MICROWAVE ZEBRA PATTERN STRUCTURES IN THE X2.2 SOLAR FLARE ON 2011 FEBRUARY 15

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ABSTRACT

A zebra pattern (ZP) structure is the most intriguing fine structure on the dynamic spectrograph of a solar microwave burst. On 2011 February 15, an X2.2 flare event erupted on the solar disk, which is the first X-class flare since the solar Schwabe cycle 24. It is interesting that there are several microwave ZPs observed by the Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou) at a frequency of 6.40–7.00 GHz (ZP1) and at a frequency of 2.60–2.75 GHz (ZP2) and by the Yunnan Solar Broadband Radio Spectrometer (SBRS/Yunnan) at a frequency of 1.04–1.13 GHz (ZP3). The most important phenomenon is the unusual high-frequency ZP structure (ZP1, up to 7.00 GHz) that occurred in the early rising phase of the flare and the two ZP structures (ZP2, ZP3) with relatively low frequencies that occurred in the decay phase of the flare. By scrutinizing the current prevalent theoretical models of ZP structure generations and comparing their estimated magnetic field strengths in the corresponding source regions, we suggest that the double plasma resonance model is the most probable one for explaining the formation of microwave ZPs, which may derive the magnetic field strengths at about 230–345 G, 126–147 G, and 23–26 G in the source regions of ZP1, ZP2, and ZP3, respectively.

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

1. INTRODUCTION

After a super-long quietness, the Sun began a new Schwabe cycle. On 2011 February 15, an X2.2 flare event erupted in the active region NOAA AR 11158 on the solar disk, which was the first X-class GOES flare of the current solar Schwabe cycle 24. Several instruments observed this event, including the Solar Dynamics Observatory (SDO), Nobeyama Radio Polarimeter (NoRP) and Nobeyama Radio Heliograph (NoRH), RHESSI, Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou), and Yunnan Solar Broadband Radio Spectrometer (SBRS/Yunnan). Especially from the broadband radio spectrogram observations at SBRS/Huairou and SBRS/Yunnan, strong microwave bursts with spectral fine structures, such as zebra patterns (ZPs) are registered. The most interesting and important phenomenon is the microwave ZP structures. We have registered three ZP structures at different frequency bands and in different phases of the flare. We will focus on investigating these ZP structures in this work.

A ZP is a fine spectral structure superposed on the solar radio broadband type IV continuum spectrogram that consists of several almost parallel and equidistant stripes. Most often, ZP structures are observed in meter and decimeter frequency ranges (Slottje 1972, etc.). In the microwave range, such a structure is very rare. From the publications up to now the highest frequency at which the ZP structure has been observed is about 5.70 GHz (Altyntsev et al. 2005). Recently, Chernov et al. (2011) found evidence of some ZPs evidence at a frequency of 5.70–7.20 GHz from the observations of a solar flare on 2003 May 29 obtained at SBRS/Huairou. However, it is too infrequent to observe the ZP structure at such a high frequency range. Additionally, ZP structures typically occur around the impulsive phase and/or the decay phase of solar flares. It is very rare to find a ZP structure in the early rising phase of a solar flare.

The formation mechanism of ZP structures has been a subject of wide discussion for more than 40 years. The historical development of observations and theoretical models are assembled in the review of Chernov (2006), Zlotnik (2009), and so on. There are several theoretical models for interpreting ZP structures, which are mainly developed to apply to meter and decimeter wavelengths (Rosenberg 1972; Kuijpers 1975; Zheleznyakov & Zlotnik 1975; Chernov 1976, 1990; LaBelle et al. 2003; Kuznetsov 2005; Ledenev et al. 2006; Tan 2010, etc.). These models can be classified into the following three classes.

1. Isogenous models—models which propose that all stripes in a ZP structure are generated from a small compact source.

The model of Bernstein mode (BM model) is the first one to interpret the formation of the ZP structure. The emission mechanism is the nonlinear coupling between two Bernstein modes, or the Bernstein mode 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 magnetized ($f_{pe} \gg f_{ce}$), and the magnetic field is uniform. These electrons excite longitudinal electrostatic waves at a frequency of the sum of the so-called Bernstein mode frequency $f_{be}$ and the upper hybrid frequency $f_{uh}$. The BM excitation occurs in a relatively narrow frequency band. The emission frequency (Rosenberg 1972; Chiuderi et al. 1973; Zaitsev & Stepanov 1983) is

$$f = f_{uh} + s f_{ce} \approx f_{pe} + s f_{ce}. \quad (1)$$

Here, $f_{pe}$ is the electron plasma frequency, $f_{ce}$ is the electron gyrofrequency, and $s$ is the harmonics number. This model presents the frequency separation between the adjacent zebra stripes just as the electron gyrofrequency: $\Delta f = f_{ce}$ (Zheleznyakov & Zlotnik 1975).

2. Heterogenous models—models which propose that zebra stripes in a structure are generated from some extended source regions in the magnetic flux tube (Kuijpers 1975; Fomichev & Fainshtein 1981; Mollwo 1983; Ledenev et al. 2001; Chernov et al. 2005; Altyntsev et al. 2005).


One of the important heterogenous models is based on the plasma waves interaction with whistler waves (Chernov 1996, 2006), called the whistler wave model (WW model). The coupling of the plasma wave and WW can operate in different conditions: when whistlers generate at the normal Doppler cyclotron resonance they can escape along the magnetic loop and yield fiber bursts; when whistlers generate at the anomalous Doppler cyclotron resonance 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. The WW group velocity peaks at whistler frequency $f_w \sim 0.25 f_{ce}$. The frequency separation $\Delta f$ between adjacent zebra stripes is about two times the whistler frequency: $\Delta f \approx 2 f_w$, and then we may obtain $f_{ce} \sim 2\Delta f$.

The most developed heterogenous model for ZP structure generation is called the double plasma resonance model (DPR model), which explains the ZP structure in a natural way (Pearlstein et al. 1966; Zheleznyakov & Zlotnik 1975; Berney & Benz 1978; Winglee & Dulk 1986; Zlotnik et al. 2003; Yasnov & Karlicky 2004; Kuznetsov & Tsap 2007).

This model proposes that the 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:

$$f_{ah} = \left( f_{pe}^2 + f_{ce}^2 \right)^{1/2} = s f_{ce}. \quad (2)$$

The emission frequency is dominated not only by the electron gyrofrequency but also by the plasma frequency. When the emission is generated from the coalescence of two excited plasma waves, the polarization may be very weak, the emission frequency is $f \approx 2 f_{pe} \approx 2 s f_{ce}$, and the frequency separation between the adjacent zebra stripes is $\Delta f = (2 s f_{ce} H_b / s H_b - (s + 1) H_p)$. Here, $H_b = f_b (d f_b / d r)^{-1} = B (B / d r)^{-1}$ and $H_p = f_p (d f_p / d r)^{-1} = 2 n_e (d n_e / d r)^{-1} = 2 H_n$. $H_b$ and $H_p$ are the scale heights of magnetic field $B$ and the plasma density $n_e$ in the source regions, respectively. For $f_{ce} \ll f_{pe}$ and $s \gg 1$, we may obtain

$$\Delta f \approx \frac{2 H_b}{|H_b - 2 H_n|} f_{ce}. \quad (3)$$

When the emission generates from the coalescence 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 frequency separation between the adjacent zebra stripes is $\Delta f = (s f_{ce} H_b / s H_b - (s + 1) H_p)$. For $f_{ce} \ll f_{pe}$ and $s \gg 1$, we may obtain

$$\Delta f \approx \frac{H_b}{|H_b - 2 H_n|} f_{ce}. \quad (4)$$

Equations (3) and (4) indicate that the frequency separation between the adjacent zebra stripes is dominated by both the scale heights of the magnetic field and plasma density.

Ledenev et al. (2001) proposed another heterogenous model to interpret the formation of ZP structures. This model (named the Ledenev model) suggests that the emission is generated from an anisotropic energetic electron beam at low cyclotron harmonics in a significantly inhomogeneous magnetic field. The electron beam is formed as a result of a fast local energy release in the corona, such as magnetic reconnection, and it will excite longitudinal waves at the normal Doppler resonance. The coalescence of upper hybrid waves and low-frequency longitudinal waves $(U + L \rightarrow T)$ can produce electromagnetic waves $(T)$. This model gives the cyclotron frequency harmonics ratio as (Sawant et al. 2002)

$$\frac{f_s}{f_{s+1}} = f_{pe,s} \left[ \frac{s^3 (s + 2)}{(s + 1)^3 (s - 1)} \right]^{1/2}. \quad (5)$$

Here, $f_{pe,s}$ and $f_{pe,s+1}$ are the electron plasma frequencies corresponding to the level of $s$ and $s + 1$ harmonics. If density changes slowly in source regions, then $f_{pe,s} \approx f_{pe,s+1}$, and the frequency ratio of the cyclotron frequency harmonics can be presented roughly as $s = 2$, $f_2/f_3 \approx 1.089$; $s = 3$, $f_3/f_4 \approx 1.027$; $s = 4$, $f_4/f_5 \approx 1.012$; $s = 5$, $f_5/f_6 \approx 1.006$, etc. In this regime, the magnetic field strength in the source region can be estimated: $B \approx (f_{\text{max}}/2.8 \times 10^5 s) (G)$, where $f_{\text{max}}$ is the frequency on the zebra stripe with maximum harmonic number $s$.

3. Propagating models—models which propose that ZP stripes are formed in the propagating processes after being emitted from its source region. The interference model suggests that ZP is possibly formed from some interference mechanism in the propagating processes (Ledenev et al. 2006). They suppose that some inhomogeneous layers with a small size may exist in the solar coronal plasma, and such structure will change the radio wave into direct and reflected rays. When the direct and reflected rays meet at some places, interference will take place and form the ZP structure. However, this model needs a structure with a large number of discrete narrowband sources of small size. Tan (2010) proposed that such a structure may exist in the current-carrying flaring plasma loop, where the tearing-mode instability forms a large number of magnetic islands that may provide the main conditions for the interference mechanism. ZP is the most intriguing fine structure on the dynamic spectrogram of solar radio observations, and the microwave ZP structures, especially, may provide the original information of the solar flaring region, such as the magnetic field, particle acceleration, and the plasma parameters, etc. In this work, the observations and data analysis of the microwave ZP structures associated with the X2.2 flare are presented in Section 2. Section 3 presents the physical discussion on the microwave ZP structures, especially the estimations of the magnetic field strengths from different ZP models, and pinpoints the reasonable interpretation of the ZP structures. Finally, some conclusions are summarized in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

The active region AR 11158 appeared near the center of the solar disk in the rising phase of the current solar cycle 24. It developed from a simple $\beta$- to a complex $\beta \gamma \delta$-configuration rapidly during 2011 February 12–21. It produced an X2.2 flare on 2011 February 15. This flare was a two-ribbon white-light flare shown in the image of the Helioseismic and Magnetic Imager on board SDO and accompanied with a large coronal
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Figure 1. Panels (1)–(8) show profiles of the microwave flux at frequencies of 1.00, 2.00, 2.85, 3.75, 6.82, 9.40, 17.00, and 35.00 GHz in 01:45 to 02:30 UT, 2011 February 15. NoRP indicates the observation of Nobeyama Radio Polarimeter, and SBRS/Huairou indicates the observation of the Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou). Panel (9) shows the GOES soft X-ray profiles at 1–8 Å (GOES8) and 0.5–4 Å (GOES4), and the plasma temperature induced from the GOES soft X-ray emission. The arrows indicate the positions of ZP structures on the profiles.

mass ejection that launched toward the Earth. From the soft X-ray emission obtained by GOES, the flare starts at 01:46 UT, reaches its maximum at 01:56 UT, and ends at 02:07 UT (Maurya et al. 2011).

In this work, we focused on the observations obtained from SBRS/Huairou and SBRS/Yunnan. SBRS/Huairou is an advanced solar radio telescope with a super-high cadence, broad frequency bandwidth, and high-frequency resolution that can distinguish the super-fine structures from the spectrogram (Fu et al. 1995, 2004; Yan et al. 2002). It includes three parts: 1.10–2.06 GHz (with the antenna diameter of 7.0 m, cadence of 5 ms, frequency resolution of 4 MHz), 2.60–3.80 GHz (with the antenna diameter of 3.2 m, cadence of 8 ms, frequency resolution of 10 MHz), and 5.20–7.60 GHz (share the same antenna of the second part, cadence of 5 ms, frequency resolution of 20 MHz). The antenna points to the solar center automatically controlled by a computer. The spectrometer can receive the total flux density of solar radio emission with dual circular polarization (left- and right-handed circular polarization), and the dynamic range is 10 dB above quiet solar background emission. The observation sensitivity is $S/S_0 \lesssim 2\%$, where $S_0$ is quiet solar background emission. Similar to several other spectrometers, such as Phoenix (100–4000 MHz; Benz et al. 1991), Ondřejov (800–4500 MHz; Jiricka et al. 1993), and the Brazilian Solar Spectroscope (200–2500 MHz; Sawant et al. 2001), SBRS/Huairou has no spatial resolution. However, as the Sun is a strong radio emission source, a large number of works (e.g., Dulk 1985, etc.) show that the microwave bursts received by spectrometers are always coming from the solar active region when the antenna points to the Sun. Additionally, we also adopt the observations at SBRS/Yunnan, which has an operating frequency band of 0.65–1.50 GHz, with a spectral resolution of 1.4 MHz, and time resolution of 80 ms, by using a 10 m diameter antenna.

During the X2.2 flare, SBRS/Huairou had two parts (2.60–3.80 GHz and 5.20–7.60 GHz) on duty, and SBRS/Yunnan and NoRP also obtained perfect radio observations. Figure 1 presents the profiles of the microwave flux at frequencies of 1.00, 2.00, 2.85, 3.75, 6.82, 9.40, 17.00, and 35.00 GHz in 01:45–02:30 UT observed at SBRS/Huairou and NoRP. As a comparison, the profiles of GOES soft X-ray intensities at wavelengths of 1–8 Å (GOES8) and 0.5–4 Å (GOES4) are plotted in panel (9) of Figure 1. Additionally, the plasma temperature derived from the ratio of GOES soft X-ray emission fluxes at the two wavelength bands (Thomas et al. 1985) is also overplotted. Here, we find that the maximum temperature (at about 01:53 UT) occurs about three minutes prior to the GOES flare peak (01:56 UT).

From scrutinizing the microwave spectrogram, we find that there is a strong microwave type IV burst with a spectral continuum in the frequency range of 0.65–1.50, 2.60–3.80, 5.20–7.60 GHz, and the corresponding microwave
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Figure 2. Left panel is the spectrogram of the zebra pattern that occurred at a frequency of 6.40–7.00 GHz and was observed by SBRS/Huairou at 01:49:50–01:49:51.5 UT, 2011 February 15. The white dashed curves outshine the zebra stripes. The right panel is the profile of emission flux at a frequency of 6.80 GHz in the same time interval as the zebra pattern. A, B, and C represent, respectively, the stripes at high, middle, and low frequencies, which intersect with the horizontal level at a frequency of 6.80 GHz in the left panel.

enhancements also occurred at frequencies of 9.40, 17.00, and 35.00 GHz. Superposed on these continuum enhancements, we identify many kinds of fine structures, such as type III bursts, spike bursts, patches, fast quasi-periodic pulsations (QPPs), fibers, and ZP structures. The main part of the microwave bursts at low frequencies occurred after the GOES flare peak. However, at the higher frequency range, the main part of the microwave bursts is prior to that of lower frequencies. Most of the fine structures occurred at the moderate frequency band of 2.60–3.80 GHz after the GOES flare peak. Only one segment of the microwave ZP structure occurred prior to the GOES flare peak (marked as ZP1 in Figure 1) when the frequency was around 6.70 GHz.

In this work, our interest is mainly focused on microwave ZP structures. There are three segments of microwave ZP structures registered on the microwave spectrogram: the first one occurred at a frequency of about 6.70 GHz (ZP1), the second one at about 2.68 GHz (ZP2), and the third one at about 1.08 GHz (ZP3). With a simple glance, we find that the higher frequency of the ZP structure appears at the earlier flare phase, while the lower frequency of ZP structures takes place in the later flare phase. The following are the details.

1. Microwave ZP Structure at 6.40–7.00 GHz. In the frequency of 5.20–7.60 GHz, the microwave emission always behaves as a continuous type IV burst, and the fine structure is very rare during solar flares. Therefore, it is an interesting phenomenon that a ZP structure occurred at a frequency of around 6.70 GHz in the X2.2 flare. The left panel of Figure 2 is the spectrogram of the ZP structure observed by SBRS/Huairou. It shows that the frequency range of the structure occurred from 6.40 to 7.00 GHz with a central frequency of 6.70 GHz. The time interval is from 01:49:50.2 to 01:49:51.5 UT, just about four minutes after the onset of the flare (01:46 UT) and about six minutes before the GOES flare peak (01:56 UT). The duration of the ZP structure lasted for about 1.3 s. It is composed of three stripes in a distorted sinusoidal wave shape arrayed on the longitudinal direction. The whole sinusoidal wave shape drifts slowly to the low frequency, and the drifting rate is about −300 MHz s⁻¹. The frequency bandwidth of the zebra stripes is about 40–60 MHz. The frequency separation between the adjacent zebra stripes is about 80–120 MHz, and the relative frequency separation is \( \Delta f/f \simeq 1.17\%–1.76\% \) and increases slowly with respect to time. The emission of the structure is strongly left-handed circular polarized with a polarization degree (defined as \( \text{pol} = (R - L)/(R + L) \times 100\% \); here \( R \) and \( L \) are the emission flux subtracted the background emission) close to 100%. Additionally, the ZP presents superfine structures: each zebra stripe consists of millisecond spikes that are practically vertical bright lines in the spectrogram with a duration at the limit of the time resolution (5 ms) and a bandwidth of about 40–60 MHz.

The right panel of Figure 2 is the temporal profile of the microwave flux at a frequency of 6.80 GHz associated with the ZP1 structure. In this figure, the average level of the ambient background emission before and after the ZP structure is also presented (the dashed line), which is about 535 sfu at left- and right-handed circular polarization. The intensity of the zebra stripes has enhancements of about 40–80 sfu with respect to the ambient emissions, which is much higher than the instrument sensitivity (here 2% \( S_\odot \) is about 4–5 sfu at a frequency of 6.20–7.20 GHz). The positions of stripes are marked with the letters A, B, and C,
which represent, respectively, the stripes at high, middle, and low frequencies. At the same time, Figure 2 is also implying another feature: the emission intensity on the zebra stripes decreases from the low-frequency stripe to the high-frequency stripes.

Figure 2 indicates that the zebra stripes of ZP1 are in distorted sinusoidal wave shapes. If we suppose that the pattern is a mixture of a general ZP structure and a QPP, then it is easy to understand the distorted sinusoidal wave shapes. Figure 3 is the result of Fast Fourier Transformation (FFT) analysis on the microwave emission at a frequency of 6.80 GHz, which indicates that the period of QPP is about 375 ms. This QPP belongs to a very short period pulsation (VSP).

2. Zebra Pattern Structure at 2.60–2.75 GHz. The second ZP structure is a weak one (marked as ZP2 in Figure 1) at a frequency of 2.60–2.75 GHz at 02:01:19–02:01:21 UT on the left-handed circular polarization spectrogram observed by SBRS/Huairou (Figure 4). There are two stripes in this structure that can be discriminated from the spectrogram. The frequency separation between the adjacent zebra stripes is 60–70 MHz, and the relative frequency separation is about $\frac{\Delta f}{f_0} \simeq 2.23%-2.60\%$. The ZP structure lasts for about 1.5 s. It is so weak, that the emission flux at the zebra stripes is only 15–25 sfu higher than that of the background emissions. In the first-half part of the ZP structure, the frequency drift rate is about 26–42 MHz s$^{-1}$ with an average value of about 35 MHz s$^{-1}$. In the second half, the frequency drift rate reverses to about $-67$ to $-90$ MHz s$^{-1}$, with an average value of about $-78$ MHz s$^{-1}$. The average value of the drift rate in the whole structure is approximated to 0. From Figure 4, it is reasonable to assume that the ZP structure would be extended to the frequency range lower than 2.60 GHz and the stripe number should be $>2$. However, as lack of observation at the lower frequency range, we could not confirm this conjecture.

Figure 3. FFT analysis on the microwave emission at a frequency of 6.80 GHz; the upper panel is the profile of emission intensity, and the lower panel is the spectral power of the FFT analysis.

Figure 4. Spectrogram of a zebra pattern structure at a frequency of 2.60–2.75 GHz observed by the Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou) at 02:01:19 to 02:01:21 UT on 2011 February 15.
From the background of ZP2 on the spectrogram, a fast QPP is also registered with a frequency band of 2.62–2.90 GHz and a period of about 30 ms. On the high-frequency side of the ZP structure, a group of dot bursts occurred at 2.92–3.09 GHz, whose frequency bandwidth is about 75–85 MHz, the polarization degree is pol $\sim 30\%–35\%$ at the right-handed circular polarization, and the lifetime of a single dot burst is in the range of 0.12–0.28 s. The distribution of the dots has a frequency drift rate of 180 MHz s$^{-1}$.

Several clusters of fiber bursts on the spectrogram occurred after the flare peak at a frequency of 2.60–3.00 GHz. One example of the fiber burst occurred at 02:03:34–02:03:43 UT and was observed by SBRS/Huairou. The frequency drift rates of the fibers are in the range of $-211.9$ MHz s$^{-1}$ to $-403.2$ MHz s$^{-1}$, with an average value of $-303.5$ MHz s$^{-1}$. This frequency drift rate is much faster than previous observations (e.g., the value was in the range of 42.3–87.4 MHz s$^{-1}$ in the observations at the similar frequency range of Wang & Zhong 2006, etc.). The central frequency is about 2.80 GHz. The polarization of the fiber emission is strongly left-handed circular polarized, and the polarization degree is pol $\sim 90\%$.

Two type III bursts were also observed by SBRS/Huairou. The first type III burst occurred at a frequency of 2.62–2.90 GHz at 02:07:50.70–02:07:50.85 UT, the frequency bandwidth is 280 MHz, and its frequency drift rate is in the range of 11.25–11.67 GHz s$^{-1}$. The second type III burst occurred at a frequency of 2.64–2.93 GHz at 02:07:51.55–02:07:51.67 UT, the frequency bandwidth is 290 MHz, its frequency drift rate is around 12.81 GHz s$^{-1}$, and it is also weakly right-handed circular polarized with pol $\sim 20\%–25\%$.

3. Zebra Pattern Structure at 1.04–1.13 GHz. It is obvious that a ZP structure occurred at 1.04–1.13 GHz at 02:10:56.8–02:11:00 UT on 2011 February 15, which is 15 minutes after the flare peak time (Figure 5). It was observed by SBRS/Yunnan and marked as ZP3 in Figure 1. Figure 6 presents the spectrogram, which indicates that there are five stripes in the ZP structure, and the duration is about 3.2 s. In the first half of the structure (before 02:10:58.6 UT), the frequency drift rate approximates to 0, but in the second half of the structure (after 02:10:58.6 UT), the frequency drift rate is about $-98$ MHz s$^{-1}$. The frequency separation between the adjacent zebra stripes is 14–16 MHz, and the relative frequency separation of the zebra stripes is about $\Delta f/f \simeq 1.3\%$. The emission of the ZP structure is mildly right-handed circular polarized, with a polarization degree pol $\sim 35\%–40\%$.

Recently, a similar ZP structure in the decay phase of an X1.5 flare was registered at a frequency of 1.20–1.40 GHz from the observations of the Frequency Agile Solar Radiotelescope Subsystem Testbed and the Owens Valley Solar Array on 2006 December 14 (Chen et al. 2011). The main properties (central frequency, frequency separation, and the frequency drifting rate, etc.) are very similar to the ZP3 of this work.

Figure 6 presents the features of the image of extreme ultraviolet 171 Å observed by the SDO Atmospheric Imaging Assembly (AIA) and the solar radio intensity contours of the left-(dashed) and right-(solid) handed polarizations at a frequency of 17 GHz observed at NoRH just one and a half minutes before ZP1 and only two minutes after the onset of the flare. From this figure, we find that the flare eruptive process started from several separate small regions, which behave as several small discrete bright points on the image at an extreme ultraviolet 171 Å observed by SDO/AIA. The microwave emission, with a maximum intensity of 17 GHz, was also distributed close to the small discrete bright points. These facts indicate that the magnetic reconnection and the energy release may break out from several places of a small size. ZP1 starts at this rising phase, where most of the stored magnetic energy has not been released, and the magnetic field in the active region remains strong. The plasma in the magnetic loops may become very dense because of the confinement of the strong magnetic field. The magnetic reconnection accelerates electrons to form anisotropic energetic electron beams that can
excite low-frequency electrostatic waves, then couple with the upper hybrid plasma waves and form ZP structures.

Additionally, from Figure 1 we find that the temperature associated with the source region plasma is about 22 MK, 16 MK, and 15 MK corresponding to the ZP structures occurring at frequencies of 6.40–7.00 GHz, 2.60–2.75 GHz, and 1.04–1.13 GHz, respectively.

Table 1 is a brief summary of the ZP structures observed in this flare event. Here, the method of derived plasma density will be introduced in the next section. We find that the frequency separation between zebra stripes increases with respect to the central emission frequency, and the number of zebra stripes decreases with respect to the central emission frequency.

In an ordinary ZP structure, the frequency separation between the adjacent stripes grows with the emission frequency: from 4–5 MHz at 200 MHz to about 80 MHz at 3.0 GHz, and the relative frequency separation of the zebra stripes is about constant: \( \Delta f/f \approx 2\%–3.5\% \). However, in this X2.2 flare event, we find that ZP1 and ZP3 have a narrow relative frequency separation of the zebra stripes, which is smaller than 1.8%, although the relative frequency separation of ZP2 stripes is very close to the above general ZP structure.

Table 2 presents the frequency ratio of the adjacent zebra stripes in each ZP structure. We find that the frequency ratios of the adjacent zebra stripes are approximated to a constant of about 1.020 in ZP1 and 1.013 in ZP3. This feature is much more obvious in ZP3 where there are five zebra stripes, and while the maximum ratio is 1.015 and the minimum ratio is 1.012, all of them are very close to 1.013. This fact indicates that the Ledenev’s model is not suitable to interpret the formation of the ZP structures observed in this work.

3. PHYSICAL DISCUSSION ON THE ZEBRA PATTERNS

At first, almost all the theoretical models (BM model, WW model, or DPR model) for the generation of ZP structures indicate that the ZP emission frequencies are approximately around the plasma frequency or its second harmonics. With this point, the plasma density in the ZP source regions can be estimated: \( n_e \approx f^2/81s^2 \). As ZP1 and ZP2 have strong polarization, \( s = 1 \). As for ZP3, its has a moderate polarization degree (35%–40%). According to the calculation of Dulk (1985), the polarization degree of the second harmonic plasma emission is only 10%–20%. Therefore, ZP3 also possibly belongs to the fundamental emission \( s = 1 \). Substituting the emission frequencies of ZP structures into this expression, the range of plasma density in the ZP source regions can be obtained, respectively, as follows:

- ZP1, \( 5.1 \times 10^{11}–6.0 \times 10^{11} \) cm\(^{-3} \), the averaged value is \( 5.5 \times 10^{11} \) cm\(^{-3} \);

- ZP2, \( 8.3 \times 10^{10}–9.3 \times 10^{10} \) cm\(^{-3} \), the averaged value is \( 8.8 \times 10^{10} \) cm\(^{-3} \);

- ZP3, \( 3.3 \times 10^{9}–4.0 \times 10^{9} \) cm\(^{-3} \), the averaged value is \( 3.6 \times 10^{9} \) cm\(^{-3} \).

Generally, the source region with a plasma density up to \( 5.5 \times 10^{11} \) cm\(^{-3} \) is always located very close to the base of the solar corona where the height from the solar photosphere is only several thousand kilometers, while the source region with a plasma density of about \( 10^{10} \) cm\(^{-3} \) is located near the bottom of the solar corona. However, it should be different around the active regions, especially around the flaring regions. The X-ray observations indicate that the plasma densities around the flaring core region are in the range of \( 10^8–10^{11} \) cm\(^{-3} \), and their heights can be in several decades of thousands kilometers above the solar photosphere (Ohyaama & Shibata 1998).

One of the crucial and most difficult problems in solar physics is to determine the coronal magnetic field confidently. There are many publications that present the estimations of the coronal magnetic field by using solar radio observations (Mann et al. 1987; Gelfreikh 1998; Huang & Nakajima 2002; Huang 2008, etc.). Recent observations of microwave bursts with fine structures open up new possibilities for determining the coronal magnetic field (Karlicky & Jiricka 1995; Ledenev et al. 2001, etc). The ZP structure is one of the most important microwave fine structures that can be used to diagnose magnetic field strength in the coronal source regions, although the results depend on the theoretical models. Different ZP models will deduce different values of the magnetic field in the ZP source region. Practically, it is always difficult to decide which model is the best one fitted to observations. From the estimations of the magnetic field strengths from the ZP structures, we can get a considerable restriction for the theoretical models.

1. The BM model indicates that the frequency separation of the adjacent zebra stripes is just equal to the electron gyrofrequency. From this we can obtain a direct measurement of the magnetic field in the coronal source region:

\[
B \simeq \frac{2\pi m_e}{e} \Delta f \approx 35.6 \times 10^{-8} \Delta f. \tag{6}
\]
Here, the unit of $B$ is in gauss and $f$ is in Hz. Substituting the frequency separation of ZP1, ZP2, and ZP3 into the above expression, we may get the magnetic field strength as $28–43$ G, $21–25$ G, and $5–6$ G, respectively. In this regime, the magnetic field strength only depends on the frequency separation between the adjacent zebra stripes.

2. From the WW model, we can get the magnetic field strength in the ZP source region:

$$B \simeq 2 \frac{2\pi m_e}{e} \Delta f \simeq 71.2 \times 10^{-8} \Delta f.$$  

(7)

With this relation, the magnetic field strength is two times of that estimated from the BM model: $55–85$ G, $42–49$ G, and $10–11$ G, corresponding to ZP1, ZP2, and ZP3, respectively. This regime is also independent of the inhomogeneous scale height in the source region.

3. From the DPR model, we can obtain the measurement of the magnetic field strength in the ZP structure source region. Based on Equations (3) and (4), the magnetic field strength can be derived:

$$B \simeq \frac{2\pi m_e}{e} \cdot Q \cdot \Delta f.$$  

(8)

Here, $Q$ is an inhomogeneous factor that is dominated mainly by the scale heights of plasma density $n_e$ and the magnetic field $B$ in the source region. It can be expressed as

$$Q = \frac{|2H_n - H_0|}{sH_b}.$$  

(9)

Here, $s$ is the harmonic number. When the emission generated from the coalescence of an excited plasma wave and a low-frequency electrostatic wave, the emission frequency nearly equals the plasma frequency, $s = 1$ (fundamental emission); and when emission is generated from the coalescence of two excited plasma waves, the emission frequency equals nearly double the plasma frequency, $s = 2$ (second harmonics).

The scale heights of plasma density $H_n$ and the magnetic field $H_b$ are two crucial parameters that control the magnitude of $Q$. However, they are dependent on the atmospheric models around the source region. We may adopt the Newkirk model to express the plasma density around the source region: $n(r) = M \times 10^{-32} r^7$. $M$ is a constant in the Newkirk model, which may change depending on the different coronal regions. However, it does not change the following estimations when we change the magnitude of $M$ (it does not appear in the expression of $H_n$). The scale height of the plasma density can be deduced as:

$$H_n \simeq 70 r^2, (Mm).$$  

(10)

As for the coronal magnetic field above the active region, the Dulk & McLean model is always adopted: $B(r) = 0.5m/(r - 1)^{1.5}, (1.02 \leq r \leq 10)$ (Dulk & McLean 1978). While this model represents only an average decrease of the magnetic field strength with height, the real values may deviate by a factor of $m$ of up to 3. $r$ is the height from the solar center in the unit of the solar optical radius $R_\odot$.

More precisely, we can use the coronal loop model to obtain the scale height of the magnetic field in the ZP source regions. The magnetic field strength in a coronal loop can be written as $B(h) \sim B_0(1 + h/d)^{-3}$ (Takakura 1972). Here, $B_0$ is the magnetic field at the footpoint of the loop, $d$ is the distance between the two footpoints, and $h$ is the height from the photosphere. Then the scale height of the magnetic field can be deduced as:

$$H_b = \frac{d}{3} \left(1 + \frac{h}{d}\right).$$  

(11)

According to the work of Maurya et al. (2011), we know that the maximum magnetic field on the sunspot is about 1400 G. From this figure, we also find that the distance between the maximum centers of left- and right-handed polarizations at a frequency of 17 GHz is only about 40 arcsec, approximated to 29 Mm. Because the maximum centers of left- and right-handed polarizations at a frequency of 17 GHz are close to the footpoints of the plasma loop, we can assume $d \sim 29$ Mm.

Equations (8)–(11) indicate that the magnetic field strength depends on another unknown key parameter: $r$ or $h$, where $h = (r - 1)R_\odot$. Because of a lack of imaging observations at the corresponding frequencies, we may give some assumptions. Considering the frequency of ZP1 (6.40–7.00 GHz) and previous works (the review by Gary & Keller 2004), its source region is very close to the core region of the flaring energy release, and we may assume that its height is about 20 Mm (above the solar photosphere). Then, the heights of ZP2 and ZP3 can be deduced as 39 Mm and 61 Mm by the Newkirk model and plasma emission mechanism. With the above estimations, assumptions, and observations, we can obtain that the magnetic fields in the source regions of ZP1, ZP2, and ZP3 are $230–345$ G, $126–147$ G, and $23–26$ G, respectively. The values of ZP1 and ZP2 are very close to the estimations from the Takakura model, and also close to the estimations from the Dulk & McLean model when $m = 3$. However, the value of ZP3 only approaches the Dulk & McLean model estimate when $m = 1$, which is much smaller than that estimated from the Takakura model.

Additionally, there are several clusters of fiber bursts at a frequency of 2.60–3.00 GHz, which is very close to the frequency band of ZP2. The fiber bursts have been thought to be another promising way to diagnose the coronal magnetic field in the source region. It can be generated by packets of low-frequency WWs propagating along the magnetic field lines of the coronal loop. From the frequency drift rate, we can derive the magnetic field (Benz & Mann 1998):

$$B \simeq \frac{\pi H_m e}{ec \sqrt{\chi \cdot \cos \theta}} \frac{df}{dt} \approx 5.93 \times 10^{-20} \frac{H_m}{\sqrt{\chi \cdot \cos \theta}} \frac{df}{dt} \text{(Tesla)}.$$  

(12)

$H_m$ can be calculated from Equation (10) in about 78 Mm, $x = (f_e/f_c)$, and $\chi$ is the ratio between the whistler frequency and the electron gyrofrequency, and $\theta$ declines with respect to the magnetic field line. Generally, $\theta \sim 0$ and $x \sim 0.01$, then we may substitute the frequency drift rates of the fiber burst at a frequency of 2.60–3.00 GHz, and the magnetic field strength can be obtained as $98.6–187.7$ G, with an average value of 143.1 G. This value covers the result estimated by the DPR model of ZP2.

It can be regarded as collateral evidence for the estimations of the magnetic field in the ZP source regions from the DPR model.
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Table 3

| ZP Event        | ZP1   | ZP2   | ZP3   |
|-----------------|-------|-------|-------|
| ZP BM model     | 28–43 | 21–25 | 5–6   |
| ZP WW model     | 55–85 | 42–49 | 10–11 |
| ZP DPR model    | 230–345 | 126–147 | 23–26 |
| Dulk & McLean model: \(m = 1\) | 102   | 38    | 19    |
| \(m = 2\)      | 204   | 76    | 38    |
| \(m = 3\)      | 306   | 114   | 57    |
| Takakura model  | 290   | 109   | 48    |

has more consistency than the Takakura model and the Dulk & McLean model when \(m = 3\). Especially in ZP2, estimations of the magnetic field from the DPR model and Takakura model are also consistent with the results obtained from fiber bursts at a similar frequency range. Therefore, we believe that the DPR model is possibly the real model for the ZP structures observed in this work. However, there is a difference of two between the DPR model and Takakura model in the ZP3 source region. It may just reflect that the Takakura model is valid only within a magnetic loop. In our above estimations, the height of the ZP3 source region is about 61 Mm, which is more than two times the distance (\(d \sim 29\) Mm) between the two footpoints of the loop, but this height should be much higher than the loop top. It is possible that the source region of ZP3 is located at a different magnetic loop with a larger \(d\) and a much lower \(B_0\). However, with a lack of this observations, we cannot confirm this inference.

In Section 2, we have pointed out that ZP1 is possibly a mixture of a general ZP structure and a QPP, and the QPP is a VSP. From the work of Tan et al. (2007, 2010), we may suppose that the QPP is possibly a result of modulations of the resistive tearing-mode oscillations in the current-carrying flare plasma loops with high temperatures. Panel (9) of Figure 1 indicates that the temperature around ZP1 (22 MK) is very close to the maximum of the profile, and it is possible that the modulations of the resistive tearing-mode oscillations take place. The current-carrying plasma loop can drive the tearing-mode oscillation and modulate the microwave emission to form a VSP. On this VSP background, some mechanism generates the ZP structure.

4. CONCLUSIONS

On 2011 February 15, an X2.2 flare event erupted on the solar disk, which was the first X-class flare that occurred since solar cycle 24. Associated with this flare event, three microwave ZP structures at different frequencies are registered in different phases of the flare: the first is registered from SBRSHuairou at a frequency of 6.40–7.00 GHz, which is very unusual at such a high-frequency band and in the early rising phase of the flare; the second is also registered from SBRSHuairou, at a frequency of 2.60–2.73 GHz in the decay phase of the flare, it may possibly extend to a frequency lower than 2.60 GHz; and the third is registered from SBRSYunnan at a frequency of 1.04–1.13 GHz in the decay phase long after the flare peak.

By scrutinizing the current prevalent theoretical models of ZP structures (including the Bernstein model, the WW model, the DPR model, and the Ledenev model) and comparing their estimated magnetic field strengths in the corresponding source regions, we find that the DPR model is much better at explaining the generation of microwave ZP structures. It derived the magnetic field strengths at about 230–345 G, 126–147 G, and 23–26 G in the source regions of ZP1, ZP2, and ZP3, respectively. Comparing the diagnostics of fiber bursts and the previous empirical model, we suggest that such estimations are acceptable.

It should be noted that the DPR model is not self-contained when we adopt it to diagnose the magnetic fields in ZP source regions. It needs to be supplemented with the inhomogeneity model of plasma density and magnetic field. However, it is not easy to get the exact inhomogeneity models. So far, all the existing models (e.g., the Dulk & McLean model, the Takakura model, etc.) of plasma density and magnetic fields propose that the plasma density and magnetic field change with height and are expressed as functions of height (\(r\) or \(h\)). Such methods imply that the inhomogeneous scale heights of the magnetic field are also a function of the magnetic field, and this is the origin of the self-contradiction. We need a more perfect model that can provide the inhomogeneous scale lengths of the plasma density and magnetic field and are independent of the magnitude of magnetic field strength. The magnetic field diagnostics of the BM model and the WW model are independent of the inhomogeneity models; they seem to be the perfect models to diagnose the magnetic field in the source region of ZP structures. But they are not likely to agree with the ZP structures observed in this work.

However, we should note that both the Dulk & McLean model and the Takakura model are only simplified models. The actual regime during the microwave burst with ZP structures should be an extremely dynamic processes, and the real magnetic topology is also much more complex and changeable than the depiction of the above models. So far, the only thing we can do is to obtain the approximated estimations. In the ZP3 source region, the relatively large difference in magnetic estimations between the DPR model and Takakura’s model solely reflects that its source region should be located at a different magnetic loop with a different distance of the footpoints and a different initial magnetic field.

From the above discussion, we know that the exact inhomogeneity models of the magnetic field and plasma density are the most important. However, so far, because of a lack of imaging observations with spatial resolutions in the corresponding frequencies, it is difficult to obtain the configuration features of the coronal magnetic field in the source region. To overcome such problems, we need new telescopes, for example, the Chinese Spectral Radio Heliograph (CSRH, 0.4–15 GHz, will be finished before 2014) in the decimetric-to-centimeter-wave range (Yan et al. 2009) and the proposed American Frequency Agile Solar Radiotelescope (50 MHz–20 GHz; Bastian 2003). When these instruments are finished we may obtain solar radio observations with high spatial–temporal resolutions at multi-frequency channels. One of the most important ways to measure the coronal magnetic field is to probe ZP structures in each of the subareas with high spatial resolutions and deduce the magnetic field from certain theoretical models. With these developments, we will get a more perfect understanding of the elementary processes in solar flares.

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