becomes exhausted. So, the buildup of the free energy will take a long time, while the energy release lasts for much less time, and causes \( W_p \gg W_g \). The strong right-circular polarization indicates that the emission source arises in some small places with simple magnetic configurations.

4.3. VSP Mechanism

In contrast to VLPs, LPPs, SPPs, and some slow-VSPs (Group I), fast-VSPs and most slow-VSPs are attributed to another group (Group II), dispersively distributed away from the line (Figure 12). This implies that the generation mechanisms of fast-VSPs and some slow-VSPs are intrinsically different from those of Group I. In the work of Tan et al. (2007) and Tan (2008), VSP is explained as a result of modulations of the resistive tearing-mode oscillations in some electric current-carrying flare loops, and the pulsating emission is explained as plasma emission. The period is
\[ P_{\text{tear}} = \frac{4\pi^2 a^2 \sqrt{\varepsilon}}{I_p \sqrt{M \mu_0}} \approx 1.44 \times 10^{-9} \frac{a^2}{I_p} \sqrt{\frac{n_e}{M}}. \]  
Here, \( M \) is a parameter related to the distribution of the electric current in the plasma loop and the mode numbers of the tearing-mode perturbations, \( \mu_0 \) is the permeability of free space. From Figure 6 of Tan et al. (2007), we know that \( P_{\text{tear}} \) can produce almost all kinds of VSPs with a period of sub-seconds.

Additionally, the duration of the quasi-periodic pulsation structure is \( D \approx 0.1513 \left( \frac{\Delta}{j m B_0} \right)^{2/3} \frac{1}{A t_f} \) (Tan 2008), where \( \Delta \) is the tearing mode instability factor, \( m \) is the mode number, \( t_f \) is the Alfvén time scale (unit of second), \( j \) is the current density (unit of A m\(^{-2}\)), and \( B_0 \) is the radial derivation of the poloidal magnetic field. We obtain the plausible result that the duration is about 200–300 s, which is much longer than the observed durations (2.2–23 s). The most reason is that there are many loops participating in the eruptive processes in the flaring region, and the pulsating structure is evident only when the contribution comes from a single flare loop. If the contribution comes from several loops, the pulsating structure will become diffuse or disappear because of superposition or interference. So, our observations of VSPs are always of fractional sections.

5. SUMMARY

From investigations in this work, we obtain the following conclusions: the timescales of microwave QPPs associated with the X3.4 flare/CME event of 2006 December 13 in active region AR 10930 are distributed in a broad range from hectoseconds
(VLP), decaseconds (LPP), a few seconds (SPP), deciseconds (slow-VSP), to centiseconds (fast-VSP). These QPPs occurred successively around this event and form a broad hierarchy. Higher up in the hierarchy, QPPs have longer periods and durations, higher magnitude of the pulse emission fluxes, wider frequency bandwidths, and are more weakly circular polarized, with lower frequency drift rates; lower down in the hierarchy, QPPs have shorter periods and durations, lower magnitude of the pulse emission fluxes, narrower frequency bandwidths, and are more strongly circular polarized, with higher frequency drift rates.

In logarithmic period–duration space, VLPs, LPPs, SPPs, and some slow-VSPs are approximately distributed around a line which implies that all of them have a similar generation mechanism. Fast-VSPs and most slow-VSPs depart far from the above line which implies that they possibly have different mechanisms.

Estimates show that VLPs possibly resulted from the standing slow sausage mode coupling and resonated with the underlying photospheric 5 minute p-mode oscillations. It may be associated with the evolutionary behaviors of the internal solar structures. As VLPs have the largest magnitude of emission fluxes, we suggest that the modulations are amplified and form the main framework of the entire flare/CME eruptive processes. From Equations (2) and (3), we can estimate the radius of the emission source region as:

$$r \approx 9.3 \times 10^{21} \frac{P}{f L} F^{\frac{1}{2}}.$$  \hspace{1cm} (7)

Here, the period (P), radio central frequency (f), and radio emission intensity (F) can be obtained from radio observations, and the loop length (L) can be estimated from the optical or other imaging observations approximately. Then, we can obtain the radius of the radio emission source region (r) by adopting Equation (7) even if we have no radio imaging observations. By substituting the parameters obtained in the above sections, we find that the radii of the emission source regions from VLP graphs A, B, C, and D are 2.04 \times 10^5 km, 2.06 \times 10^5 km, 1.62 \times 10^5 km, and 0.92 \times 10^5 km, i.e., the source region is undergoing an evolutive process of expanding at first, and then shrinking. However, as we have no radio imaging observations at the corresponding frequencies, we do not know the exact sites of the emission source region; the only thing we can do is to adopt the averaged loop length in our above estimations, which may have many uncertainties.

Similar to VLPs, LPPs and SPPs (and some slow-VSPs) are also caused by MHD oscillations. However, their MHD modes may have some differences. They may be related to the standing fast sausage or kink modes. The propagating MHD modes and the LRC-circuit resonance of current-carrying plasma loops are also possible candidates of the generating mechanism.

Fast-VSPs and most slow-VSPs are generated by a completely different mechanism: the modulation of the resistive tearing-mode oscillations in electric current-carrying flare loops. In this mechanism, both the period and duration of QPPs are coupled with the magnetic field, plasma density, electric current, and the loop parameters. By using their relation, we may deduce the physical conditions of the emission source region.

The timescale of the periods of QPPs implies a limit on the pulsating emission source size. Regardless of the generating mechanism, the pulsating source must be smaller than that given by the product of the speed of light and period (P). If not, the pulsating structure would be smeared out (Elgarny, 1986). So, it is reasonable to suppose that the short periodic QPP may come from a smaller source region. The broad hierarchy of timescales of QPPs that occurred in a flare event may imply that there is a multi-scale hierarchy of sizes of the magnetic configurations in the flaring region and timescales of the dynamic processes. The frequency drift rate and the bandwidth of the pulsating emission are dominated by the emission mechanism which is always related to the magnetic field strength, plasma density, and possibly to the plasma temperature. It may be reasonable to suppose that the frequency drift features of QPPs imply the motion of the pulsating source regions, and the bandwidth of the pulsating emission is related to the dimensional size of the pulsating source regions.

The period ratio between different classes of QPPs have no obvious trend. This fact may imply that there is no original link between different classes of QPPs, even if they occurred simultaneously in the same frequency range. Actually, it is possible that the short periodic QPP (e.g., fast-VSP, etc.) is a small quasi-periodic perturbation superposed on the longer periodic QPPs (e.g., VLP, etc.), and the latter may dominate the whole evolution of the flaring processes.

However, so far, because of the lack of imaging observations with spatial resolutions in the corresponding frequency range, there are many unresolved problems regarding QPPs, such as, for example, the spatial behaviors, the spatial scales of the source region, etc. To overcome such problems, we need some new instruments, for example, the Chinese Spectral Radioheliograph (0.4–15 GHz) in the decimeter to centimeter-wave range currently under construction (Yan et al., 2009) and the proposed American Frequency Agile Solar Radiotelescope (50 MHz–20 GHz; Bastian, 2003). When these instruments begin to work, we may be able to get more insight into the solar eruptive processes.

The authors thank the referee for friendly and valuable comments on the paper. B.T.’s work is supported by NSFC grant nos. 10733020 and 10873021 and Y. Z.’s work is supported by NSFC grant No. 10903013. This work is also partly supported by MOST grant no. 2006CB806301 and CAS-NSFC no. 10778605.

REFERENCES

Abrami, A. 1970, Sol. Phys., 11, 104
Aschwanden, M. J. 1987, Sol. Phys., 111, 113
Aschwanden, M. J. 2004, ApJ, 608, 554
Aschwanden, M. J., & Benz, A. O. 1986, A&A, 158, 102
Aschwanden, M. J., & Benz, A. O. 1988, ApJ, 332, 466
Aschwanden, M. J., Benz, A. O., Dennis, B. R., & Kandu, M. R. 1994, ApJS, 90, 631
Aschwanden, M. J., Fletcher, L., Schrijver, C. J., & Alexander, A. 1999, ApJS, 520, 880
Bastian, T. 2003, Proc. SPIE., 2051, 98
Benz, A. O., Gudel, M., Isliker, H., Miszkowicz, S., & Stehling, W. 1991, Sol. Phys., 133, 385
Berger, M. A., & Field, G. B. 1984, J. Fluid Mech., 147, 133
Dulk, G. A. 1985, ARA&A, 23, 169
Elgarny, O. 1986, Sol. Phys., 104, 43
Fleishman, G. D., Fu, Q. J., Wang, M., Huang, G. L., & Milnikov, V. F. 2002, Phys. Rev. Lett., 88, 251101
Foullon, C., Fletcher, L., Hannah, I. G., Verwichte, E., Cecconi, B., Narkariakov, V. M., Phillips, K. J. H., & Tan, B. L. 2010, ApJ, 719, 151
Foullon, C., Verwichte, E., Narkariakov, V. M., & Fletcher, L. 2005, A&A, 440, L59
Fu, Q. J., Qin, Z. H., Ji, H. R., & Pei, L. B. 1995, Sol. Phys., 160, 97
Fu, Q. J., et al. 2004, Sol. Phys., 222, 167
Golwens, B. L. 1972, Sol. Phys., 25, 232
Inglis, A. R., & Narkariakov, V. M. 2009, A&A, 493, 259
