Solar Phys (2008) 250: 115–131
DOI 10.1007/s11207-008-9210-z

Unusual Zebra Patterns in the Decimeter Wave Band

G.P. Chernov · Yihua Yan · Qijun Fu · Chengming Tan · Shujuan Wang

Received: 26 June 2007 / Accepted: 20 May 2008 / Published online: 13 June 2008

Abstract An analysis of new observations showing fine structures consisting of narrow-band fiber bursts as substructures of large-scale zebra-pattern stripes is carried out. We study four events using spectral observations taken with a newly built spectrometer located at the Huairou station, China, in the frequency range of 1.1 – 2.0 GHz with extremely high frequency and time resolutions (5 MHz and 1.25 ms). All the radio events were analyzed by using the available satellite data (SOHO LASCO, EIT, and MDI, TRACE, and RHESSI). Small-scale fibers always drift to lower frequencies. They may belong to a family of ropelike fibers and can also be regarded as fine structures of type III bursts and broadband pulsations. The radio emission was moderately or strongly polarized in the ordinary wave mode. In three main events fiber structure appeared as a forerunner of the entire event. All four events were small decimeter bursts. We assume that for small-scale fiber bursts the usual mechanism of coalescence of whistler waves with plasma waves can be applied, and the large-scale zebra pattern can be explained in the conventional double plasma resonance (DPR) model. The appearance of an uncommon fine structure is connected with the following special features of the plasma wave excitation in the radio source: Both whistler and plasma wave instabilities are too weak at the very beginning of the events (*i.e.*, the continuum was absent), and the fine structure is almost invisible. Then, whistlers generated directly at DPR levels "highlight" the radio emission only from these levels owing to their interaction with plasma waves.

Keywords Sun · Flare · Radio emission · Fine structure

G.P. Chernov (✉)
IZMIRAN, Troitsk, Moscow Region 142190, Russia
e-mail: gchernov@izmiran.rssi.ru

G.P. Chernov · Y. Yan · Q. Fu · C. Tan · S. Wang
National Astronomical Observatories, Chinese Academy of Sciences, A 20 Datun Road,
Beijing 100012, People's Republic of China

1. Introduction

The fine structure of radio emission in the form of more or less regular stripes of emission and absorption, called zebra patterns (ZPs) or fiber bursts, with an intermediate frequency drift (IDB) against the continuum emission of type IV radio outbursts at meter or decimeter wavelengths is well known in the literature, beginning from the first report of Elgaroy (1959). They have been classified and studied for more than 25 years ago (Kuijpers, 1975a; Krüger, 1979; Slottje, 1981; Chernov, 2006).

More recent 2.6- to 3.8-GHz observations with high frequency and time resolutions (10 MHz and 8 ms) using the new spectrograph of the National Astronomical Observatories at Huairou, Beijing, testify that this type of fine structure displays the same variety at centimeter wavelengths as well (Chernov *et al.*, 2001). Recent observations with higher resolutions (5 MHz and 1.25 ms) reveal many new effects and a wide variety in such structures in the decimeter wave band.

Specific ideas have already been formed about the mechanisms of the generation of stripes in emission and absorption against the background of continuous radio bursts (Chernov, 2006). More than 10 different models have been proposed for ZPs, most of them including some emission of electrostatic plasma waves at the double-plasma-resonance (DPR) frequency (Kuijpers, 1975b; Zheleznykov and Zlotnik, 1975; Mollwo, 1983, 1988; Winglee and Dulk, 1986; Ledenev *et al.*, 2001; LaBelle *et al.*, 2003; Yasnov and Karlický, 2004).

The collected observational data suggest that the zebra structure stripes and fibers with intermediate frequency drift are related, and that their origin can be explained by a common mechanism – namely the interaction of plasma waves with whistlers: $l + w \rightarrow t$ (Chernov, 1976, 1996; Mal'tseva and Chernov, 1989). The fibers are likely associated with ducted propagation of whistlers from the depths of the corona along a trap, whereas the zebra structure is associated with nonducted propagation, oblique to the magnetic field, mainly at the top of the trap (Chernov, 1990, 2006).

Chernov *et al.* (2003) have found that the stripes of the zebra pattern in the microwave range often have a superfine structure, consisting of separate spikelike pulses of millisecond duration. But sometimes strange stripes are observed that are difficult to unambiguously associate with any specific type of structures. For instance, in some events ropelike narrowband fibers were observed (Chernov, 1997, 2007). Here, we analyze strange fiber structures in four events in decimeter range that may belong to a family of ropelike fibers, but this time small-scale fibers are organized into large-scale ZPs. We use spectral observations of the new Chinese spectrometer (Huairou station of NAOC, Beijing) in the range of 1.1 – 2.0 GHz with extremely high resolution of 5 MHz and 1.25 ms (Fu *et al.*, 2004).

2. Observations

2.1. 24 July 2004 Event

Figures 1 and 2 demonstrate a new variety of stripes in emission in the event on 24 July 2004. At the beginning, in Figure 1 separate narrowband stripes (small fibers) were located along the frequencies, forming almost instantaneous pulsations (around 06:04:20 UT); then they decomposed and aligned along the inclined straight lines that are parallel to the individual small fibers. At the end of this time interval the small fibers formed almost a braided ZP (around 06:04:26 UT). The circular polarization of the fibers was dominantly of right-hand sign.

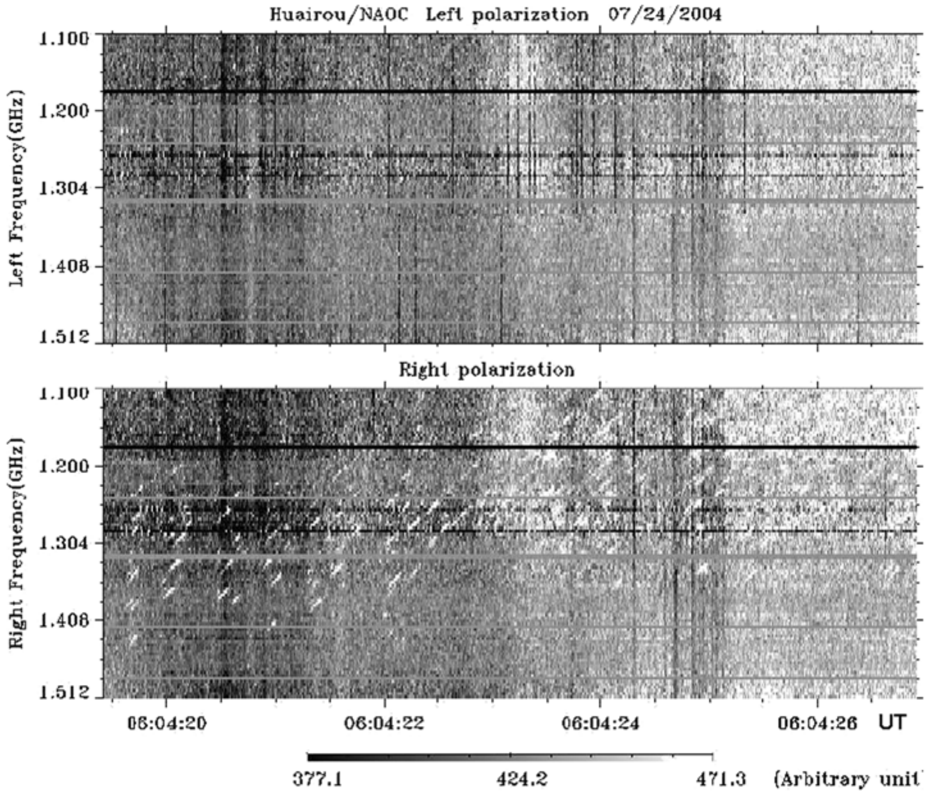

Figure 1 Dynamic spectrum in the range 1.100 – 1.512 GHz in left and right circular polarizations recorded by the spectrometer of NAOC on 24 July 2004.

One second later (Figure 2(a)), they were located once more along the inclined straight lines (06:04:27.0 – 06:04:28.5 UT), and a new special feature was seen two seconds later (06:04:30 UT): They were localized along the straight lines, but with the reverse (positive) drift. One second later (06:04:31 – 06:04:33 UT), this special feature was already clearly the basic prevailing structure (Figure 2(b)), almost regarded as large-scale ZP stripes drifting to higher frequencies with a speed of about 270 MHz s^{-1}. These structures were terminated at a certain high-frequency boundary that drifted to lower frequencies with a speed of approximately -67 MHz s^{-1}.

In Figure 2 only right polarization channels are presented because the polarization degree was 100%. The fiber structure appeared as a forerunner of the rise of continuum, which continued for more than three minutes, but no more fine structure was observed.

2.2. 22 October 2004 Event

In this event small-scale fibers showed fast pulsations and some stripes of ZP (Figure 3). At lower frequencies these pulsations looked like type III bursts (according to spectral data of IZMIRAN in the 270- to 25-MHz band). According to Zurich spectral data of Phoenix-2 these type III bursts had starting frequencies near 2300 MHz. The polarization was moderate and of right-hand sign.

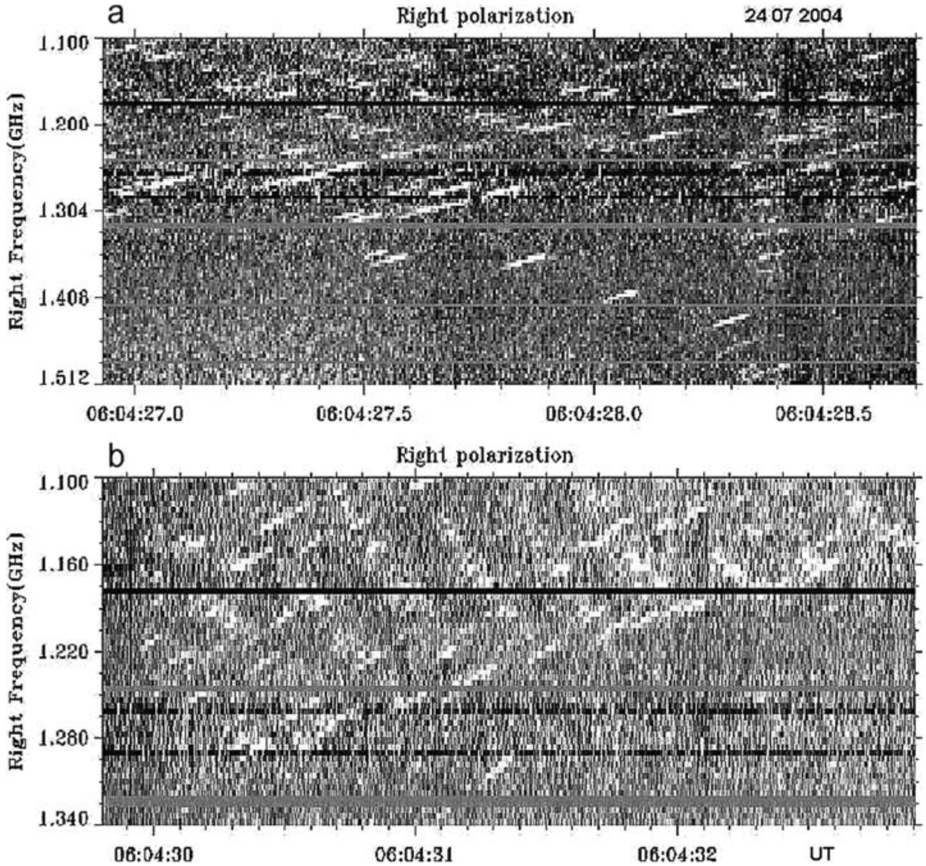

Figure 2 The continuation of the 24 July 2004 event in the range 1.100 – 1.340 GHz in the right circular polarization. (The radio emission was fully polarized.)

A similarity with the previous event is noticed only toward the end of the time interval shown in Figure 3 (08:06:46 UT), between 1.100 and 1.400 GHz, where small fibers were localized along ZP stripes with positive frequency drift of ≈ 90 MHz s^{-1}. The small fibers had only very slow negative frequency drift ($\mathrm{d}f/\mathrm{d}t \approx -40$ MHz s^{-1}). The type III bursts consisted completely of fibers that showed almost no frequency drift (like the known "striae" structure in the meter band). Some type III bursts had reverse drift, and it is evident that in this case they were U bursts with a turning frequency slightly below ≈ 1100 MHz, which indicates the presence of closed loops at this level in the corona. The fiber structure shown in Figure 3 was observed at the very beginning of the rise of continuum, and it appeared also as a forerunner of the event.

In the subsequent several minutes the event demonstrated strong evolution of the fine structure. In contrast to the previous 24 July 2004 event, here, an entire collection of fine structures was observed. After 10 s, $\approx$08:06:56 UT, in a new series of type III bursts small fibers became less prolonged (like dot spikes), but they also ended with a weak large-scale ZP. After 40 s, $\approx$08:07:40 UT (at the moment close to the maximum of the event), a continuum, speckled by the spikes that formed a braided ZP, was observed. Between 08:07:50 and 08:08:00 UT, several weak usual stripes of ZP appeared against a background

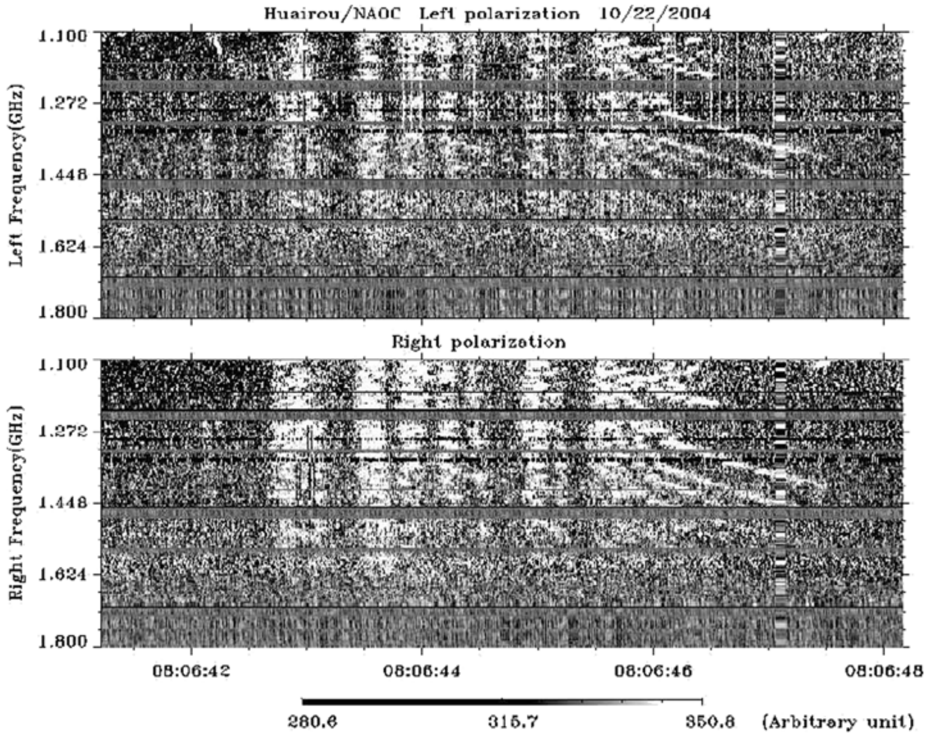

Figure 3 The beginning of the 22 October 2004 event in the range 1.100 – 1.800 GHz.

of strong type III bursts in the band 1.60 – 1.85 GHz. But from 08:09:03 to 08:09:14 UT a series of usual prolonged fiber bursts appeared on the high-frequency edge of the spectrum. All these subsequent developments were observed in the strong left-hand polarization.

2.3. 3 November 2004 Event

This event was most powerful and most prolonged, with diverse fine structures of about 2-hour duration in the course of repetitive brightenings of the flare. We selected for the analysis only its first part (with a duration of about 25 minutes), at the beginning of which small-scale fibers were observed (Figure 4), and as in the previous events also as a forerunner of the entire event.

A first glance at Figure 4 reveals certain similarity to the event of 24 July 2004: At first the small-scale fibers occurred chaotically scattered along the frequencies, then they localized at some frequencies and formed large-scale ZP stripes, and at the end they broke up again to separate chaotic fibers, which gradually (during ≈ 1.5 minutes) broke up into a cloud of chaotic spikes. The essential difference lies only in the different polarizations. Here, it was of moderate right-hand sign.

Figure 5 helps to better estimate the parameters of the small fibers that comprised the large-scale ZP. The time profiles at the fixed frequency of 1.216 GHz show that all profiles are symmetrical and have an almost Gaussian shape. The frequency drift of fibers was stable and constant, $\approx -270\ \mathrm{MHz\,s^{-1}}$, and for large-scale ZP it was $\approx 630\ \mathrm{MHz\,s^{-1}}$.

This figure allows highlights an important feature of this structure: The fibers did not settle down along the line of continuation of their frequency drift (at least, over no more

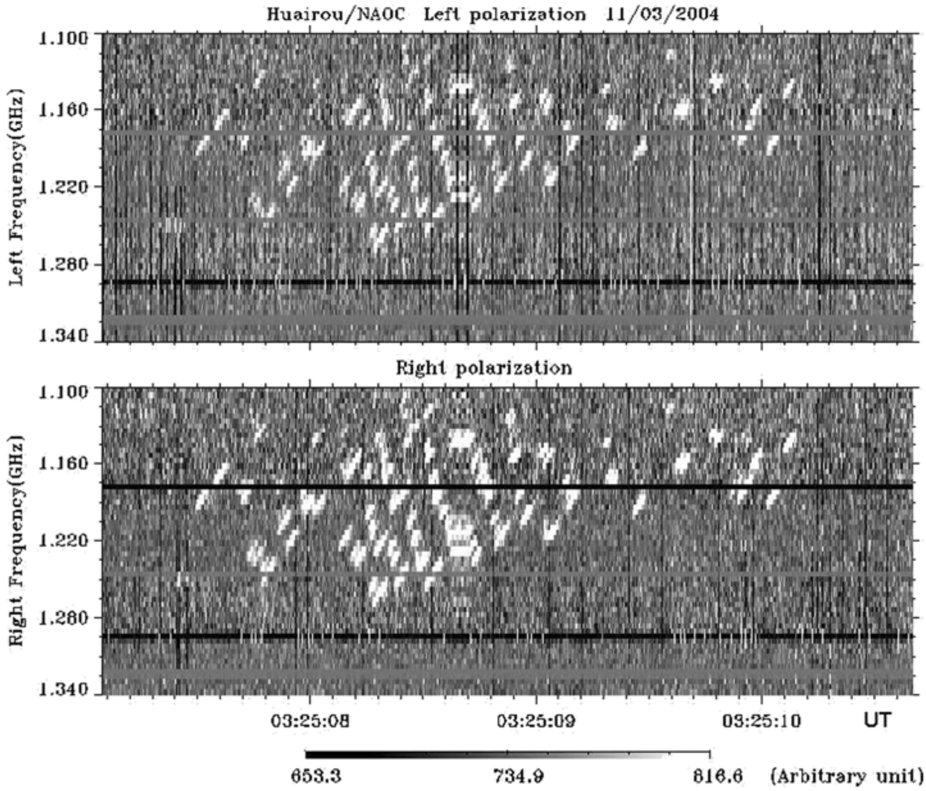

Figure 4 The beginning of the 3 November 2004 event in the frequency range 1.100 – 1.340 GHz, showing moderate right-hand polarization: The small-scale fibers are regrouped into large-scale ZP stripes.

than the two next stripes of the large-scale ZP). Along ZP stripes they were not strictly repetitive as well and looked rather like isolated bursts. Similar to the event of 24 July a certain high-frequency boundary of termination of structure existed too. It drifted to lower frequencies with a speed of approximately -80 to $-90\ \mathrm{MHz\,s^{-1}}$.

The frequency separation between adjacent fibers was not strictly constant but varied from 15 to 20 MHz, whereas in the large-scale stripes of ZP it was about 70 MHz. In the course of the event a fragment of usual stripes of ZP (without fiber structure) appeared (04:07:19 UT) with frequency separation of about 20 MHz.

Unlike usual fibers and ZP, absorptions were not observed here, though after approximately 4 minutes classical fibers with absorption from the low-frequency edge appeared and persisted until the end of the event. Moreover, whole families of fibers with different frequency drift (even with reverse drift) and with a different frequency bandwidth occurred simultaneously in different polarization channels.

2.4. 31 October 2004 Event

In this event, the fibers were seen as fine structures of rapid pulsations, which had a duration of 0.06 – 0.20 s, shorter than the on – off time period, which was on average 0.4 s (Figure 6). More precisely, the pulsations consisted of drifting fibers, whose speed of drift

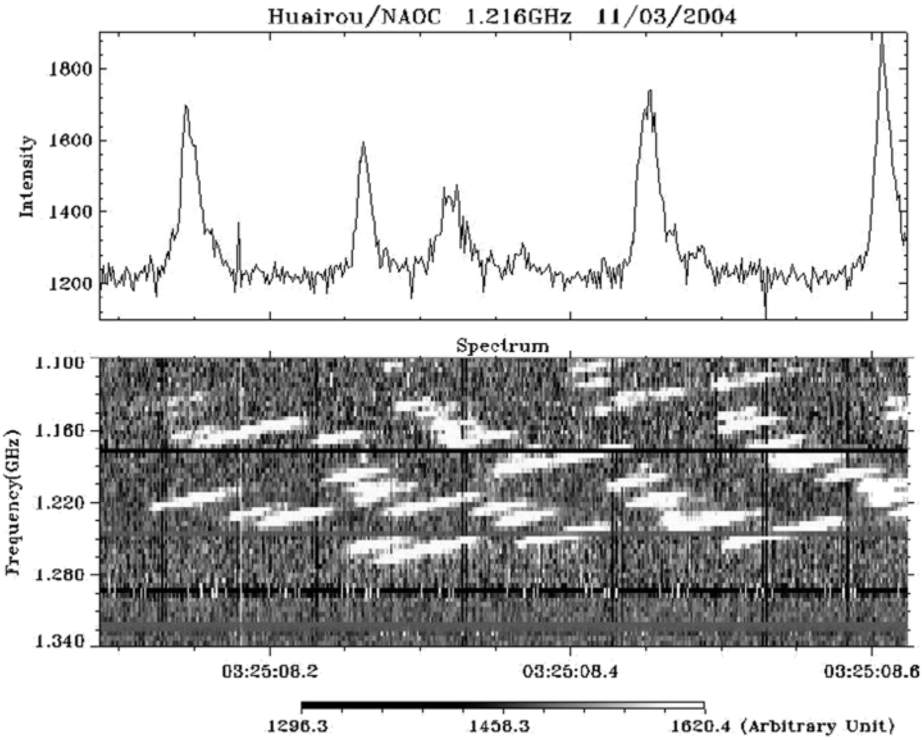

Figure 5 The magnified dynamic spectrum (bottom) and the time profile at 1.216 GHz (top) of the fiber structure on 3 November 2004.

gradually increased, in the course of the duration of pulsations of about 20 s, from −160 to −270 MHz s^{-1}. In contrast to the three previous events, these pulsations have appeared toward the end of a small burst of ≈ 7 minute duration, and the fibers did not reform into ZP stripes. At the beginning of the phenomenon only numerous clouds of millisecond spikes were observed, although it is known that sometimes ZP occurs as instant pulsing columns over a wide frequency range. The pulsations of 31 October differ from others only in that the fibers did not change the direction of the frequency drift. They are also similar to the 22 October event as far as the shape of the spectrum is concerned; namely, the pulsations completely consisted of fibers.

Figures 6(a) and (d) represent shorter (than (b) and (c)) sections of spectra (2.5 s), to measure more precisely the parameters of fibers. The fibers do not reveal any strict periodicity in frequency; they sometimes occurred in pairs or were chaotic, and they were accompanied by some fragments in absorption between fibers. The pulsations were seen sometimes in a limited frequency band, and in this connection Figure 6(b) is remarkable, showing weak pulsations that are visible throughout the whole spectral band and bright fibers present only at low frequencies.

2.5. General Descriptions of Events

In the four examined events, the whole radio emission consisted only of fibers (*i.e.*, a continuum was absent), and the small-scale fibers were fine structures in *i*) large-scale ZPs, *ii*) type

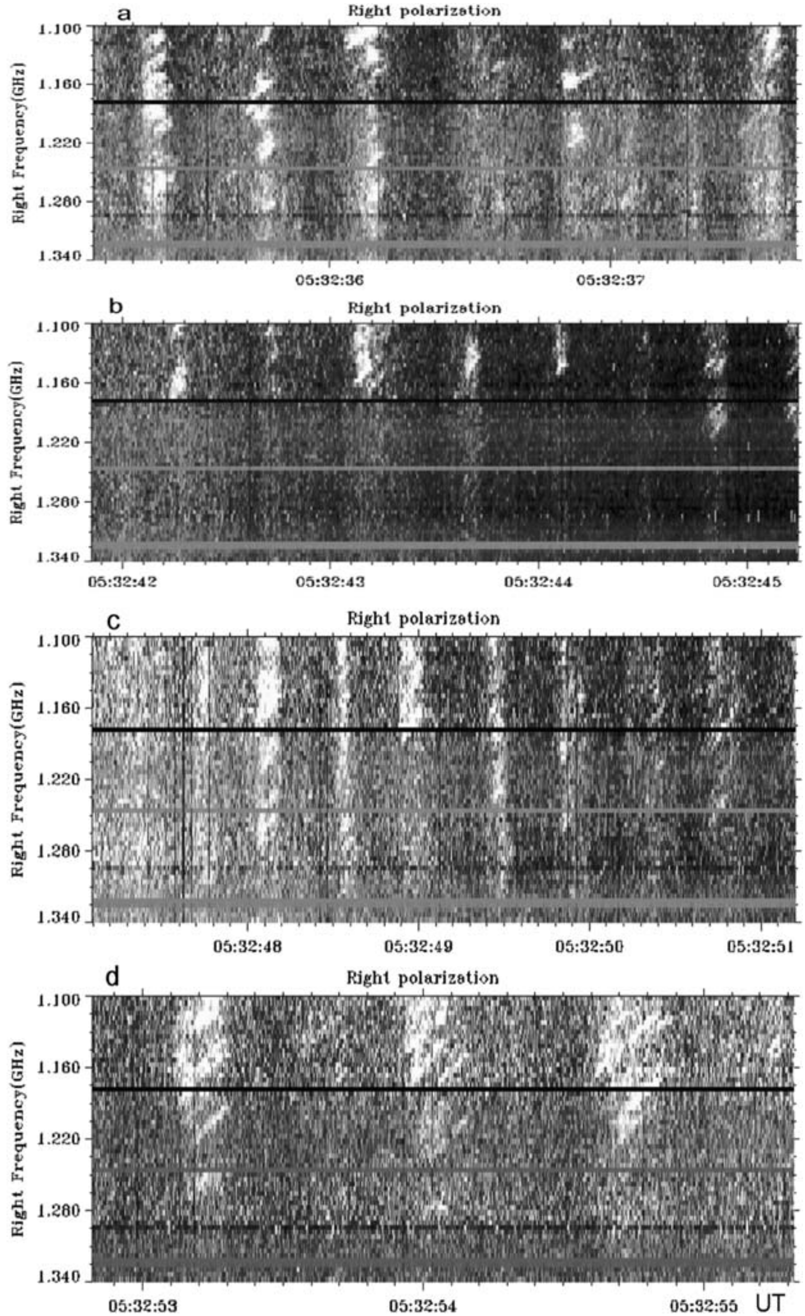

Figure 6 Small-scale fibers in the event of 31 October 2004. All four panels represent only in the right polarization channel since the emission was completely right-hand polarized.

III bursts, or *iii*) pulsations. Sometimes they resemble the ropes of fibers, familiar in the meter range (Chernov, 2008). The basic parameters of the four events and of the fine structure are summarized in Table 1. We can derive the following conclusions from the observations:

– Narrowband fibers drift almost always to lower frequencies with a speed that is typical in usual fiber bursts, and sometimes they are similar to the ropes of fibers in the meter range.
– In two events the fibers evolved from chaotic features in the dynamic spectrum to a regulated structure (in the form of large-scale ZP stripes) and again into disorder, being gradually converted into the spike bursts.
– Large-scale ZP was limited at high frequencies by a boundary drifting to lower frequencies with a speed of -70 to $-90\ \mathrm{MHz\,s^{-1}}$.
– Small-scale fibers can be regarded as a fine structure in type III bursts and broadband pulsations.
– The radio emission are moderately or strongly polarized.
– In the first three events, the fiber structure appeared as a forerunner of the entire event.
– The fibers, as well as large-scale ZP, do not reveal absorptions at the low-frequency edge.
– A superfine structure in small-scale fibers was not detected with a time resolution of 1.25 ms.

Of the similar structures known earlier it is possible only to note the drifting spikes, observed with the spectrograph of Torun Observatory by Dabrowski *et al.* (2005) in approximately the same frequency band. All spectral properties of these spikes are very close to our small-scale fibers; in their drifting spikes only large-scale ZP stripes were missing. Several groups of spikes shown in their Figure 17 look quite similar to our short-duration ropes with positive frequency drift. In our 3 November event small-scale fibers were gradually transformed also into chaotic spike bursts.

To understand the generation mechanisms of fibers and structures in the dynamic spectrum, let us examine the general properties of the analyzed events. All four events are small radio bursts in terms of intensity and duration and comprise a kind of small flare continuum. As always, a basic obstacle for such an analysis comes from the absence of a full and identical set of all observational data. In the absence of data on the positions of radio sources in the decimeter range we have tried to determine the place of the flare on the EUV images (TRACE data) and we compared the assumed position of radio source against the location of particle acceleration (RHESSI data) and the maps of radio sources at 17 GHz (Nobeyama). If the magnetic maps are available and if we can determine the polarity of the magnetic field under the radio source, then it is possible to identify the mode of radio emission.

The most complete data in this analysis are for the 24 July 2004 event. A flare of M1.0 1F class has occurred at 06:01 – 06:04 – 06:10 UT in the active region (AR) 10652 (N°07,W°20). The analyzed fiber structure was observed after several strong pulsations at the very beginning of the smooth rise of a flare continuum in the unpolarized emission whose duration was about 5 minutes (Table 1). According to the spectral data of IZMIRAN in the frequency range of 25 – 270 MHz, the pulsations had a continuation in the meter-wave range in the form of type III bursts, where they stopped at frequencies near 200 MHz in the form of J bursts. Later the flare continuum lost any fine structure, and the event ended, without type II burst and any coronal mass ejection (CME).

In the absence of spatially resolved radio observations, the position of the radio source can be inferred from Figure 7, where the image of the flare in the chromosphere (TRACE 1700 Å data) at 04:07 UT is superimposed on the magnetogram (Solar Flare Telescope, NAOJ/Mitaka). Three bright flare kernels (dark blue patches) are located to the west of the preceding sunspot of this AR, above the quadrupole-like structure of the magnetic field with a peculiar X point at the center of the flare region.

Table 1 Selected events with unusual fiber structure (FS).

Date and time (UT)	Duration (min)	Duration FS(s)	Flux (sfu)	Polarization (R, L)	Δf_s (MHz) Z	Δf_s (MHz) F	Δf_e (MHz) Z	Δf_e (MHz) F	Δt(s) F	df/dt (MHz s^{-1}) F	df/dt (MHz s^{-1}) Z
24 July 04 06:01	5	14.5	450	100% R	80	20 – 40	20 – 30	10 – 15	0.07 – 0.1	270	−125
22 October 04 08:06	5	5	100	weak R	35 – 70	30	25	15 – 20	0.12 – 1.4	90	0 – −40
03 November 04 03:23	25	2.7	400	weak R	72	15 – 20	30	10 – 15	0.05 – 0.06	630	−270
31 October 04 05:25	7	20	< 100	100% R		20 – 30	Puls.	10	0.04		−160 – −270

Notes. Z – large-scale zebra pattern; F – narrowband fibers; Puls. – pulsations (without ZP);
Δf_e – frequency bandwidth of isolated stripes in emission;
Δf_s – frequency separation between adjacent stripes.

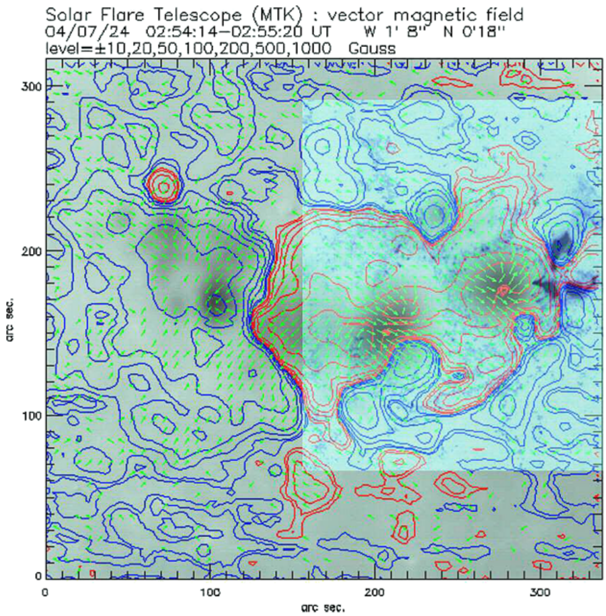

Figure 7 A TRACE 1700 Å image of the flare on 24 July 2004 in the chromosphere at 04:07 UT, superimposed on the magnetogram (Solar Flare Telescope, NAOJ/Mitaka).

The two flare kernels were located above the S polarity; therefore the radio emission of right circular polarization should correspond to the ordinary wave mode. The flare kernels in the 195 Å images were also located exactly above the bright regions seen in the 1700 Å images, and the radio source in right circular polarization at 17 GHz (Nobeyama Radio Heliograph) was also located in this location. The largest radio flux was recorded in decimeter and meter ranges, indicating magnetic reconnection high in the corona. In fact, in the 1700 Å images we see bright tops of the flare loops. The decimeter radio source is expected to be found below the flare current sheet (where the acceleration of fast particles would take place) and in the lower closed magnetic loops, of which we see the bright tops in Figure 7. The positive frequency drift of the large-scale ZP stripes may be caused by the downward motion of a plasma ejection from the reconnection region with the Alfvén velocity. On its way this ejection would meet a flare loop arcade that was expected to be rising. The high-frequency boundary of the termination of emission can be the consequence of this collision.

2.5.1. 22 October 2004 Event

A flare of M2.1 1N class occurred at 07:52 – 08:11 – 08:16 UT in AR 10687 (N°9, E°44). The analyzed fiber structure was observed at 08:06:40 UT in the composition of weak type III bursts, at the very beginning of the smooth rise of a flare continuum in the strong polarized emission whose duration was about 5 minutes (Table 1). According to the spectral data of IZMIRAN, the type III bursts continued in the meter range, up to 25 MHz.

According to the Hα images (Meudon spectroheliograms), the flare started above the following sunspot in this AR, but at the moment of the rise of a continuum up to the maximal value of $\approx$ 100 s.f.u., the brightest flare area was seen above the leading sunspot. A large flare area in UV (SOHO EIT 195 Å data) appeared also above the leading spot. Thus, right-hand circular polarization of the fiber structure in weak type III bursts from the source above the following spot of S magnetic polarity in the beginning of the event corresponds to the ordinary wave. Later (after 08:07 UT) the polarization of the fine structure changed its sign to left hand when the big flare area developed above the leading spot of N polarity. Thus, the radio emission continued to remain in the same ordinary mode.

The constant frequency drift of large-scale ZP stripes of about 90 MHz s^{-1} indicates a downward movement of the radio source with a velocity less than the Alfvén speed.

2.5.2. 3 November 2004 Event

A flare of M1.6 1N class occurred at 03:23 – 03:35 – 03:57 UT in AR 10696 (N°09, E°45). The analyzed fiber structure was observed at 03:25:07 UT at the very beginning of the smooth rise of a flare continuum in the nonpolarized emission, whose duration was about 25 minutes (Table 1). According to Culgoora spectral data, strong type II bursts began at 03:33 UT at frequencies near 120 MHz (with an estimated shock speed of 750 km s^{-1}), accompanied by a powerful CME (SOHO LASCO C2) after 03:54 UT (whose estimated speed was 918 km s^{-1}).

After about 03:30 UT the polarization of the fine structure changed sign, and the left-handed polarization became predominant. The dynamics of flare processes can be tracked according to Figures 8(a) and (b), in which for two moments at the beginning of the event the sources of hard X rays (RHESSI HXR) in the 6.0- to 7.0-keV energy band are superimposed on the 17-GHz (Nobeyama) radio map. Figure 8(a) shows that at 03:26 UT the radio source had a triple structure (in accordance with the distribution of sunspots in the AR) with a big source of predominantly right-hand circular polarization above the following spot of the S polarity. A single HXR source (A) was located above this radio source. At 03:30 UT (Figure 8(b)) a new HXR source (B) appeared in the southwestern portion of the AR. Thus, the strengthening of the radio source at this moment was connected with the development of the flare above the small leading spot of N polarity. In the higher energy band, 14.0 – 16.0 keV, two new sources have appeared in the same location. So, it is possible to conclude that the radio emission corresponded to the ordinary wave mode both at the beginning and in the maximum of the event.

2.5.3. 31 October 2004 Event

Unlike the three previous events, in this case the fiber structure was observed only in fast pulsations and in the decay phase of the event. In this context it is interesting to investigate the differences in the development of the flare.

The radio burst was also of moderate intensity (about 240 s.f.u. in the burst maximum and about 100 s.f.u. in the course of pulsations), although the X-ray class was higher, M2.3. The flare took place in AR 10691 (N°12, W°36) at 05:23 – 05:32 – 05:39 UT. Radio pulsations have occurred after powerful type III bursts and one minute before the meter type II burst (Hiraiso data). Such a situation is almost similar to the 3 November and 22 October events. But in this event the maximal radio flux was recorded at 15.4 GHz and we have no other evidence about possible magnetic reconnection high in the corona. The flare probably occurred at very small heights.

A similar comparison between the HXR sources (25 – 50 keV, RHESSI data) and the radio sources at 17 GHz (Nobeyama) shows that at the moment of pulsations we see multiple sources located along the NE – SW direction (*i.e.*, along the magnetic neutral line), instead of one central source at the beginning of the event. The small 17-GHz radio source in right-hand circular polarization was located just at the continuation of this neutral line. This indicates the existence of a loop arcade along the neutral line. The RHESSI HXR sources are probably located at the tops of this arcade. Therefore the analyzed radio pulsations could

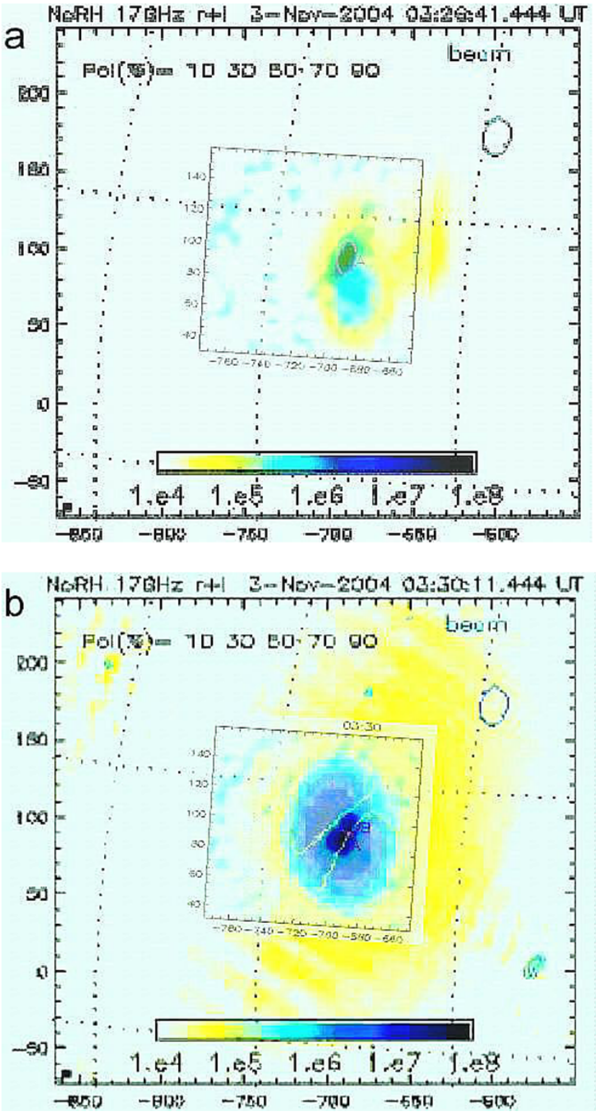

Figure 8 17 GHz radio maps (Nobeyama) at two moments at the beginning of the 3 November 2004 event. The sources of hard X rays (RHESSI) in the 6.0- to 7.0-keV energy band are superimposed [green patch in (a) and dark blue patch in (b)].

be caused by MHD fluctuations in the mentioned loop arcade. For propagating MHD waves (Aschwanden, 1987) the mean period of pulsations of 0.4 s yields a radius for the magnetic loop of about 150 km. By assuming the bounce resonance in the loop of fast particles with a velocity of 10^{10} cm s^{-1} we obtain a loop length of $\approx 1.5 \times 10^9$ cm. Actually, a loop of such a size could cover only the height interval responsible for decimeter-wave emission. As new HXR sources as well as the radio source at 17 GHz were located along the magnetic neutral line, because of the lack of exact information about the radio source positions in the AR, we cannot determine the radio wave mode.

In summary, in the first three events where the small fibers were organized into large-scale ZP and served as a forerunner of the main event, the corresponding flare occurred high in the corona and a disturbance (plasma ejection) propagated downward from the current sheet (if we judge the direction by the positive frequency drift of the ZP). In the forth event the flare took place at a lower height corresponding to the centimeter-wave emission, and fibers were made of fast pulsations that can be interpreted as resulting from MHD oscillations in a flare loop arcade.

3. General Discussion

Small-scale fibers differ from usual fiber bursts only by their narrow total frequency bandwidth and they are similar to ropes of fibers; therefore the usual (most accepted) mechanism for fiber bursts should work, namely the coalescence of plasma wave (l) with whistlers (w): $l + w \rightarrow t$ (Kuijpers, 1975b; Chernov, 1976, 1990). However, the propagation of whistlers is limited by a small magnetic trap in the form of fast shock fronts escaping from a region of magnetic reconnection (Chernov, 1997). In our case a periodicity of fibers was not so evident, and fibers were organized as large-scale stripes of ZP. So, these ZP stripes become visible only when whistlers propagate through the ZP source.

More than 10 different models have been proposed for ZPs. Most of them include some emission of electrostatic plasma waves at the DPR frequency (Kuijpers, 1975a; Zheleznykov and Zlotnik, 1975; Mollwo, 1983, 1988; Winglee and Dulk, 1986; Chernov, 2006):

$$\omega_{\mathrm{UH}} = \left(\omega_{\mathrm{Pe}}^2 + \omega_{\mathrm{Be}}^2\right)^{1/2} = s\omega_{\mathrm{Be}}, \tag{1}$$

where ω_{UH} is the upper hybrid frequency, ω_{Pe} is the electron plasma frequency, ω_{Be} is the electron cyclotron frequency, and s is the harmonic number. The model that best describes the observations and conditions in the corona is the one by Winglee and Dulk (1986), which is based on unsaturated electron cyclotron maser emission by electrons with a loss-cone distribution.

In our events the radio sources cannot be pointlike ones, since in such a case one whistler wave packet should produce all zebra stripes simultaneously, but we did not see such a feature. Since the small fibers were not connected by a unique straight line in the dynamic spectra, we cannot assume that one whistler wave packet passes through several DPR levels consecutively in an extensive source. So, the unique possibility remains that whistlers are excited at the same DPR level simultaneously with the plasma waves. Without whistlers, ZP stripes cannot be visible, at least in the DPR model with a loss-cone distribution function, in accordance with numerical results of electrostatic instability in Kuznetsov and Tsap (2007). Whistlers without plasma waves cannot be detected either, but a plasma wave of low energy will be sufficient (at places of DPR) to emit radio waves of sufficient intensity. Thus, whistlers "highlight" DPR levels.

To confirm this hypothesis, let us estimate the magnetic field strength B in two ways: from the observations of separate fibers using the whistler model and from large-scale ZP in the DPR model. If the hypothesis is correct, these values of the field strengths should be equal.

From the whistler model for small fibers we have $\Delta f_{\mathrm{e}} \approx f_{\mathrm{w}} \approx 0.1 f_{\mathrm{Be}}$ (where f_{w} is the Whistler frequency) and a mean value $\Delta f_{\mathrm{e}} = 12.5$ MHz (for the events of 24 July and 3 November), and we obtain $B \approx 45$ G.

In the DPR model the frequency separation depends on the scale heights of density (N_{e}) and magnetic field [$L_{\mathrm{Ne}} = 2N_{\mathrm{e}}(\mathrm{d}N_{\mathrm{e}}/\mathrm{d}r)^{-1}$ and $L_B = B(\mathrm{d}B/\mathrm{d}r)^{-1}$] (Zlotnik *et al.*, 2003)

$$\Delta f_s / f_B \approx L_B / |L_{\mathrm{Ne}} - L_B|. \tag{2}$$

For $\Delta f_s = 72$ MHz (for the 3 November event) we obtain about the same value of B (= 46 G) for $L_{\mathrm{Ne}} = 1.4 \times 10^9$ cm and $L_B = 5 \times 10^8$ cm. In the flare region the plasma is very inhomogeneous and such scale heights are realistic. In our events only three or four large-scale stripes of ZP (or DPR levels) are simultaneously formed in the spectrum, which demonstrates the small sizes of local L_{Ne} and L_B in flare inhomogeneities. Four DPR levels are simply realized at harmonic number $s = 10 - 14$ with such a ratio of scale heights.

The stable frequency drift of fibers implies that the magnetic field changes little during the lifetime of the structure (Chernov, 1990). The frequency drift of fibers is mainly determined by the group velocity (v_{gr}) of whistlers, and we have $v_{\mathrm{gr}} = 2cf_{\mathrm{Be}}/f_{\mathrm{Pe}}[x(1-x)^3]^{1/2}$, where $x = f_{\mathrm{w}}/f_{\mathrm{Be}}$ is the ratio of whistler frequency to cyclotron frequency (Kuijpers, 1975a). If we assume the parameter x varies little during the lifetime of the structure, and $f_{\mathrm{Be}}/f_{\mathrm{Pe}}$ has a consistent value owing to the DPR condition, then v_{gr} would vary little and consequently the whistlers would cause a stable frequency drift of fibers, at least within a certain DPR level. Therefore the positive frequency drift of large-scale ZP can be connected with the downward motion of the source. In the absence of a good analytical model of electron concentration in the upper chromosphere, we will use a graphical representation given, for example, in the model of Allen (in Figure IV.1 of Krüger, 1979). By passing the dependence of plasma frequency (f_{Pe}) on to height (r), it is possible to roughly estimate the value of the gradient of f_{Pe} between 1000 and 2500 MHz on the order of 240 MHz/10^8 cm. Then, we can use the simplest expression for the definition of the velocity of propagation:

$$V \approx 2\frac{\mathrm{d}f/\mathrm{d}t}{f}\frac{N_{\mathrm{e}}}{\mathrm{d}N_{\mathrm{e}}/\mathrm{d}r} = \frac{\mathrm{d}f/\mathrm{d}t}{\mathrm{d}f_{\mathrm{Pe}}/\mathrm{d}r}. \tag{3}$$

The frequency drift $\mathrm{d}f/\mathrm{d}t = 630$ MHz s^{-1} will correspond to a velocity of about 2590 km s^{-1}. Such a value might be more than a typical Alfvén velocity. Therefore it is possible to assume that the plasma ejection that moves downward from the magnetic reconnection region has caused a shock wave.

In the 24 July event the drift of 220 MHz s^{-1} implies a velocity of ≈ 900 km s^{-1}, which is somewhat more than the Alfvén velocity ($V_{\mathrm{A}} \approx 700$ km s^{-1} for the estimated value of $B = 45$ G).

The drifting boundary of the emission termination at the high-frequency edge of the large-scale ZP may mean that a moving shock front meets a rising closed magnetic loop. So, the conditions for DPR are realized only in a narrow height interval, below of the magnetic reconnection region, and only at the very beginning of events. After such a collision they will be destroyed, and large-scale zebra stripes will be transformed into a braided ZP (Figures 2(b), 4(b), and 7). Thus, the radio source showing such a fiber structure differs from the radio source of the rope of fibers only by the absence of a magnetic trap (only one shock front), where fast particles could make periodic bounce motions, and by short living conditions for DPR. The absence of any absorption is simply explained by the absence of continuum emission at the very beginning of events. Only the pulsations in the 31 October event were observed against a weak continuum, and we could detect some fragments of absorption between fibers (Figure 6).

The small frequency drift of fibers in the 22 October event may be interpreted as whistlers propagating almost in parallel to the levels of equal density (plasma frequency), which is likely if one considers the small closed loops. The detection of J bursts will prove this hypothesis.

In the 31 October event, weak whistler wave packets were likely to be excited, and they "highlight" weak pulsations of plasma waves that resulted from MHD oscillations in the course of a new flare enhancement. All these conditions are very specific; therefore they are very rare. Nevertheless they fit with the general known models of fine structure formation and do not require any new mechanisms. The ordinary emission mode answers the proposed mechanism. The model with a Bernstein mode requires emission of an extraordinary mode from a pointlike source.

Thus, we assume that the usual mechanisms can be applied for the interpretation of such a fiber structure: the coalescence of whistler waves with a plasma wave for fiber bursts and the DPR model for the large-scale ZP. However, the following special features of the plasma wave excitation in the radio source must be present. Both whistler and plasma wave instabilities are too weak at the very beginning of the events (the continuum is almost absent), and the fine structure is almost invisible. Moreover, according to the recent simulations of Kuznetsov and Tsap (2007), the fast electrons with a loss-cone distribution cannot excite a high enough level of electrostatic waves at the DPR levels so that the separate stripes would be visible. Then, whistlers generated directly at the DPR levels by the same fast electrons will "highlight" the radio emission only from these levels owing to the interaction with plasma waves and we observe small-scale fibers as a substructure of ZP. More precisely, the whistler packets may bring about sufficient plasma wave energy as well as a new composition of particle distribution; therefore the DPR levels could be more pronounced and "highlighted."

In the recent paper of Wu *et al.* (2007) the small-scale fibers in the 3 November event are interpreted as drifting spikes emitted from "solitary kinetic Alfvén waves" (SKAWs) by fast electrons accelerated by the electric field and trapped in SKAWs. However, they did not discuss the reasons for the formation of fibers along the stripes of large-scale ZP. Furthermore, the source of the strong Alfvén waves, which accelerate a large fraction (≈ 0.1) of the background electrons at the beginning of the event, was not examined.

We have not adopted the new model of LaBelle *et al.* (2003), since it is supposed to be applied to the explanation of a large number of stripes with narrow frequency separation. In the large-scale ZP in question, in contrast, the frequency separation is considerably wider than in the usual ZP. A recent evaluation by Chen and Yan (2007) on the validity of the mechanism of LaBelle *et al.* (2003) indicated that, with realistic values of the density contrast (of $\delta \leq 0.2$), the model cannot account for a large number of ZP stripes.

However, we cannot completely exclude the possibilities of the application of the new models, based on the existence of the bands of transparency and opacity when the radio waves propagate through a spatially periodic medium (for example, Laptuhov and Chernov, 2006). It is possible that the large-scale ZP is the result of this selectivity with the specific scale of thermal heterogeneities, which move downward from the flare region, and that small-scale fibers are caused by additional quasi-periodic modulation of these heterogeneities, for example, by a fast magnetosonic wave propagating from below. Or alternatively and more simply, the radio waves meet on their way the small- and large-scale heterogeneities, which move in different directions (*i.e.,* a radio wave is filtered by transparency bands twice). These possibilities require more detailed study, which is outside the scope of this article.

Acknowledgements The authors are grateful to Chen Bin (NAOC) for fruitful discussions. We are grateful to the staff at Meudon, Nancay, Nobeyama, Zurich (Bleien), and Culgoora (spectral data) and to the SOHO (LASCO/EIT), TRACE, and RHESSI teams for operating the instruments and performing the basic data reduction, and especially, for their open data policy. We are grateful also to NAOJ/Mitaka for the solar magnetograms. G.P. Chernov appreciates the support of the Chinese Academy of Sciences and the NSF of China, which enabled work with NAOC colleagues, and the Russian Foundation of Basic Research (RFBR), Grant No. 08-02-00270. The Chinese authors are supported by the National Basic Research Program of the Ministry of Science and Technology of China (Grant Nos. G2000078403 and 2006CB806301) and CAS-NSFC Key Project (Grant No. 10778605).

References

Aschwanden, M.J.: 1987, *Solar Phys.* **111**, 113.
Chen, B., Yan, Y.: 2007, *Solar Phys.* **246**, 431.
Chernov, G.P.: 1976, *Sov. Astron.* **20**, 582.
Chernov, G.P.: 1990, *Sov. Astron.* **34**, 486.
Chernov, G.P.: 1996, *Astron. Rep.* **40**, 561.
Chernov, G.P.: 1997, *Astron. Lett.* **23**, 827.
Chernov, G.P.: 2006, *Space Sci. Rev.* **127**, 195.
Chernov, G.P.: 2008, *Astron. Lett.* **34**(6). accepted.
Chernov, G.P., Yan, Y.H., Fu, Q.J.: 2003, *Astron. Astrophys.* **406**, 1071.
Chernov, G.P., Yasnov, L.V., Yan, Y.H., Fu, Q.J.: 2001, *Chin. J. Astron. Astrophys.* **1**, 525.
Dabrowski, B.P., Rudawy, P., Falewicz, R., Siarkowski, M., Kus, A.J.: 2005, *Astron. Astrophys.* **434**, 1139.
Elgaroy, Ø.: 1959, *Nature* **184**, 887.
Fu, Q.J., Ji, H.R., Qin, Z.H., Xu, Z.C., Xia, Z.G., Wu, H.A., *et al.*: 2004, *Solar Phys.* **222**, 167.
Krüger, A.: 1979, *Introduction to Solar Radio Astronomy and Radio Physics*, Reidel, Dordrecht.
Kuijpers, J.: 1975a, Collective Wave-Particle Interactions in Solar Type IV Radio Source. Ph.D. Thesis, Utrecht University.
Kuijpers, J.: 1975b, *Solar. Phys.* **44**, 173.
Kuznetsov, A.A., Tsap, Yu.T.: 2007, *Solar Phys.* **241**, 127.
LaBelle, J., Treumann, R.A., Yoon, P.H., Karlický, M., 2003, *Astrophys. J.* **593**, 1195.
Laptuhov, A.I., Chernov, G.P.: 2006, *Plasma Phys. Rep.* **32**, 866.
Ledenev, V.G., Karlický, M., Yan, Y., Fu, Q.: 2001, *Solar Phys.* **202**, 71.
Mal'tseva, O.A., Chernov, G.P.: 1989, *Kinemat. Fiz. Nebesnykh Tel.* **5**, 44.
Mollwo, L.: 1983, *Solar Phys.* **83**, 305.
Mollwo, L.: 1988, *Solar Phys.* **116**, 323.
Slottje, C.: 1981, *Atlas of Fine Structures of Dynamic Spectra of Solar Type IV-dm and Some Type II Radio Bursts*, Utrecht Observatory.
Winglee, R.M., Dulk, G.A.: 1986, *Astrophys. J.* **307**, 808.
Wu, D.J., Huang, J., Tang, J.F., Yan, Y.H.: 2007, *Astrophys. J.* **665**, L171.
Yasnov, L.V., Karlický, M.: 2004, *Solar Phys.* **219**, 289.
Zheleznykov, V.V., Zlotnik, E.Ya.: 1975, *Solar. Phys.* **44**, 461.
Zlotnik, E.Ya., Zaitsev, V.V., Aurass, H., Mann, G., Hofmann, A.: 2003, *Astron. Astrophys.* **410**, 1011.