RELAXATION OF MAGNETIC FIELD RELATIVE TO PLASMA DENSITY REVEALED FROM MICROWAVE ZEBRA PATTERNS ASSOCIATED WITH SOLAR FLARES

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ABSTRACT

It is generally accepted that the emission of microwave zebra pattern (ZP) structures requires high density and high temperature, which is similar to the situation of the flaring region where primary energy is released. Therefore, a parameter analysis of ZPs may reveal the physical conditions of the flaring source region. This work investigates the variations of 74 microwave ZP structures observed by the Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou) at 2.6–3.8 GHz in nine solar flares, and we find that the ratio between the plasma density scale height \( L_N \) and the magnetic field scale height \( L_B \) in emission sources displays a tendency to decrease during the flaring processes. The ratio \( L_N / L_B \) is about 3–5 before the maximum of flares. It decreases to about 2 after the maximum. The detailed analysis of three typical X-class flares implies that the variation of \( L_N / L_B \) during the flaring process is most likely due to topological changes of the magnetic field in the flaring source region, and the stepwise decrease of \( L_N / L_B \) possibly reflects the magnetic field relaxation relative to the plasma density when the flaring energy is released. This result may also constrain solar flare modeling to some extent.

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

Online-only material: color figures

1. INTRODUCTION

It is widely accepted that the magnetic free energy stored in the corona is the main energy source responsible for powering solar flares. The storage of magnetic free energy requires a non-potential magnetic field, which has always been viewed as a sheared and/or twisted magnetic structure (Hudson 2011). In the processes of solar flares, magnetic free energy is converted to thermal and kinetic energy of the plasma via the dissipation of electric current, accompanied by a topological change of the magnetic field to a lower energy state than the pre-flare state (Priest & Forbes 2002; Longcope 2005; Low 2006; Shibata & Magara 2011). This scenario can successfully interpret many observational features of solar flares. However, the detailed evolution of such coronal phenomena is not yet fully understood, especially in the process of energy release (Shibata & Magara 2011), due to the lack of direct quantitative measurements of the coronal magnetic field in the source region (Bastian 2004).

The microwave spectral fine structures provide a unique diagnostic of the magnetic field and ambient plasma around the source. The zebra pattern (ZP) is one of the most intriguing spectral structures in the solar radio emission, and consists of a number of almost parallel and equidistant stripes superimposed on the background type IV radio bursts in the dynamic spectrum. The Bernstein pattern model (BM model; Rosenberg 1972; Chiuderi et al. 1973) was the first to interpret such a fine structure. Another important model is the whistler wave model (WW model; Kuijpers 1975; Chernov 2006), based on the interaction between plasma electrostatic waves and whistler waves. The most developed model for ZP is the double plasma resonance model (DPR model; Zheleznyakov & Zlotnik 1975). The detailed information related to these theoretical models can be found in the reviews by Chernov (2006, 2010). The microwave ZPs are closely related to the inhomogeneous plasma and magnetic fields around flaring regions in the corona through the DPR model. According to this model, the emission source is considered to be a magnetic flux tube filled with nonequilibrium energetic particles. The anisotropic distribution of energetic particles in the flux tube develops kinetic instabilities and stimulates electrostatic waves. The excitation of dominating electrostatic upper hybrid waves is greatly enhanced at some resonance levels, where the upper hybrid frequency \( f_{uh} \) is close to the harmonics of the electron cyclotron frequency \( f_c \) in the flux tube:

\[
f_{uh} = \left(f_{pe}^2 + f_c^2\right)^{1/2} \approx sf_c,
\]

where \( f_{pe} \) is the plasma frequency of electrons and \( s \) is the harmonic number. Then, these waves escape from the local regions through some nonlinear plasma processes as they are transformed to transverse waves.

It is generally considered that the emission of microwave fine structures like ZPs requires high density and high temperature, coinciding with the situation of the expected primary energy release site of a flare (Bastian et al. 1998) and implying that the source of a microwave ZP may be located near the flare core region where the magnetic energy is released. This also indicates that a parameter analysis of ZPs may present some features of the flaring core region. Yan et al. (2007) estimated the ratio between the plasma density scale height \( L_N \) and the magnetic field scale height \( L_B \) derived from three ZPs in an X3.4 solar flare event on 2006 December 13 observed by the Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou; Fu et al. 2004) using the DPR model. They pointed out that \( L_N / L_B \) decreases by a factor of two from the impulsive phase of the flare to its maximum. This is the motivation behind this
work: given that \( L_N / L_B \) is closely related to the geometrical structure of the coronal magnetic field, a topological change of magnetic field during the energy release process would leave a trace on \( L_N / L_B \), i.e., the ZP is an indirect tracker of the physical processes of solar flares.

With the aid of high temporal, high spectral resolution observational data obtained at the SBRS/Huairou in 2.6–3.8 GHz (Yan et al. 2002; Fu et al. 2004), we are encouraged to address this issue. In this work, we investigate the temporal variations of \( L_N / L_B \) derived from 74 ZPs which appeared in the flaring processes of nine eruptive solar flares from 1997 to 2006. This paper is organized as follows. In Section 2, we describe the observational data of ZPs associated with solar flares and present the data analysis. Section 3 presents the results. Discussions and the conclusion are presented in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

Figure 1 shows the microwave dynamic spectrograms of a typical ZP structure in left- and right-handed circular polarization (LHCP and RHCP) recorded on 2006 December 13. The upper and middle panels show the LHCP and RHCP components, respectively. The horizontal line denotes the average value of \( L_N / L_B \) in the whole ZP structure, taken as the ratio \( L_N / L_B \) of this ZP.

(A color version of this figure is available in the online journal.)

2.1. Observations and Data Analysis

The frequencies \( f \) of the ZP stripes at every sampling time are marked by filled circles. Equation (5) implies that the larger the difference \( \Delta s \) in Equations (5), the larger the ratio \( L_N / L_B \). One stripe is determined to be the plasma frequency of electrons \( f_{ce} \) and the plasma frequency of electrons \( f_{pe} \) can be expressed as

\[
\frac{f_{ce}}{f_{pe}} = \frac{f_{ce0} e^{-\Delta \phi / L_N}}{f_{pe0} e^{-\Delta \phi / (2L_N)}}.
\]

The observational sensitivity is \( S / S_{\odot} \leq 2\% \), where \( S_{\odot} \) is the quiet solar background radiation (Yan et al. 2002; Fu et al. 2004). During solar cycle 23, SBRS/Huairou obtained excellent observational data at 2.6–3.8 GHz, and numerous ZPs are observed at this bandwidth. We found 74 ZPs in nine solar flares, whose \( L_N / L_B \) can be calculated, which were observed by SBRS/Huairou at 2.6–3.8 GHz from 1997 to 2006. The parameters of the nine flare events are summarized in Table 1. Among the nine events listed, we found three typical flares (2006 December 13, 2002 April 21, and 2001 October 19) in which discernible ZPs appeared both before and after the soft X-ray maxima in the flaring processes. In the other six events, ZPs appeared either prior to or after the flaring peaks. It should be noted that in the 11th column in Table 1, the number of stripes of each ZP is generally below 10, while in the event of 2002 April 21, the number reaches 34.

We now consider that the DPR model is responsible for emitting the ZP. It is reasonable to assume both the magnetic field strength \( (B) \) and the plasma density \( (n_e) \) decrease exponentially with height \( (h) \) along the flux tube in the corona:

\[
B = B_0 e^{-\Delta \phi / L_B}, \quad n_e = n_{e0} e^{-\Delta \phi / L_N},
\]

where \( B_0 \) and \( n_{e0} \) are the magnetic field and the plasma density at \( h_0 \), respectively, and \( L_N = n_e (\partial n_e / \partial h)^{-1} \) and \( L_B = [B(\partial B / \partial h)]^{-1} \). The electron cyclotron frequency \( f_{ce} \) and the plasma frequency of electrons \( f_{pe} \) can be expressed as

\[
\frac{f_{ce}}{f_{pe}} = \frac{f_{ce0} e^{-\Delta \phi / L_B}}{f_{pe0} e^{-\Delta \phi / (2L_N)}}.
\]

According to the DPR model (Kuznetsov & Tsap 2007), the frequency separation of the adjacent ZPs at harmonics \( s \) and \( s + 1 \) is related to \( B \) and \( n_e \):

\[
\Delta f_s \approx f_{pe0} (h_{s+1} - h_s) f_{pe} = f_{pe0} e^{-\Delta \phi / (2L_N)},
\]

where \( h_{s+1} \) and \( h_s \) are the heights of neighboring resonance levels \( s + 1 \) and \( s \). For a given ZP, with zebra stripes corresponding to harmonics \( s_1 \) and \( s_2 \), we can determine the frequencies of the two stripes at a given time. Denoting \( \Delta s = s_2 - s_1 \) and \( \delta s = \Delta f_s / f_s \), Equation (4) can be transformed to

\[
\frac{\Delta s}{\delta s} = \frac{L_N}{L_B} \approx \frac{1}{2} \left( 1 + \frac{1}{|\delta s| s_1} \right).
\]

Therefore, the ratio \( L_N / L_B \) can be calculated from the observation of a ZP using the DPR model.

Figure 1 illustrates the method we employed to obtain the \( L_N / L_B \) of a typical ZP. This ZP was recorded at 03:03:00 UT on 2006 December 13. It lasted for about seven minutes, but only the part during 03:03:00–03:03:10 UT can be well discriminated from the spectrograms due to saturation in the frequency range 2.75–2.90 GHz. The upper two panels are the dynamic spectrograms of the ZP in LHCP and RHCP. Six stripes can be well discriminated from the background emission in this case. We applied a sufficient sampling rate to calculate \( L_N / L_B \) of every ZP, depending on the time duration of the ZP. For a given time, the frequency \( f \) of one stripe is determined to be the center frequency of the stripe at the sampling time, denoted by filled circles. Equation (5) implies that the larger the difference
Figure 2. $L_N/L_B$ estimated from 74 microwave ZPs in the nine flare events listed in Table 1 is plotted against time relative to the GOES soft X-ray flaring peak (vertical dotted line) of each flare. The symbols used to denote the ratio $L_N/L_B$ are also listed in Table 1.

Table 1

| Event       | Class | AR NOAA | SXR Peak | Start (UT) | End (UT) | $f$ (GHz) | $\Delta f$ (MHz) | Pol | No. | $N_s$ | Ref | $S$ |
|-------------|-------|---------|----------|------------|----------|-----------|------------------|-----|-----|-------|-----|-----|
| 2000 Apr 9  | M3.1  | 8948    | 23:42    | 23:55:12   | 23:55:18 | 2.60–3.10 | 20–40            | STRONG R | 1   | 3    | 1   | ◊  |
| 2000 Oct 29 | C4.4  | 9209    | 01:57    | 02:06:32   | 02:35:05 | 2.60–3.10 | 65–80            | R | 17 | 3–7 | 2   | △  |
| 2000 Nov 24 | X2.0  | 9236    | 05:02    | 04:59:56   | 05:01:57 | 2.60–3.80 | 55–60            | L&R | 4   | 3    | 2   | □  |
| 2000 Nov 25 | M8.2  | 9240    | 01:31    | 00:59:19   | 01:09:30 | 2.60–3.80 | 50               | L&R | 4   | 5–6 | 2   | ◆  |
| 2000 Oct 19 | X1.6  | 9661    | 01:05    | 00:51:00   | 01:19:55 | 2.60–3.00 | 55–75            | R | 18 | 3–8 | 2   | ×  |
| 2002 Apr 21 | X1.5  | 9906    | 01:50    | 01:45:40   | 02:01:45 | 2.60–3.80 | 30–70            | L | 10 | 10–34 | 3 | * |
| 2003 Nov 18 | M3.9  | 10501   | 08:31    | 08:22:42   | 08:26:50 | 2.60–3.50 | 30–50            | STRONG R | 3   | 3–5 | 1   | ▲  |
| 2005 Jul 9  | M2.8  | 10786   | 22:06    | 22:03:16   | 22:04:53 | 2.60–3.50 | 50–80            | L&R | 6   | 8   | 1   | ■  |
| 2006 Dec 13 | X3.4  | 10930   | 02:40    | 02:22:30   | 03:03:00 | 2.60–3.80 | 50–250           | R | 13 | 3–6 | 4   | *  |

Notes. Start (UT)—time of the first ZP in the event; End (UT)—time of the last ZP in the event; AR NOAA—number of NOAA active region; SXR peak (UT)—time of soft X-ray peak; $f$ (GHz)—frequency range of ZPs; $\Delta f$ (MHz)—frequency separation of adjacent stripes; Pol—left- or right-handed circular polarization; No.—number of ZPs in the event; $N_s$—number of stripes of ZPs in the event; Ref—reference; $S$—the symbols used in Figure 2.

References. (1) Huang et al. 2008; (2) Chernov et al. 2003; (3) Chernov et al. 2005; (4) Yan et al. 2007.

3. RESULTS

In Figure 2, we plot the ratio $L_N/L_B$ derived from 74 ZPs listed in Table 1 against the time relative to the GOES soft X-ray flaring peak of each flare. The symbols used to denote the ratio in different events are shown in the last column of Table 1. The standard deviations $\sigma$ of the ZPs are shown as error bars. The irregular drift of ZP stripes indicates that the resonance levels do not remain at precisely the same height in the flux tube, which may account for the $\sigma$. The time of the GOES soft X-ray peak is assigned as 00:00, marked with the vertical dotted line. The temporal variation of the ratio (Figure 2) shows that: (1) during the flaring processes of these flares, the ratio is mainly in the range between 1.5 and 5; (2) before the flaring peak, the ratio is mainly in range 3–5, except for the event of 2002 April 21 (+); after the peak, the ratio decreases to 1–3; and (3) in the events of 2006 December 13 (*), 2002 April 21, and 2001 October 19 (×), whose ZPs appeared both before and after the flaring peaks, the ratio shows interesting temporal variation during the flaring process.

Figure 3 compares the temporal variation of the ratio $L_N/L_B$ in the flaring process of the three flare events. The ratio for each ZP case is given by a filled diamond. The solid curve denote the normalized GOES soft X-ray profile at 1–8 Å. The vertical dotted line refers to the time of the soft X-ray peak. The error bar denotes the $\sigma$ of $L_N/L_B$. The first impression of Figure 3 is that the ratio shows a decreasing trend during the flaring
process of each event. It is also noted that the ratio displays a stepwise decrease around the soft X-ray peak in the events of 2006 December 13 and 2001 October 19, while the ratio decreases slowly during the flaring process in the event of 2002 April 21. We will analyze the three typical flare events in detail separately in the following.

3.1. The Event of 2006 December 13

On 2006 December 13, an X3.4/4B class, typical two-ribbon flare occurred (Isobe et al. 2007) in the active region NOAA 10930 (S05W33). Su et al. (2007) present the long-term evolution of the sheared magnetic fields in this active region from multi-wavelength observations. The flare started at 02:14 UT, reached its maximum at around 02:40 UT, and ended at 02:57 UT. Here we are interested in the period 02:22–03:05 UT because all 13 ZPs of this flare event were recorded during this period. A clear stepwise decrease before the flaring peak divides the process into two phases: in the first phase (before the stepwise decrease), seven ZPs are observed and the ratio $L_N/L_B$ is 3.50–5.00; the other six ZPs are observed in the second phase (after the stepwise decrease) and the ratio decreases to 1.85–2.65. In Figure 4, the left column compares the X-ray coronal structure in the flaring region taken by the X-ray Telescope (XRT) onboard Hinode (a) before and (c) after the stepwise decrease. The contours show the microwave intensity at 17 GHz observed by Nobeyama Radio Heliograph (NoRH). The first phase (Figure 4(a)) is characterized by an east–west, highly sheared, bundle of nearly parallel loops. The ratio fluctuates in the range between 3.50 and 5.00 (Figure 3(a)). Figure 4(b) shows a ZP beginning at 02:22:30 UT and the ratio is 3.90. It is similar to Figure 2, but with only one spectrogram in RHCP demonstrated, and is based on the polarization of the ZP. At the end of the first phase, significant energy release is proceeding as several saturated brightenings are present along the elongated structure between 02:22:18 and 02:24:18 UT. Note that the coronal structure underwent a topological change and formed a north–south, less sheared, expanding arcade structure (Figure 4(c)). In the second phase, the ratio has decreased to...
around 2.00 (Figure 4(d)). The NoRH 17 GHz intensity contours (Figures 4(a) and (c)) show that the microwave sources in the two phases have approximately the same positions, coincident with the position of the X-ray loops structure, suggesting that the radiation of ZPs may come from the X-ray bright loops.

3.2. The Event of 2002 April 21

On 2002 April 21, an X1.5/1F class two-ribbon flare occurred in active region NOAA 9906 close to the western solar limb (S14W84). The GOES soft X-ray emission shows that the flare started at 00:43 UT, reached its maximum at around 01:50 UT, and ended at 02:38 UT. A detailed analysis of the X1.5 flare was given by Gallagher et al. (2002). ZPs in this event (Figures 5(b) and (d)) possess intricate and long-lasting stripes (Yan et al. 2004) which are far more complicated than the ZPs in the 2006 December 13 2001 October 19 events. About 10 ZPs were observed in the time interval of 01:40–02:05 UT. It is worth mentioning that, for instance, the third and fourth “ZPs” in this event are not two separate ZPs, but one long-lasting ZP structure with fast-varying frequency parameter; therefore we treated the ZP as two separate ZPs.

Figure 3(b) shows the variation of the ratio \( L_N / L_B \) in this flare event. In contrast to the “two-phase” pattern in the 2006 December 13 event, the ratio decreases slowly during the flaring process. Figure 5 illustrates the Transition Region and Coronal Explorer (TRACE) EUV images at 195 Å superposed with NoRH 17 GHz contours and the corresponding ZPs in this event. A rising (at a rate of about 10 km s\(^{-1}\); Gallagher et al. 2002) post-flare loop system was seen during 01:40–02:05 UT. By comparing the coronal structure, we found that the coronal configuration does not show significant change in the flaring process. The NoRH 17 GHz contours show that the emission came mainly from the footpoint and the top of the coronal loops. The Siberian Solar Radio Telescope data at 5.7 GHz indicate
that the microwave source was located on top of the coronal loops (Chernov et al. 2005).

3.3. The Event of 2001 October 19

An X1.6/2B class two-ribbon flare occurred in active region NOAA 9661 (N16W18) around 00:47 UT on 2001 October 19. A detailed multi-wavelength study of this event was carried out by Li & Ding (2004). The flare started at 00:47 UT, reached its maximum at around 01:05 UT, and ended at 01:13 UT. Eighteen ZPs were recorded in the time interval 00:50–01:20 UT.

The variation of the ratio $L_N/L_B$ in this event (Figure 3(c)) shows that a similar “two-phase” pattern occurred in the event of 2006 December 13. In the first phase, eight ZPs were recorded and the ratio is 2.75–4.19; the other ten ZPs are observed in the second phase and the ratio decreases to 1.67–3.17. Figure 6 illustrates the variation of the configuration of coronal loops during this flare and the corresponding ZPs. Here we present the TRACE 171 Å images to show the configuration of the coronal loops, which can represent the variation of the coronal magnetic topology. The two-ribbon structure (Figure 6(a)) is observed in the first phase, during which the ratio concentrates in the range 3.00–4.00. The TRACE 171 Å images imply that the magnetic field topology changed rapidly at 01:09:59 UT. No ZP was recorded in the transition between the first and the second phase. In the second phase, the coronal loops evolved to an expanding post-flare loops configuration in the 171 Å images (Figure 6(c)). Figure 6(d) shows that the corresponding ZP appeared at 01:19 UT and the ratio is around 2.00. The NoRH 17 GHz contours overlaying the TRACE 171 Å images show a loop structure stretching across the two flare ribbons. At around 00:55 UT, the microwave emission originated mainly from the two footpoints of the coronal loops. About three minutes later,
Figure 6. NoRH 17 GHz contours superposed on the TRACE/171 Å images of NOAA 9661 on 2001 October 19, taken (a) before (00:59 UT) and (c) after (01:19 UT) the stepwise decrease of $L_N/L_B$. The corresponding ZPs and their $L_N/L_B$ are shown in panels (b) and (d).

(A color version of this figure is available in the online journal.)

the microwave sources gradually converged to the loop top and changed little morphologically thereafter.

4. DISCUSSION AND CONCLUSION

In this paper, we investigated the variation of 74 microwave ZPs recorded by SBRS/Huairou at 2.6–3.8 GHz in nine eruptive solar flares. By analyzing the ZP stripes appearing in the flares, we calculated the ratio $L_N/L_B$ in the emission sources. We obtained the following results.

For all cases, the ratios $L_N/L_B$ prior to the flaring peaks tend to be larger than those after the peaks. The ratios mainly concentrate in the range 3–5 before the flaring peaks, except for the case of 2002 April 21. After the free energy is released, the ratio drops to about 2. Among these cases, we found three typical flares whose ZPs appeared both before and after the flaring peaks. In the cases of 2006 December 13 and 2001 October 19, the ratio displays a stepwise decrease during the processes of energy release. In the case of 2002 April 21, the ratio shows a tendency to decrease slowly. The decrease of the ratio reveals that the magnetic field scale height increases faster relative to the plasma density scale height during the flaring process, implying the presence of a relaxation process of the magnetic field relative to the plasma density.

We compare the X-ray/EUV images taken before and after the stepwise decrease of the ratio $L_N/L_B$ of the three events. The coronal configuration underwent a topological change after the release of the stored free energy, revealing a sigmoid-to-arcade transformation (Mandrini et al. 2005; Liu et al. 2007; Jing et al. 2007) during the flaring process in the events of 2006 December 13 and 2001 October 19. As is well accepted, the shape of the X-ray/EUV loops infers current-free magnetic field lines. The loop arcades after the topological change show a relaxed form of magnetic field configuration, implying that the topological change of the magnetic field in the flaring region is a process toward a relaxed, potential state by release of the magnetic shear.
(Sakurai et al. 1992). In the case of 2002 April 21, the EUV images do not show significant change in coronal magnetic field configuration in this event. We checked the NoRH observations of these three flare events. The microwave sources of ZPs were located on the bright flare loops observed at EUV/X-ray band. The heights of the source regions of ZPs were estimated to be about 66 Mm (Huang & Tan 2012), within the altitude range \( \sim 8 \) Mm to \( \sim 70 \) Mm where the magnetic nonpotentiality decreases after the flare event of 2006 December 13 (Jing et al. 2008). This agreement supports the validity of the relation between \( \frac{L_N}{L_B} \) variation and energy release. When we suppose that \( \frac{L_N}{L_B} \) is determined by the geometrical structure of the magnetic field and the plasma density, the stepwise decreases of \( \frac{L_N}{L_B} \) (Figures 3(a) and (c)) may be related to a topological change of the coronal magnetic field structure; the slowly varying \( \frac{L_N}{L_B} \) (Figure 3(b)) infers no significant change of coronal magnetic field, and thus our results favor the \( \frac{L_N}{L_B} \) variation being due to the topological change of the flare core region where the main part of the magnetic energy is released. Figure 7 illustrates the picture of the ratio before and after the topological change. For a typical value of the ratio, the magnetic field scale height \( L_B \) is one-fourth of the plasma density scale height \( L_N \) before the topological change. After the topological change, \( L_B \) becomes one-half of \( L_N \). This result may constrain solar flare modeling to some extent.

The ratio \( \frac{L_N}{L_B} \) plays a significant role in the DPR model (Zheleznyakov & Zlotnik 1975). However, the absolute values of \( L_N \) and \( L_B \) are even more important. The smaller these values are, the more stripes of a ZP can be realized in a certain frequency range. We noted that, from Table 1, the number of zebra stripes varied from event to event, especially for the event of 2002 April 21 where it was as high as 34. In other words, the absolute values of \( L_N \) and \( L_B \) varied in different events. Whereas the ratio \( \frac{L_N}{L_B} \) is mainly in the range \( 1.5 \sim 5 \), as shown in Figure 2, this is independent of the variation in the absolute values of \( L_N \) and \( L_B \).

It is worth discussing here the validity of a particular flare event, e.g., the event of 2002 April 21, in light of the fact that up to 34 ZP stripes existed simultaneously in a short frequency range. In this event, for \( \Delta f = 0 \) MHz, we could obtain the magnetic field as \( B = 19.5 \) G, calculated from Equation (4), \( \frac{\Delta f}{f_{\text{ce}}(1 - \frac{2L_N}{L_B})m} \approx \frac{1}{(1 - \frac{2L_N}{L_B})} = \frac{1}{(1 - (2L_N/L_B))} \), where \( L_N \) is the magnetic field scale height and \( n_m \) is the plasma density scale height. Thus, the value of \( \beta \) seems overly high at this altitude of 60 Mm, according to current knowledge. This is a major obstacle for the DPR model to produce 34 ZP stripes simultaneously in the range 2.6–3.8 GHz in this event. A similar calculation was carried out showing that the DPR model fails to interpret the formation of a large number of ZP stripes (Chernov 2010). The WW model was proposed to be responsible for the formation of the multi-striped ZP structures in this event, as the ratio \( \frac{L_N}{L_B} \) is not a significant parameter in the WW model, but the absolute value of magnetic field \( B \) is. The magnetic field \( B \) can be estimated to be a reasonable value of 71.5 G with the formula \( \Delta f = 0.2 f_{\text{ce}}, \) where \( \Delta f \) is the frequency separation between two adjacent ZP stripes (Chernov 2006).

Finally, it must be mentioned that it requires further investigation to answer why \( \frac{L_N}{L_B} \) is 3–5 and 2 before and after the energy release process, respectively. Additionally, although the radio heliograph observations suggest that the microwave ZPs may come from the flare loops, we do not have enough evidence to confirm that the ZPs originated from the same position in the flare loops because it is difficult to obtain the accurate position of the radio source region due to a lack of high spatial and high temporal radio imaging observations in the corresponding frequency range (2.6–3.8 GHz). The construction of the high spatial and high temporal resolution Chinese Spectral Radio Heliograph (0.4–15 GHz; Yan et al. 2009) will provide an opportunity to give some clear answers to the above problems.

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Figure 7. Illustration of the ratio \( \frac{L_N}{L_B} \) before and after the topological change during the flaring process.
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