The microwave zebra pattern (ZP) is the most interesting, intriguing, and complex spectral structure frequently observed in solar flares. A comprehensive statistical study will certainly help us to understand the formation mechanism, which is not exactly clear now. This work presents a comprehensive statistical analysis of a big sample with 202 ZP events collected from observations at the Chinese Solar Broadband Radio Spectrometer at Huairou and the Ondřejov Radiospectrograph in the Czech Republic at frequencies of 1.00–7.60 GHz from 2000 to 2013. After investigating the parameter properties of ZPs, such as the occurrence in flare phase, frequency range, polarization degree, duration, etc., we find that the variation of zebra stripe frequency separation with respect to frequency is the best indicator for a physical classification of ZPs. Microwave ZPs can be classified into three types: equidistant ZPs, variable-distanced ZPs, and growing-distanced ZPs, possibly corresponding to mechanisms of the Bernstein wave model, whistler wave model, and double plasma resonance model, respectively. This statistical classification may help us to clarify the controversies between the existing various theoretical models and understand the physical processes in the source regions.

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

Online-only material: color figure

1. INTRODUCTION

As we have known, a zebra pattern (ZP) is a kind of spectral fine structure superposed on the solar radio broadband type IV continuum spectrum, which consists of several almost parallel and equidistant stripes. It is the most intriguing and interesting fine structure on the dynamic spectra of solar radio observations, especially at the microwave frequency range, which may reveal the original information of the solar flaring processes, such as the magnetic fields and their configurations, particle acceleration, and the plasma features in the source regions where the primary energy is released. The nature of ZP structures has been a widely discussed subject for more than 40 yr. The historical development of observations and various theoretical models is assembled in the reviews of Chernov (2006), Zlotnik (2009), and so on (Rosenberg 1972; Kuijpers 1975; Zheleznyakov & Zlotnik 1975; Chernov 1976, 1990; LaBelte et al. 2003; Kuznetsov 2005; Ledenev et al. 2006; Tan 2010; Karlický 2013). These models include the following.

1. Bernstein wave (BW) model. This is the first model interpreting the formation of a ZP structure. It proposed that all the stripes in a ZP structure are generated from a small compact source, and the emission originates from some nonlinear coupling processes, either between two Bernstein waves or a Bernstein wave and other electrostatic upper hybrid waves. The electrons with non-equilibrium distribution over velocities perpendicular to the magnetic field are located in a small source, where the plasma is weakly and uniformly magnetized ($f_{pe} \gg f_{ce}$). These electrons excite longitudinal electrostatic waves at a frequency of the sum of Bernstein modes frequency $f_{ce}$ and the upper hybrid frequency $f_{wh}$: \[ f = f_{wh} + f_{ce} \approx f_{pe} + s f_{ce} \]. Here, $f_{pe}$ is the electron plasma frequency, $f_{ce}$ the electron gyrofrequency, and $s$ the harmonics number. The BW excitation occurs in a relatively narrow frequency band. This model predicts the frequency separation between the adjacent zebra stripes just as the electron gyrofrequency: $\Delta f = f_{ce}$ (Rosenberg 1972; Chiuderi et al. 1973; Zheleznyakov & Zlotnik 1975; Zaitsev & Stepanov 1983), it approximates a constant.

2. Whistler wave (WW) model. This is an important model based on the propagation of whistler wave packets across or along the magnetic loop where the energetic electrons generate Langmuir waves (Kuijpers 1975; Chernov 1976; Maltseva & Chernov 1989). The quasi-standing whistler packets can be driven by the loss-cone distribution of fast electrons in the entire magnetic trap at some cyclotron resonance conditions. The coupling of plasma Langmuir waves and whistler wave packets can operate in different resonance conditions: when whistlers are generated at the normal Doppler cyclotron resonance, they can escape along the magnetic loop and yield fiber bursts ($f_{wh} - (k_0/2\pi) v_l - f_{ce} = 0$, $f_{wh}$ is the whistler wave frequency, $k_0$ is the whistler wave number paralleled to the magnetic field, and $v_l$ is the fast electron velocity paralleled to the magnetic field). When whistlers are generated at the anomalous Doppler cyclotron resonance ($f_{wh} - (k_0/2\pi) v_l + f_{ce} = 0$) under large angles to the magnetic field, they may form standing wave packets in front of the shock wave, and when the group velocity of whistlers is approximated to the shock velocity, a ZP structure with a slow oscillating frequency drift will appear. Each zebra stripe corresponds to one propagating whistler wave packet. The emission frequency at $f = f_{pe} + s f_{wh}$, $f_{wh} \approx 0.1-0.5 f_{ce}$ is the whistler wave frequency. Here, $f_{pe} \gg f_{ce}$. The frequency separation $\Delta f$ of adjacent zebra stripes is about two times that of the whistler wave frequency: $\Delta f \sim 2 f_{wh}$. As $f_{wh}$ varies in a small range, the whistler wave group velocity peaks at a frequency of $(1/4) f_{ce}$, therefore $\Delta f$ will vary around $(1/2) f_{ce}$.

3. Double plasma resonance (DPR) model. The most developed, heterogeneous ZP model is called DPR model, which proposed that enhanced excitation of plasma waves
occurs at some resonance levels where the upper hybrid frequency coincides with the harmonics of electron gyrofrequency in the inhomogeneous flux tube (Pearlstein et al. 1966; Zheleznyakov & Zlotnik 1975; Berney & Benz 1978; Wingee & Dulk 1986; Zlotnik et al. 2003; Yasnov & Karlický 2004; Kuznetsov & Tsap 2007): \( f_{\text{ab}} = (f_{p}^{2} + f_{c}^{2})^{1/2} = f_{ce} \). The emission frequency is dominated not only by the electron gyrofrequency, but also by the plasma frequency. When the emission is generated from the coherence of two excited plasma waves, the polarization may be very weak, the emission frequency is \( f \approx 2 f_{pe} \approx 2 f_{ce} \), and the stripe frequency separation is \( \Delta f = (2 f_{ce} H_{b}/|s H_{b} - (s + 1) H_{p}|) \). Here, \( H_{b} \) and \( H_{p} \) are the scale heights of the magnetic field and the plasma density in the source regions, respectively. When the emission is generated from the coherence of an excited plasma wave and a low frequency electrostatic wave, the polarization will be strong, the emission frequency is \( f \approx f_{pe} \approx f_{ce} \), and the stripe frequency separation is \( \Delta f = (s f_{ce} H_{p}/|s H_{b} - (s + 1) H_{p}|) \). In the DPR model, \( \Delta f \) has a regularly changing trend with a fairly large number of stripes. Here, \( \Delta f \) depends on \( H_{b} \) and \( H_{p} \), which therein depend on the models of the coronal magnetic field and plasma density. For most models, we can deduce that \( \Delta f \) will increase with respect to the frequency.

4. Propagating model. There are also some models that proposed that ZP stripes could be formed in the propagating processes after the emission is generated from source regions. The interference model suggests that a ZP is formed from some interference mechanisms in the propagating processes (Bártů & Karlický 2006; Ledenev et al. 2006). Some small, inhomogeneous layers may appear in the source region, and they can change the emission into direct and reflected rays. When the direct and reflected rays meet at certain places, interference will take place and produce a ZP. This model needs a structure with a great number of small, discrete sources, and such structures may exist in the current-carrying flaring plasma loop (Tan 2010) where the tearing-mode instability forms a great number of magnetic islands, which may provide the main conditions for the interference mechanism, similar to the crystal lattice. Very recently, Karlický (2013) proposed a new model that links ZPs with propagating compressive MHD waves. However, so far, using the propagating model, it is hard to predict the zebra stripe frequency separation, and the relationship between the zebra parameters and the magnetic field in the source region is also unknown.

Until now, the real formation of microwave ZPs has still been controversial. It is very difficult to interpret all observing properties by using a unique existing model. It is meaningful to make a classification of microwave ZPs. The different microwave ZPs may have different formation mechanisms. Therefore, a comprehensive statistical analysis of microwave ZPs is most necessary.

In previous literature, there are some statistical works on ZP structures (Huang et al. 2008, 2010; Huang & Tan 2012; Yu et al. 2012), but a physical classification is still missing. This work will present a comprehensive statistical investigation on the microwave ZPs at a frequency of above 1000 MHz. Section 2 introduces the observations and the composition of the statistical sample, and Section 3 presents the statistical properties of ZP parameters. A physical classification of ZPs is presented in Section 4. Finally, some conclusions discussions are summarized in Section 5.

2. STATISTICAL SAMPLE

2.1. Observation data

In this work, the statistical sample is obtained from the following two broadband solar radio spectrometers.

1. The Chinese Solar Broadband Radio Spectrometers at Huairou (SBRS/Huairou). SBRS is an advanced solar radio telescope with super high cadence, broad frequency bandwidth, and high frequency resolution, which can distinguish the super fine structures from the spectrogram (Fu et al. 1995, 2004; Yan et al. 2002). Its daily observational window is 0:00–8:00 UT during the winter seasons and 23:00–9:00 UT during the summer seasons. It includes three parts: 1.10–2.06 GHz (with the antenna diameter of 7.0 m), 2.60–3.80 GHz (with the antenna diameter of 3.2 m), and 5.20–7.60 GHz (with the same antenna as the second part). The antenna points to the center of the solar disk, and is automatically controlled by a computer. The spectrometer receives the total flux of solar radio emission with dual circular polarization (left- and right-handed circular polarization, LCP and RCP), and the dynamic range is 10 dB above quiet solar background emission. The observation sensitivity is \( S/S_{0} \leq 2\% \), where \( S_{0} \) is the quiet solar background emission. Our observation data includes the following.

- During 2000–2003 and 2006–2008, 1.10–2.06 GHz with a cadence of 5 ms and a frequency resolution of 4 MHz;
- During 2004–2005, 1.10–1.34 GHz with a cadence of 1.25 ms and a frequency resolution of 4 MHz;
- During 2000–2013, 2.60–3.80 GHz with a cadence of 8 ms and a frequency resolution of 10 MHz;
- During 2000–2008, 5.20–7.60 GHz with a cadence of 5 ms and a frequency resolution of 20 MHz.

2. Ondřejov radiospectrograph in the Czech Republic (ORS/Orsc). ORS is another broadband spectrometer located at Ondřejov, Czech Republic. It received solar radio total flux at frequencies of 0.80–5.00 GHz during 2000–2013 (Jíračka et al. 1993). Its daily observational window is 7:00–16:00 UT during the winter seasons and 6:00–17:00 UT during the summer seasons. Our observation data includes the following.

- During 2000–2005, 0.80–2.00 GHz with a cadence of 100 ms and a frequency resolution of 5 MHz; 2.00–4.50 GHz with a cadence of 100 ms and a frequency resolution of 10 MHz;
- During 2006–2013, 0.80–2.00 GHz with a cadence of 10 ms and a frequency resolution of 5 MHz; 2.00–5.00 MHz with a cadence of 100 ms and a frequency resolution of 12 MHz.

SBRS/Huairou and ORS/Ondřejov have an overlapping observational window: 7:00–8:00 UT during winter seasons and 6:00-9:00 UT during the summer seasons.

2.2. Statistical Parameters

It is necessary to clearly define a ZP event. Here we define a ZP event as an isolated spectral structure, which consists of at least two almost parallel stripes with an approximately equidistant separation and a slow frequency drifting rate. The time gap between two such adjacent, similar ZP events is at least longer than the duration of each ZP event, and the frequency
Table 1

List of Solar Flares with Microwave ZPs During 2000–2013

| Date       | Class | $t_{st}$ (UT) | $t_{fp}$ (UT) | $D_{ri}$ (min) | Phase | $N_{zp}$ | $f_{zp}$ (GHz) | Telescope          |
|------------|-------|---------------|---------------|----------------|--------|---------|----------------|-------------------|
| 2013 Apr 11| M6.5  | 06:58         | 07:16         | 18             | rising | 4       | 2.6–3.8        | SBRS, ORSC        |
| 2012 Jun 13| M1.1  | 12:04         | 13:15         | 71             | peak   | 3       | 1.3–1.8        | ORSC              |
| 2011 Aug 09| X6.9  | 08:00         | 08:04         | 4              | peak   | 1       | 2.6–3.8        | SBRS              |
| 2011 Feb 24| M3.5  | 07:26         | 07:35         | 9              | peak   | 2       | 2.6–3.8        | SBRS              |
| 2011 Feb 15| X2.2  | 01:46         | 01:56         | 10             | rising | 1       | 5.2–7.6        | SBRS              |
| 2010 Aug 01| C3.2  | 07:55         | 09:00         | 65             | rising | 8       | 1.1–1.5        | ORSC              |
| 2006 Dec 13| X3.4  | 02:14         | 02:40         | 26             | rising | 4       | 2.6–3.8        | SBRS              |
| 2006 Dec 05| X9.0  | 10:18         | 10:35         | 17             | rising | 6       | 2.4–3.6        | ORSC              |
| 2005 Jul 11| C1.0  | 16:33         | 16:37         | 4              | decay  | 2       | 1.3–1.6        | ORSC              |
| 2005 Jul 09| M2.8  | 21:47         | 22:06         | 19             | rising | 4       | 2.6–3.8        | SBRS              |
| 2005 Jan 01| C2.3  | 10:41         | 10:51         | 10             | rising | 1       | 1.0–1.3        | ORSC              |
| 2005 Jan 15| X2.6  | 22:25         | 23:02         | 37             | decay  | 1       | 1.1–2.06       | SBRS              |
| 2005 Jan 15| C1.2  | 02:22         | 00:43         | 21             | peak   | 1       | 2.6–3.8        | SBRS              |
| 2005 Jan 15| X1.2  | 02:54         | 06:37         | 43             | rising | 7       | 2.6–3.8, 1.1–1.34 | SBRS, ORSC       |
| 2004 Dec 02| M1.5  | 23:44         | 00:06         | 22             | rising | 4       | 1.1–1.34       | SBRS              |
| 2004 Dec 01| M1.1  | 07:00         | 07:20         | 20             | rising | 3       | 2.6–3.8, 1.1–1.34 | SBRS, ORSC       |
| 2004 Nov 10| X2.5  | 01:59         | 02:13         | 14             | decay  | 1       | 2.6–3.8        | SBRS              |
| 2004 Oct 30| M3.7  | 09:09         | 09:28         | 19             | rising | 2       | 2.1–3.4        | ORSC              |
| 2004 Oct 30| C3.7  | 12:45         | 12:51         | 6              | peak   | 1       | 2.1–2.4        | ORSC              |
| 2004 Sep 12| M4.8  | 00:04         | 00:56         | 52             | rising | 9       | 2.6–3.8        | SBRS              |
| 2004 May 17| C7.0  | 04:11         | 04:17         | 6              | peak   | 3       | 1.1–2.06       | SBRS              |
| 2004 Apr 06| M2.4  | 12:30         | 13:28         | 58             | peak   | 3       | 2.5–4.0        | ORSC              |
| 2004 Jan 09| M1.1  | 01:13         | 01:22         | 9              | peak   | 7       | 1.1–2.06       | SBRS              |
| 2004 Jan 05| M6.9  | 02:50         | 03:45         | 55             | rising | 2       | 1.1–2.06       | SBRS              |
| 2003 Nov 18| M3.9  | 08:12         | 08:31         | 19             | rising | 6       | 2.6–3.8        | SBRS              |
| 2003 Oct 28| X17   | 11:00         | 11:10         | 10             | decay  | 1       | 2.0–2.4        | ORSC              |
| 2003 Oct 26| X1.2  | 05:57         | 06:54         | 57             | rising | 14      | 1.1–2.06       | SBRS              |
| 2003 May 29| M1.5  | 02:09         | 02:18         | 9              | rising | 2       | 5.2–7.6        | SBRS              |
| 2003 May 27| M1.6  | 05:06         | 06:26         | 80             | rising | 1       | 1.1–2.06       | SBRS              |
| 2003 Mar 18| X1.5  | 11:52         | 12:08         | 16             | decay  | 1       | 2.0–2.4        | ORSC              |
| 2003 Jan 05| C5.8  | 05:51         | 06:17         | 26             | rising | 2       | 5.2–7.6        | SBRS              |
| 2002 Sep 17| C8.8  | 09:17         | 09:21         | 4              | peak   | 5       | 2.0–4.5        | ORSC              |
| 2002 Apr 21| X1.5  | 00:43         | 01:10         | 27             | decay  | 12      | 2.6–3.8        | SBRS              |
| 2001 Oct 19| X1.6  | 00:47         | 01:05         | 18             | rising | 5       | 2.6–3.8        | SBRS              |
| 2001 Sep 16| C4.3  | 07:40         | 07:45         | 5              | rising | 1       | 1.2–1.6        | ORSC              |
| 2000 Nov 25| M8.2  | 00:59         | 01:31         | 32             | rising | 10      | 2.6–3.8        | SBRS              |
| 2000 Nov 24| X2.0  | 04:55         | 05:02         | 7              | rising | 2       | 2.6–3.8        | SBRS              |
| 2000 Oct 29| M4.4  | 01:28         | 01:57         | 29             | decay  | 14      | 2.6–3.8        | SBRS              |
| 2000 Jun 06| X2.3  | 15:00         | 15:26         | 26             | decay  | 14      | 2.0–3.5        | ORSC              |
| 2000 Apr 09| M3.1  | 23:26         | 23:42         | 16             | rising | 1       | 2.6–3.8        | SBRS              |

Sum: 40 flares, 202 ZP events.

Notes. Class: the GOES soft X-ray class, $t_{st}$: flare start time, $t_{fp}$: flare peak time, $D_{ri}$: flare rising time, $t_{zp}$: the central time of ZP; $f_{zp}$: frequency range of ZP (GHz); $N_{zp}$: number of ZP events in the flare. SBRS indicates the Chinese Solar Broadband Radio Spectrometers at Huairou, and ORSC indicates the Ondřejov Radiospectrograph in the Czech Republic.

A gap between two such adjacent, similar ZP events is at least wider than the frequency range of each ZP event. Based on such a definition, we find that some flares have only one ZP event, while other flares may accompany several ZP events. By scrutinizing the broadband spectrograms, we find that there are 154 ZP events in 27 flares observed by SBRS, and 49 ZP events in 13 flares observed by ORSC during 2000–2013. There was only one ZP event observed simultaneously by SBRS and ORSC in an M6.5 flare on 2013 April 11. There were, in total, 202 ZP events in 40 flares, which are listed in Table 1.

In order to investigate the relationship between ZPs and the flaring processes, we define a phase time $P_{ph}$ to...
describe the relative time of ZP structure occurrence with respect to the maximum of solar flare:

\[ P_{ph} = \frac{(t_{zp} - t_{fp})}{(t_{fp} - t_{st})}. \]  

\( t_{zp} \) is the central time of ZP structure, \( t_{fp} \) and \( t_{st} \) are the peak and start times of the GOES soft X-ray (SXR) flare, respectively. \( t_{st} \) is defined when four consecutive one minute SXR values have met all three of the following conditions: (1) all four values are above the background threshold, (2) all four values are strictly, monotonically increasing, and (3) the last value is 1.4 times greater than the value that occurred three minutes earlier. \( D_{fr} = t_{fp} - t_{st} \) is the flare rising time. \( P_{ph} = -1.00 \) indicates the time at flare start, \( P_{ph} = 0 \) indicates the flare maximum (peak time), and \( P_{ph} > 0 \) indicates the time after the flare maximum. According to \( P_{ph} \), the flaring process can be partitioned into three phases.

1. Rising phase: \( P_{ph} \leq -0.25 \), SXR intensity is increasing rapidly. During this phase, the flaring region may continuously undergo magnetic flux emergence, reconnections, energy releasing, and plasma heating.

2. Peak phase: \( -0.25 < P_{ph} < 0.25 \), SXR intensity is relatively stable, and has only a slight variation. During this phase, the magnetic flux emergence and the magnetic energy releasing in the flaring region may reach a steady state.

3. Decay phase: \( P_{ph} > 0.25 \), SXR intensity is decreasing slowly and continuously. During this phase, besides some local, small-scale magnetic reconnections, the main energy releasing has ended, and the flaring region may undergo a process of thermal dissipations and cooling.

In the left panel of Figure 1, the dotted curve is an example profile of GOES SXR emission in a typical flare, the vertical, dashed lines partition flaring process into rising, peak, and decay phases. Right: ZP distribution with respect to the emission frequency.

Table 2
The Parameters of Microwave ZPs in a M8.6 Flare on 2005 January 15

| Phase | \( t_{zp} \) | \( P_{ph} \) | \( N_{str} \) | \( f_{zp} \) (MHz) | \( \Delta f \) (MHz) | \( \Delta f/f_{zp} \) (%) | \( r \) (%) | \( D_{zp} \) (s) |
|-------|-------------|-------------|-------------|-----------------|-----------------|----------------|---------|------------|
| rising | 06:13:10    | -0.55       | 5           | 1204            | 28              | 2.33           | 100     | 0.5        |
|       | 06:13:27    | -0.54       | 5           | 1296            | 36              | 2.78           | 100     | 4.0        |
|       | 06:14:58    | -0.51       | 2           | 2680            | 100             | 3.73           | 0       | 5.0        |
|       | 06:15:20    | -0.50       | 5           | 1192            | 26              | 2.18           | 100     | 2.0        |
|       | 06:16:32    | -0.48       | 2           | 2730            | 90              | 3.30           | 0       | 3.0        |
|       | 06:23:02    | -0.32       | 5           | 1196            | 18              | 1.51           | 100     | 0.8        |
|       | 06:24:34    | -0.29       | 4           | 1196            | 20              | 1.67           | 100     | 3.5        |
| peak   | 06:27:39    | -0.22       | 3           | 2750            | 105             | 3.82           | 0       | 4.0        |
|       | 06:28:36    | -0.22       | 3           | 2750            | 120             | 4.36           | 0       | 4.5        |
|       | 06:31:44    | -0.12       | 6           | 1240            | 52              | 6.77           | 0       | 30.0       |
| decay  | 06:49:10    | 0.28        | 5           | 1224            | 48              | 3.92           | 20      | 45.0       |
|       | 06:51:07    | 0.33        | 9           | 1180            | 18              | 1.53           | 85      | 0.8        |
|       | 07:17:32    | 1.18        | 8           | 1150            | 14              | 1.22           | 100     | 3.3        |

Notes. \( t_{zp} \): central time (UT); \( P_{ph} \): phase time, \( f_{zp} \): central frequency; \( \Delta f \): frequency separation of zebra stripes, \( \Delta f/f_{zp} \): relative frequency separation, \( N_{str} \): zebra stripe number, \( D_{zp} \): ZP duration, \( r \): averaged polarization degree.

In the right panel of Figure 1, the dotted curve is an example profile of GOES soft X-ray emission in a typical flare. The two vertical, dashed lines partition flaring process into rising, peak, and decay phases. Right: ZP distribution with respect to the emission frequency.
3. STATISTICAL RESULTS AND ANALYSIS

Based on the above sample of 202 microwave ZP events, we present comprehensive statistical investigations in this section.

3.1. The ZP Dependence with Flares

At first, we hope to know which kind of flares and what phase of the flare may be preferential to produce ZP phenomena. Table 1 indicates that among the 40 flares accompanying ZPs, there are 23 flares having ZPs at the rising phase, 14 flares having ZPs at the peak phase, and 12 flares having ZPs at the decay phase. There are only two flares having ZPs at all three phases (an M8.6 flare on 2005 January 15, and an X3.4 flare on 2006 December 13).

Table 1 also shows that there are 14 X-class flares with an averaged rising time of $D_{ri} = 25.5$ min, 18 M-class flares with an averaged rising time of $D_{ri} = 31.7$ min, and 8 C-class flares with an averaged rising time of $D_{ri} = 15.8$ min accompanying microwave ZPs. During the same observing period, the whole numbers of X-, M-, and C-class flares observed by the two instruments are 75, 805, and 1330, respectively, and their averaged rising times are 16.5 min, 14.8 min, and 11.5 min, respectively. Additionally, as for the flares accompanying microwave ZPs, the correlation coefficient between the flare's rising time and the ZP number is 0.56, which implies that they have a significant correlation. The comparison of these numerical values implies that flares with a longer rising time are preferential to produce microwave ZPs. At the same time, the powerful flares are more preferential to produce microwave ZPs than the relatively weak flares.

The left panel of Figure 1 presents the ZP distribution with respect to the phase time in flares, which shows that the microwave ZPs can occur in all rising, peak, and decay phases of flares. Among the 202 microwave ZPs, 96 (47.5%) occurred in the flare rising phase, 50 (24.7%) occurred in the flare peak phase, and 56 (27.8%) occurred in the flare decay phase. The histogram of the ZP distribution in Figure 1 implies that microwave ZPs are more preferential to originate before the flare maximum (64.9%).

3.2. The Parameter Properties of ZPs

3.2.1. ZP Frequency Distribution

Among the 202 ZPs, there are 72 ZPs with central frequencies in the range of 1.00–2.00 GHz, 87 ZPs with central frequencies in the range of 2.00–3.00 GHz, 37 with central frequencies in the range of 3.00–4.00 GHz, and only 6 ZPs with central frequencies above 4.00 GHz. However, there is a difference in observation time between different frequency ranges, we make a generalization on the above statistical values by the time lengths of the instrument observations at each frequency domain. Additionally, as the cadence of ORSC during 2000–2005 is 100 ms, which is much longer than after 2006 and SBRS/Huairou, we multiply a weight factor of 0.5 to its time length during the corresponding period, empirically. The right panel of Figure 1 is the ZP distribution with respect to the emission frequency, which shows that almost 90% of ZPs occur below 4.00 GHz, and 2.00–3.00 GHz is the most preferential frequency domain to produce ZP structures.

3.2.2. Polarization

Generally, the polarization sense of spectral fine structures is an important parameter. From Table 2, we may find that the microwave ZPs in the same flare may have almost all polarization modes from very weak (near 0) to very strong (near 100% at LCP or RCP). As there is no polarization observation from ORSC, here we only analyze the polarization properties of the 154 ZPs obtained by SBRS/Huairou. Among these 154 ZP events, 68 (44.2%) ZPs have a strong polarization degree ($\rho \geq 80\%$), 38 (24.7%) ZPs have a moderate polarization degree ($20\% < \rho < 80\%$), and 48 (31.1%) ZPs have no obvious polarizations ($\rho < 20\%$). This fact indicates that there are no dominant polarization modes in microwave ZPs.

3.2.3. Duration

Table 2 indicates that the durations of ZPs, even in same flares, are also distributed in a wide range from sub-second to several tens of seconds. The left-lower panel of Figure 2 presents the distribution of ZP durations with respect to the relative time of ZPs that occurred in the flares, which shows that ZP duration has a moderate linear increase from the flares early rising phase to its late decay phase. The dash-dotted line is a result of chi-square goodness linear fitting. Although the distribution is very disperse in the flare rising and peak phases, maybe the statistical averaged values of the ZP duration can give some supplementary inspirations. In the flare rising phase, the averaged ZP duration is 5.41 s with a variance of 8.85 s, and the relative variation is 1.64. Around the flare peak phase, the averaged ZP duration is 6.95 s with a variance of 11.03 s, and the relative...
variation is 1.59. However, in the flare decay phase, the averaged ZP duration is 17.55 s with a variance of 21.44 s, and the relative variation is 1.22, which is much smaller than those in the other two phases and in the whole sample.

Actually, the minimum duration in the whole sample (with 202 ZP events) is only 0.2 s, while the longest duration is 95 s, which covers about three orders of magnitude. The right panel of Figure 2 presents a histogram of the distribution of ZP numbers with respect to ZP durations. Here, we set the interval scale of the ZP duration in a power exponent of two. It is shown that there are 153 ZPs (75.7%) having durations in the range of 1–16 s, while only 23 ZPs (11.4%) have durations of <1.0 s, and 26 (12.9%) ZPs have durations of >16.0 s. This fact implies that the very short and very long duration ZPs are very rare.

3.2.4. Frequency Separation of Zebra Stripes

The frequency separations between the adjacent zebra stripes are in the range 14–340 MHz. It depends on the ZP central frequency. Generally, the higher the ZP central frequency, the wider the frequency separations among zebra stripes. We define a relative separation: Δf/fzp, here Δf and fzp are the zebra stripe frequency separation and the ZP central frequency, respectively. The sixth and seventh columns of Table 2 listed the Δf and Δf/fzp in a typical flare, which indicates that Δf/fzp is in the range of several percents. In fact, among the whole sample, the maximum of Δf/fzp can be as high as 10%, while the minimum can be as low as below 1%. Statistical calculation indicates that averaged Δf/fzp is 2.42% in the flare rising phase, 3.23% in the flare peak phase, and 2.49% in the flare decay phase. This variation can be fitted by an exponential curve, shown in the left-bottom panel of Figure 2 (the dash-dotted curve), although it is very scattered in a broad range around the flare peak.

It is very interesting to investigate the variations of the frequency separation with respect to its frequency in each ZP event. In order to make such an investigation, we just analyze the ZP events with at least four zebra stripes (there are at least three values of the frequency separation), and in total there are 151 ZP events occurring in 33 flares in our sample. Here, we find that three kinds of obviously different variations of the frequency separation exist.

1. Constant separation. The amplitude of Δf variation does not exceed the frequency resolution of the spectrometer, which can be approximately regarded as a constant. Panel A1 of Figure 3 is an example of this kind, and here the Δf variation is 4 MHz, which is just the frequency resolution of the telescope.

2. Varying separation. The amplitude of Δf variation exceeds the frequency resolution of the spectrometer, and is scattered in a wide range. Panel A2 of Figure 3 is an example of this kind, and here the total variation of Δf is 44 MHz, which is 11 times the frequency resolution (4 MHz) and has changes in addition and deletion.

3. Rising separation. The amplitude of Δf variation also exceeds the frequency resolution of the spectrometer and increases continuously with respect to its frequency. Panel A3 of Figure 3 is an example of this kind.

4. CLASSIFICATION OF ZPs

It is meaningful to make a physical classifications of the microwave ZPs, which may help us to understand the basic properties of their origin and applications to solar eruptions. However, so far, there is no such work in existing publications. The main reason is that it is very difficult to collect enough microwave ZP events to form a considerable, big sample for a reasonable physical classification. The statistical analysis in the above sections indicates that parameters of emission frequency, stripe frequency separation, polarization degree, stripe number, and the phase time in the associated flare are always distributed dispersively in wide ranges. For example, the ZPs that occurred in the flare rising phase may all have polarization degrees from very weak (r → 0) to very strong (r → 100%) circular polarized modes, as well as in the flare peak phase or the decay phase. Most of the other parameters also have similar dispersive characteristics.

However, the above analysis implies that it is very valuable when we combine duration and the variation of the frequency separation with respect to its frequency in each ZP event. According to these two factors, we may classify ZPs into three types with other parameters having a relatively narrow range. The detailed properties can be presented as follows.

Equidistant ZP (EZP) occurs when stripe frequency separation approximates to a constant. Among the 151 ZPs with more than four stripes, there are 55 ZPs belonging to an EZP, and their distribution to the duration is shown in panel B1 of Figure 3. Additionally, we find that (1) the durations of EZPs range from 0.3 s to 5.0 s, and most of them have durations around 1–2 s; (2) the average duration is 1.6 s. (2) Most EZPs have strong circular polarization, there are 33 short-duration ZPs observed by SBR5/Huairol which show that there are 20 events with strong circular polarizations, the averaged polarization degree r ∼ 70%. (3) Most EZPs occurred in the flare rising and peak phases, only 7 events occurred in the flare decay phase, and the averaged Pph = −0.31. (4) The zebra stripe number is less than 10 with an average value of about 6.5. (5) Most EZPs are simple and isolated, far away from the other spectral fine structures. The bottom-left panel of Figure 3 is an example of an EZP, which is a very simple and isolated ZP without any other fine spectral structures before or after it. The duration is only 0.6 s, with a strong, left-handed circular polarization.

Variable-distant ZP (VZP) occurs when stripe frequency separation varies in a wide range, with irregular increasing or decreasing. Among the 151 ZPs, there are 39 ZPs belonging to VZP, and their distribution to the duration is shown in panel B2 of Figure 3. Additionally, we find that (1) the duration of a VZP is in the range of 1.5–14 s, and most of them are around 2–10 s; the averaged value is 6.4 s. (2) The polarization degree has a very wide range from 0 to 100%. (3) VZPs can appear in flare rising or peak phases, as well as in flare decay phases. (4) The zebra stripe number of a VZP is also in a wide range of 2–28, and most of them are less than 10 stripes. (5) Most VZPs are relatively complex and always accompany other fine structures. The bottom-middle panel of Figure 3 is a typical example of a VZP, which occurred in the rising phase of an X1.2 flare on 2003 October 26. The duration is 2.2 s with weak polarization. It is a complex ZP modulated by a quasi-periodic pulsation with a period of about 100 ms, similar to the quasi-periodic wiggles modulated by some mass oscillations (Yu et al. 2013).

Growing-distant ZP (GZP) occurs when stripe frequency separation has a big variation and continuously increases with respect to its frequency. Among the 151 ZPs, there are 57 ZPs belonging to GZPs, and their distribution-to-duration ratio is shown in panel B3 of Figure 3. Additionally, we find that (1) their duration ranges from 0.2 s to 95 s, most of them are longer than 10 s, and the average duration is 27.6 s. (2) Most GZPs have moderate or very weak circular polarizations. Among these
57 GZPs, there are 35 events having a polarization degree of $r < 50\%$. (3) Most GZPs occurred in the flare decay phase. In total, there are 41 ZPs occurring in flare decay phase, and therefore 25 ZPs belong to a GZP. (4) Most GZPs have more than 15 zebra stripes; the average stripe number in each ZP is 14.9, which is much more than those occurring in EZPs and VZPs. (5) Most GZPs are very complex and accompanied by or superimposed with many other spectral fine structures, such as fibers, spikes, narrow-band type III bursts, fast quasi-periodic pulsations, etc. The bottom-right panel of Figure 3 is a typical example of a GZP, which occurred in the very deep decay phase of a long-duration X1.5 flare on 2002 April 21. The ZP duration is about 70 s; beside its left-handed circular polarization, one can distinguish bright zebra stripes, and zebra stripes can clearly...
be identified in the right-handed circular polarization. It is a very complex ZP, accompanying many other spectral fine structures. On the whole, it is a combination of a ZP structure with quasi-periodic wiggles at the relatively low frequency side, and a fiber structure at the relatively high frequency side. On the details, each zebra stripe consists of superfine millisecond spikes (Chernov et al. 2005, Chen & Yan 2007).

Figure 3 presents a clear comparison among the three kinds of ZP types. Actually, the comparison indicates that the above classification showed that different types of microwave ZPs would reveal different physical processes, although there is some overlap between EZPs and VZPs, or between VZPs and GZPs at certain durations. Sometimes, there may be a transition from an EZP to a VZP, or from a VZP to a GZP in the same ZP structure.

Since we know that the BW model demonstrated that the frequency separation between the adjacent zebra stripes is a constant and approximates the electron gyrofrequency $f_{ce}$, all stripes may originate from a small compact source region. The corresponding duration will be very short, and the resulting spectrum has only a few harmonics (less than ten). These items conform to the basic characteristics of the EZPs. Therefore, the BW model possibly reveals the basic mechanism of EZPs, and the stripe frequency separation can directly measure the magnetic field in the source region: $B \approx 3.56 \times 10^{-7} \Delta f$. Here, the unit of $B$ is G, and $\Delta f$ is Hz. Panel C1 of Figure 3 presents the magnetic fields in the source regions deduced from EZPs. Here, we find that the magnetic field strength ranges mainly from 10 G to 45 G, and has an increasing trend with emission frequencies.

The DPR model proposes that zebra stripes originate from some resonance levels where the upper hybrid frequency coincides with the harmonics of electron gyrofrequency in the inhomogeneous flux tube, and the frequency separation is dominated not only by the electron gyrofrequency, but also by the gradient of plasma density. Since the DPR levels present in the non-uniform trap and the kinetic instability can be excited by a small quantity of trapped non-equilibrium electrons, the DPR mechanism can provide a fairly large number of stripes (e.g., more than 20 stripes) in the ZP spectra, with comparatively long durations. Based on the common value of the magnetic field and plasma density around the flaring source region, we know that the frequency separation will slowly increase with respect to the frequency. These facts conform to the main characteristics of EZPs, which shows that the DPR model may explain their formation. By using the DPR model, we can also deduce the magnetic fields in the source region: $B \approx 3.56 \times 10^{-7} Q \cdot \Delta f$, $Q = (1/n)(2H_p/H_0 - 1)$, when polarization is strong $n = 1$, and when polarization is weak $n = 2$. The C3 panel of Figure 3 is the distribution of magnetic field strength with respect to emission frequency deduced from EZPs. The magnetic field strength ranges from 10 G to 75 G, which is more dispersed than that of EZPs and VZPs.

It seems very difficult to reasonably explain the formation of VZPs due to their irregular variation of frequency separations. The WW model demonstrated that the zebra stripe frequency separation is about $\Delta f = 2 f_w$, and the whistler wave frequency $f_w \approx 0.1–0.5 f_{ce}$, where $f_{ce} \ll f_{pe}$. Therefore, $\Delta f$ will have variations in a relatively narrow band. These properties seem to indicate that the WW model could be the possible mechanism to explain the formation of VZPs. Applying the WW model, an approximated estimation of the magnetic field in the source region can be obtained. Since we know that the whistler wave group velocity peaks at a frequency of $(1/4) f_{ce}$, this indicates that the frequency separation $\Delta f$ may vary around $(1/2) f_{ce}$. Then, we may estimate the magnetic field strength just by the frequency at whistler peak group velocity: $B \approx 7.12 \times 10^{-7} \Delta f$.

Panel C2 of Figure 3 is the distribution of the magnetic field strength with respect to emission frequency deduced from VZPs using the above method. Here, we find that the magnetic field strength ranges from 10 G to 145 G, which is a stronger and much wider distribution than that in the source of EZPs. However, we know that the WW model has many unresolved problems that need to be studied comprehensively. The diversity of the polarization sense of the VZPs implies that it is also possible that the VZPs may be a blended spectral structure produced by some combined mechanisms (for example, the propagating model, or the combination of DPR and WW models, etc.).

Because the BW mechanism requires a larger number of non-equilibrium electrons than the DPR mechanism, and there are more non-equilibrium electrons in the flare rising phase for the continuously magnetic reconnection than in the flare decay phase, the BW mechanism may be more preferential to work in the flare early phase and the small source region to produce EZPs. The DPR mechanism may be more preferential to work in the flare decay phase and produce GZPs from different resonance levels in a relatively stable flaring loop. In the flare decay phase, there are many small-scale magnetic reconnections and energy releases in the hot, magnetized plasma loops; many small-scale microwave bursts (Tan 2013) such as microwave spikes, narrow band type III bursts, and fast quasi-periodic pulsations or wiggles, may accompany microwave ZPs (Tan et al. 2007; Yu et al. 2013). In the WW mechanism, the low-frequency whistler waves are excited by non-equilibrium electrons with loss-cone distributions in coronal traps with intermittent non-uniform layers (Chernov 2006). Such conditions may appear in all phases of solar flares, and therefore VZPs may take place in all flaring phases.

5. CONCLUSIONS AND DISCUSSIONS

There are many parameters that can be applied to describe the characteristics of microwave ZPs associated with solar flares, such as the central frequency ($f_{zo}$), phase time ($P_{ph}$), polarization degree ($r$), zebra stripe number ($N_{zp}$), duration ($D_{zp}$), frequency separation between adjacent zebra stripes ($\Delta f$), and the relative value ($\Delta f/f$). However, from the statistical investigation, we find that most parameters cannot act as the classifying indicators of microwave ZPs, while the combination of duration and the variation of the frequency separation with respect to its frequency in each ZP event may provide a physical classification. With such a combination, we may classify the microwave ZPs into three types.

1. **EZP.** Simple and isolated with a constant frequency separation of the adjacent zebra stripes, very short duration (1.0–2.0 s), relatively strong polarization, less than ten stripes, and mainly occurring in the flare rising phase.

2. **VZP.** Relatively complex with an irregular, varying frequency separation of the adjacent zebra stripes and mid-term durations (2.0–10.0 s), diverse polarization modes, and always overlapped by some other structures, such as quasi-periodic pulsations or wiggles, etc.

3. **GZP.** Very complex with an increasing frequency separation of the adjacent zebra stripes and long duration (> 10 s), relatively weak polarization, and mainly occurring in the...
flaring source regions, many physical details are still not
theories of the BW model, WW model, and DPR model are far
sies among the existing various ZP models. Of course, since the
flaring source regions.

Different types of microwave ZPs may have different forma-
tion mechanisms, and therefore may reveal different physical
processes in the source regions. The main properties of EZPs
indicate that the BW model should be the best mechanism to
explain its formation. VZPs may originate from the WW wave
mechanism or from some complex multi-mechanisms, and the
DPR model may reveal the physical processes of GZPs. The es-
imation of the magnetic field strengths deduced from the above
models and ZP structures shows that the magnetic field in the mi-
trowave ZP source regions ranges from 10 G to 145 G, which
is in the acceptable domain of the magnetic field in coronal
flaring source regions.

The above classification may help us to clarify the controver-
sies among the existing various ZP models. Of course, since the
theories of the BW model, WW model, and DPR model are far
from perfect (Zlotnik 2009), many physical details are still not
clear. We do not know exactly which model is the best one to
explain the formation of a given ZP event. For example, it is dif-
ficult to distinguish whether a ZP with only three or fewer zebra
stripes belongs to an EZP, a VZP, or even a GZP. We have to
look for other properties of ZPs and further theoretical and ob-
servational investigations. The other problem is the formation of
VZPs for their diversity and irregularity, and it is possible
that they are formed from some complex mechanism. Addition-
ally, the question of why some zebra stripes are composed of
many millisecond spikes with super-high brightness tempera-
ts is still a problem. Also, what is the physical relationship
between a ZP structure and its inner millisecond spikes? We
need to study these questions more comprehensively, especially
the observational information with high spatial resolutions at
the corresponding frequencies.

From the statistical analysis, it is found that microwave ZPs
can occur in the flare rising and peak phases as well as in the
flare decay phase, and they are especially more prevalent to
originate from long-duration, powerful flares around a frequency
of 3.00 GHz. Such a fact implies that there are some common
characteristics attached to microwave ZPs. Since we know the
microwave emission source region around 3.00 GHz is possibly
very close to the core region of solar flaring and energy releasing,
microwave ZPs may reveal some fundamental nature of solar
eruptive processes.

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