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Fine Structure of Large Flare Radioemission

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Abstract—Several recent phenomena with zebra patterns (ZPs) and fiber bursts on the dynamic spectra of solar type IV radio bursts have been complexly analyzed using all available ground-based and satellite data (SOHO, TRACE, RHESSI). ZPs and fiber bursts were observed at frequencies of 50–3800 MHz. The main relative spectral parameters and the degree of circular polarization of ZPs and fiber bursts are almost identical. The fine structure was observed in powerful and weak phenomena (and was more impressive in weak phenomena) during impulsive and decline phases at instants of recurring continuum bursts. The shape of the fine structure depends on that of the magnetic loops in a radio source, the type of fast particle acceleration (impulsive or prolonged), and the presence of shock waves and coronal mass ejections. Several new effects of the interaction between zebra stripes and fiber bursts have been detected. Specifically, up to 40 fiber bursts with different frequency ranges were simultaneously observed in the frequency range 1–2 GHz against a background of sudden absorptions. It has been indicated that different effects in the ZP stripe behavior can be explained within the scope of the model with whistlers, if the quasi-linear diffusion of fast particles on whistlers (which deforms the particle velocity distribution function) is taken into account.

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INTRODUCTION

Bands in the emission and absorption against a background of the solar type IV radio burst continuum are traditionally divided into two types: zebra patterns (ZPs) and fiber bursts. ZPs represent more or less regular bands in the dynamic spectrum (frequency–time), more frequently with positive, but variable frequency drift. Fiber bursts have an almost constant negative frequency drift. Many observational properties of these structures are well known, have long been studied, and are classified in reviews and monographs (Slottje, 1981; Kruger, 1983). However, unusual bands with abruptly changing parameters are sometimes registered. High-resolution (10 MHz and 8 ms) spectrographic observations at the Beijing Observatory in the frequency range 2.6–3.8 GHz indicate that a similar fine structure is also quite diverse in the microwave range (Chernov et al., 2001, 2003).

The interpretation of such a complex fine structure lagged behind obtaining more varieties of new observational data. However, the interaction between plasma electrostatic waves (l) and whistlers (w) (generated by the same fast electrons with the velocity loss-cone distribution) with the free emission of an ordinary wave (t): $l + w \longrightarrow t$ can be considered as the main radioemission mechanism for fiber bursts (Kuijpers, 1975a;
a Chernov, 1990b)).

The ZP formation theory developed much more complexly. More than ten different models were proposed, and most of these theories include the emission of electrostatic plasma waves at a double-plasma resonance (Zheleznyakov and Zlotnik, 1975; Kuijpers, 1975b; Fedorenko, 1975; Zheleznyakov, 1977; Mollwo, 1983; Winglee and Dulk, 1986):

$$\omega_{UH} = (\omega_{Pe}^2 + \omega_{Be}^2)^{1/2} = s\omega_{Be}, \qquad (1)$$

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 (Winglee and Dulk, 1986) based on an unsaturated electron cyclotron maser emission of electrons with a loss-cone distribution is most adequate to the observations and conditions in the corona. However, all these versions of the ZP theory have several disadvantages:

(i) the frequency separation between ZP stripes (Δf_s) should make up a certain fraction of the electron cyclotron frequency (depending on the relationships between the scale heights of a change in the field and the density in the corona); however, an irregular pattern is often observed;

(ii) a magnetic field, determined based on the Δf_s value, is often so small that it is difficult to obtain plasma $\beta < 1$ (an evident value for the magnetic trap above the active region);

(iii) almost all models explain the emission bands, although mostly absorption stripes are sometimes observed;

(iv) all models assume an important property of the do not
loss-cone distribution: whistlers are also generated, and the interaction between the whistlers and fast particles

cardinally changes the velocity distribution; i.e., the transverse anisotropy decreases, but a beam with longitudinal velocities originates.

Moreover, the main spectral properties of zebra-type stripes and fiber bursts and the polarization of their radioemission coincide, which indicates that the emission mechanism is common for both structures and is based on the coalescence of plasma waves with whistlers but under different conditions of whistler stability. The entire magnetic trap is filled with periodic whistler wave packets generated by the loss-cone distribution of fast electrons in the regions of cyclotron resonance:

$$\omega_{\mathrm{w}} - k_{\|} v_{\|} - s\,\omega_{\mathrm{Be}} = 0, \qquad (2)$$

where ω_w is the whistler frequency, $k_{\|}$ is the whistler wavenumber, and $v_{\|}$ is the velocity of fast electrons (parallel to the magnetic field). Depending on the distribution function form, the instability develops when whistlers propagate against fast particles along the magnetic field (the normal Doppler effect, $s = +1$ in (2)) or in parallel with these particles at large angles with respect to the magnetic field and form zebra-type stripes with a different frequency drift (Mal'tseva and Chernov, 1989a, 1989b; Chernov, 1990a, 1990b; Chernov et al., 1998). The fast periodicity of the whistler instability is related to the instability of quasi-linear character (scatter of the fast particles on the whistlers) and results in periodic upsets of the electrostatic wave instability in a whistler packet volume, which is responsible for the absorption stripes accompanying fiber bursts and zebra-type emission bands (Chernov, 1996). Whistlers can contribute to the formation of stripes in emission and absorption as a result of their interaction with plasma waves at the sum and difference frequencies $\omega_{\mathrm{l}} \pm \omega_{\mathrm{w}} = \omega_{\mathrm{t}}$ (Chernov, 1976, 1989; Chernov and Fomichev, 1989).

Since a unified ZP theory is absent, many researchers continue developing new versions of the mechanism at a double plasma resonance (Ledenev et al., 2001; Zlotnik et al., 2003). When LaBelle et al. (2003) tried to eliminate the difficulties caused by low magnetic field strengths in the regions of double plasma resonance, they proposed a new ZP theory based on the mechanism of the emission of auroral chorus, i.e., magnetospheric bursts with fine structures similar to ZP received at ground-based stations at frequencies of 2–4 MHz. It is assumed that the Z mode is emitted according to the cyclotron maser mechanism by analogy with (Winglee and Dulk, 1986). Although the Z mode itself at the upper hybrid frequency is not emitted from the source, this mode can be transformed into an ordinary mode at discrete frequencies (natural harmonics) in the presence of the density inhomogeneities of the corresponding scales. However, this theory ignores the process of emission and the dynamics of harmonics. Moreover, the bands should form a continuous general spectrum (continuum) because of numerous inhomogeneities (formed by propagating ion acoustic waves). The simultaneous appearance of fiber bursts against a background of ZP is also not considered.

Observations of the solar radioemission fine structure can be reliably used to diagnose the solar corona plasma and to verify theoretical models and the results of laboratory plasma experiments devoted to studying wave–wave and wave–particle interactions. Recently, the observations of the fine structure have become considerably more extensive, and new effects in ZP have been detected. An analysis of new phenomena usually includes a more detailed study of the flare processes in the optic and X-ray bands. Therefore, it is now important to distinguish new aspects in the fine structure observations and to analyze these aspects within the scope of different theoretical models. Precisely these problems are considered in the present work.

NEW ZP OBSERVATIONS

Recently, the spectrometers of the Natural Observatory of China (NAOC) in the ranges 1–2, 2.6–3.8, and 5.2–7.6 GHz have been considerably modernized. These spectrometers make it possible to register fine structures with the best spectral resolution: 10 MHz and 5–8 ms. During several phenomena, the data obtained using these spectrometers were compared with the simultaneous IZMIRAN spectrographic observations in the range 25–270 MHz.

Phenomenon of April 21, 2002

An explosive long-duration X1.5 flare on April 21, 2002, occurred in AR 9006 near the western limb (S14W84) between 00:43 and 02:38 UT. In the 195 Å EUV range, TRACE (Transitional Regional and Coronal Explorer) observed the formation of a bright post-flare arcade of loops (Gallagher et al., 2002). A dark matter, which precipitated on an arcade from above and obscured an arcade of loops, was observed from 01:34 to 02:15 UT. According to the radio and hard X-ray emissions, the entire long-duration event is divided into two phases. At the phase of the increase in the soft X-ray emission, the first maximums were observed at about 01:15–01:18 and 01:30 UT in the bands of hard X-ray (HXR) and radio emissions, respectively (GOES MTI/HXRS data). At this phase, the maximal energy was released in the meter and decimeter ranges (data from a Korean spectrograph, Cho, private communication). In the microwave range, the maximum of the first phase was higher than that of the second phase; however, a fine structure around a frequency of 3 GHz was not observed. An arcade of loops started forming only after approximately 01:30 UT. ZP was observed during the distinguished series with an average duration of about 1 min, but only at the second phase of a burst in the hard X-ray band between 01:44 and 02:25 UT (Fig. 1). We also note that the precipitation of the dark matter was maximal precisely in this time interval (TRACE satellite data). Figure 2 indicates that new bright centers

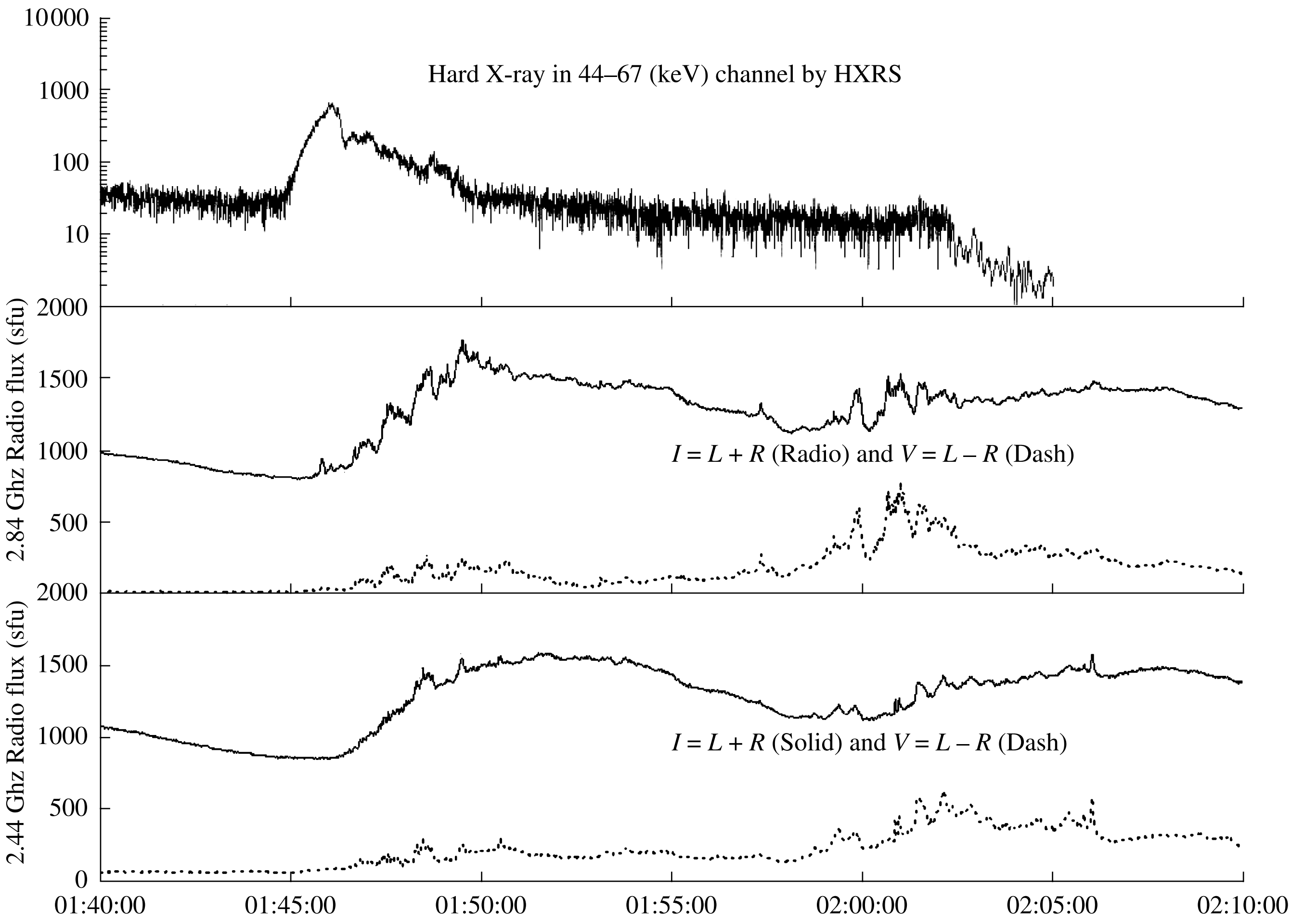

Fig. 1. The upper plot: the profile of a hard X-ray burst in the 44–67 keV channel (MTI/HXRS) on April 21, 2002, coincident with the ZP interval in the range 2.6–3.8 GHz. The lower plots: the profiles of radioemission at 2.84 and 3.44 GHz (NAOC, Huairou station), indicating the radio flux in the intensity ($I = L + R$) and polarization ($V = L - R$) marked by the solid and dotted lines, respectively. All fast bursts are related to the FS. It is evident that the degree of polarization increased by the end of the burst.

originate as X points of a magnetic reconnection in an arcade of loops at the loop intersection at the beginning of this phase (the upper left-hand frame). At 01:51–01:53 UT, the ZP stripes almost disappeared, and these bright centers simultaneously disappeared in the 195 Å line of the TRACE flare images (Fig. 2, the upper right-hand frame). The difference image between 01:50:57 and 01:48:16 UT indicates several bright loops (the middle left-hand frame), where ZP sources could be located. Three new sources of hard X rays (RHESSI HXR, Galagher et al., (2002)) appeared below the X-ray points of the magnetic reconnection mentioned above during the maximal ZP (Fig. 2, the lower left-hand frame). Such an assumption is confirmed by the location of radio sources at 5.7 GHz according to the data of the Siberian solar radio telescope (SSRT), shown by the contours in the polarized emission 右 (parameter V) in the lower left-hand frame in Fig. 2. The light and dark contours in the lower left-hand frame indicate the locations of the hard X-ray sources (RHESSI HXR) in the 50–100 and 12–25 energy channels, respectively (Gallagher et al., 2002). Burst continuum sources (SSRT), tinted gray and black in the lower right-hand frame in Fig. 2, occupy approximately the same positions.

After ~02:29 UT (when ZP disappeared), an arcade of bright loops reached higher altitudes (Fig. 2, the middle right-hand frame), and the activity maximum shifted into the decimeter frequency range.

In all series, the ZP stripes drifted toward low frequencies, which is more typical of fiber bursts. Figure 3 demonstrates the 20-s spectrum (beginning from 01:48:18 UT) of the most developed ZP at frequencies of 2.6–3.8 GHz (NAOC spectrometer, Beijing). Up to 34 ZP stripes are simultaneously present in the spectral range of this fragment with a width of 1.2 GHz, and the frequency separation barely increases between the stripes from 27 MHz at 2.8 GHz to 43 MHz at 3.7 GHz. Note that the relative value of the frequency separation is approximately the same as in the meter range: $\Delta f/f >$ 0.012. The frequency shift of the stripes at the HF edge

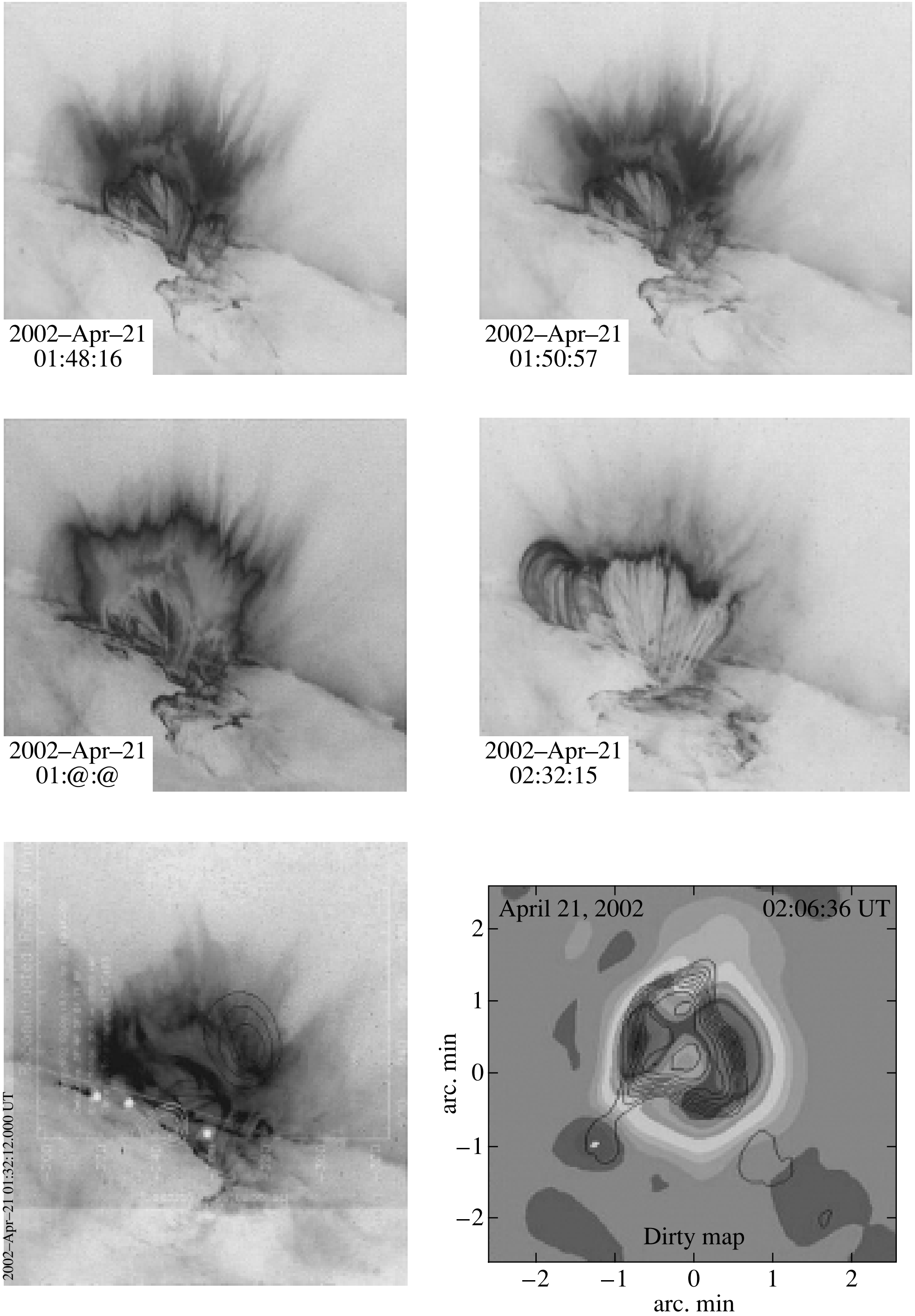

Fig. 2. Evolution of the flare of April 21, 2002, according to the TRACE 195 Å EUV and RHESSI HXR data. The difference image between 01:50:57 and 01:48:16 UT (the left-hand middle panel) contains many light loops, where the ZP sources can be located. The lower left-hand panel demonstrates three new HXR sources (open circles, RHESSI HXR; Gallagher (2002)). The lower right-hand panel shows the locations of the radio sources, obtained by SSRT at 5.7 GHz (kindly supplied by R. Sych), in intensity (parameter *I*, tinted gray and black) and in polarization (parameter *V*, shown by contour lines).

of the spectrum was almost constant (about –120 MHz s^{-1}), but with a pronounced deceleration at the LF edge of the range. However, the drift was interrupted and insignificantly changed with a slight time delay within several adjacent stripes at an interval of 1–2 s. Frequency shifts sometimes result in the coalescence or splitting of the stripes. Such effects are well known for ZP in the meter range. The lower panel of Fig. 3 demonstrates a short fragment of the intensity of about 3-s time profiles at four frequencies. It is clear that the

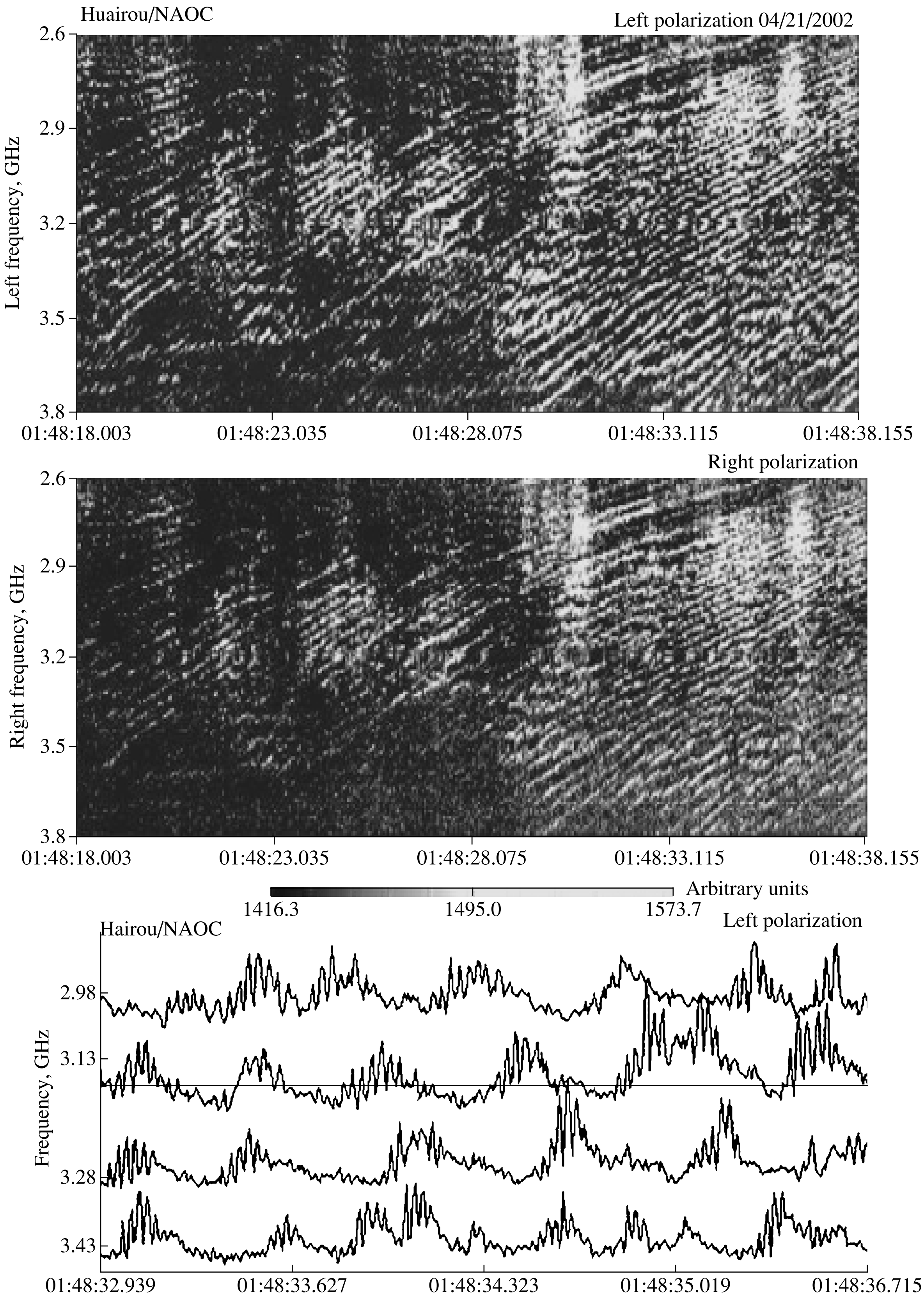

Fig. 3. Zebra pattern during the phenomenon of April 21, 2002, in the range 2.6–3.8 GHz (NAOC spectrometer) at 01:48:18–01:48:38 UT in the left and right polarization (two upper panels). The lower panel shows the intensity profiles at four frequencies on a short interval (3 s), which indicate that the structure of the stripes in the emission is superfine and is observed in the form of millisecond spikes.

emission bands show a superfine structure in the form of millisecond spikes. The emission bands (between light ZP stripes) do not show such a spiky structure, and the emission level in these bands can be lower than the average background burst continuum indicated by a straight line at a frequency of 3.12 MHz. Thus, the background emission is absorbed in dark stripes in this ZP fragment. The ZP circular polarization was low and mostly left-hand. We can assume that two polarized radio sources at 5.7 GHz (Fig. 2) were located above the leading (left-hand polarization) and tail (right-hand polarization) spots. It becomes more difficult to determine the wave type because the limb sources and a magnetic map cannot be unambiguously superposed.

Changes in certain ZP parameters can be observed in each of its next series. For example, by 02:00 UT, the degree of polarization became higher and continued increasing not only in time but also in frequency; at the HF edge of the range, the ZP stripes became more similar to isolated fibers drifting negatively (without a strict periodicity); and the frequency drift strongly decelerated (almost to zero) at the LF edge. The multichannel time profiles of the intensity indicate that the emission bands also include millisecond spikes; however, the fixed emission level in dark spikes was not lower than the burst continuum.

In the first series, the ZP stripes started forming from a cloud of millisecond spikes (see Fig. 4). This property of prime importance indicates that the spikes and ZP stripes are of a similar origin. A similar evolution of the ZP stripes from a cloud of spikes was previously detected in the phenomenon on January 21, 2001 (Chernov et al., 2003).

Active Period in October–November, 2003

Several large flares in October–November 2003 make it possible to trace the appearance of a fine structure (FS) depending on the phenomenon power in comparison with previously known data. The fine structure abundance weakly depends on the flare power. Moreover, minimum data on FS were obtained during the largest phenomena, even taking into account that it is very difficult to register FS at a high level of the continuum emission. FS usually appears in a narrow frequency band (<50 MHz) in the meter range, >100 MHz in the decimeter range, and up to 1 GHz and higher in the centimeter range. However, in all phenomena, FS was not observed simultaneously at all frequencies (from meter to centimeter). An FS band usually spasmodically migrates from initial frequencies only during long-duration events (lasting several hours). We now briefly consider only unusual or unexpected manifestations of FS, which make it possible to construct theoretical models without describing phenomena in detail.

About 20 short ZP series against a background of fast decimeter pulsations were observed during the large flare (X1.2, AR 10486) of October 26, 2003. The first series with the most developed ZP that lasted about 7 s is shown in Fig. 5 in the range 1–2 GHz (NAOC spectrometer). The emission was almost not polarized, which is unusual for the decimeter range. The ZP stripes slowly negatively drifted against a background of fast pulsations in the emission with an average period of $\gtrsim$0.1 s. A patchy background burst is also observed. The frequency separation between stripes pronouncedly decreases with a decreasing frequency. The main property of the ZP stripes in this figure consists in that these stripes rapidly drift in the frequency and change signs when crossing the regions with pulsations. This can take place only when agents responsible for both FS types (e.g., beams of particles and waves) interact in a source.

On October 27, 2003, many groups of millisecond spikes in the decimeter and centimeter ranges were observed during a small flare in the adjacent region: M2.7, AR 10484. Chains of spikes gradually formed structures similar to ZPs, as in the case shown in Fig. 4.

One of the largest flares occurred on October 28, 2003: X17.2, AR 10486. The continuum level in the meter range was the highest (490 000 ssu) at 245 MHz. A type II burst was observed with the IZMIRAN spectrograph. This burst was not very powerful for such a flare, although the velocity of the corresponding shock wave was higher than 2000 km/s. Some ZP fragments at a very high continuum level were observed before a type II burst (Fig. 6). The ZP stripes at 55–65 MHz with a negative drift of –0.42 MHz s^{-1} can, to a greater extent, be related to fiber bursts, which were gradually transformed into twisted ZP (braided or lace bursts (Karlicky et al., 2001)) against a background of other drifting bursts. The frequency separation between the adjacent stripes (Δf) was about 0.46 MHz near 55 MHz, and the relative value was $\Delta f/f \approx 0.0084$.

A small flare (M3.5) but rather magnificent FS with the energy release maximum in the decimeter range was observed on October 29, 2003, in the same AR 10486: a typical ZP and second pulsations gradually changing into fiber bursts with a positive drift.

The small flare (M3.2) of November 18, 2003, in AR 10501 began with a powerful type II burst with harmonics (07:47–07:59 UT), which was accompanied by powerful type III bursts and other complex structures. An unusual FS against the background of a strong continuum appeared before a type II burst: fast pulsations (or fiber bursts) rapidly drifting in a narrow frequency range (185–205 MHz) are shown in Fig. 7 (IZMIRAN spectrograph). In this case, more typical fiber bursts are observed at the HF edge of the spectrum against the background of a strong continuum burst. Then, the second weaker type II burst was observed in the meter range at 08:15–08:22 UT, and a powerful burst was observed ~1 min later at 2.6–3.8 GHz; this burst resulted in unusual drifting stripes similar to a type II burst shown in Fig. 8. This burst differed from meter type II bursts only in a strong right polarization. The

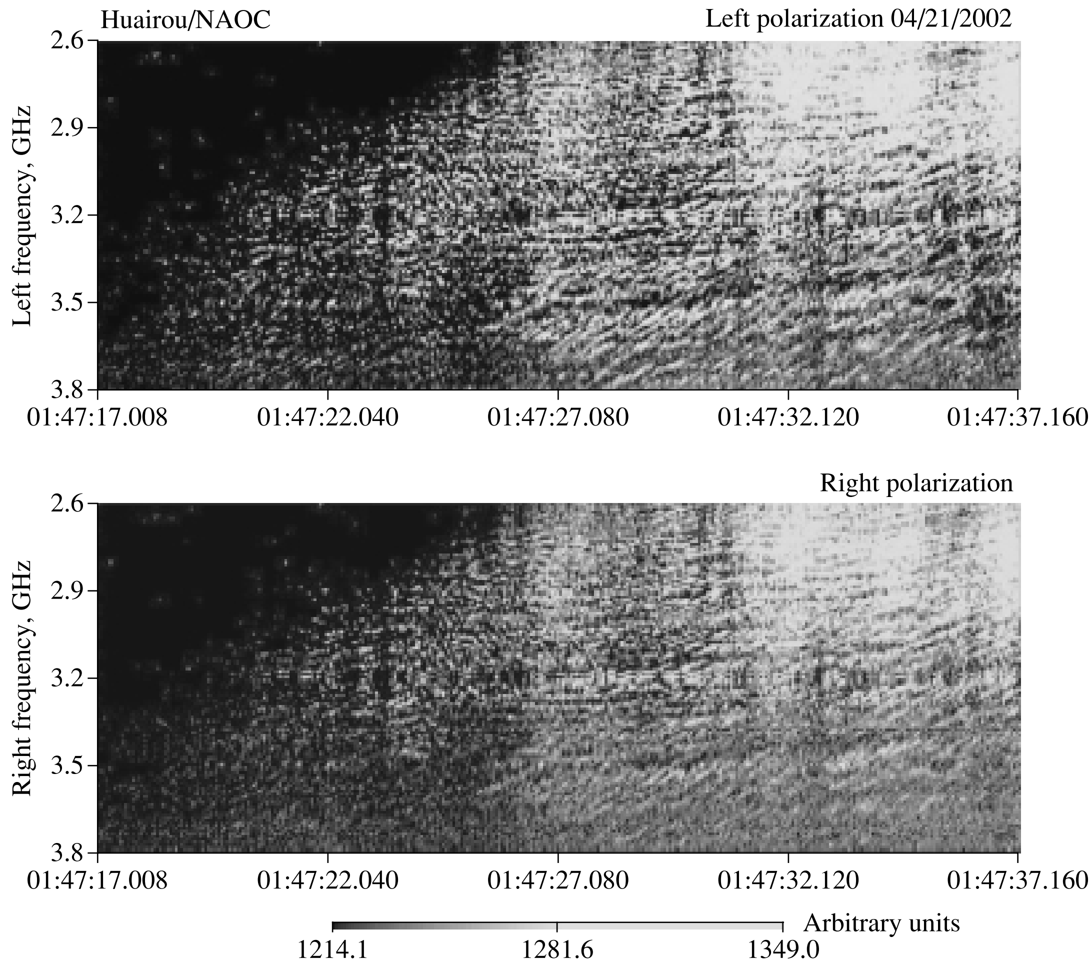

Fig. 4. An example of the formation of the ZP stripes in a cloud of millisecond spikes during the phenomenon of April 21, 2002.

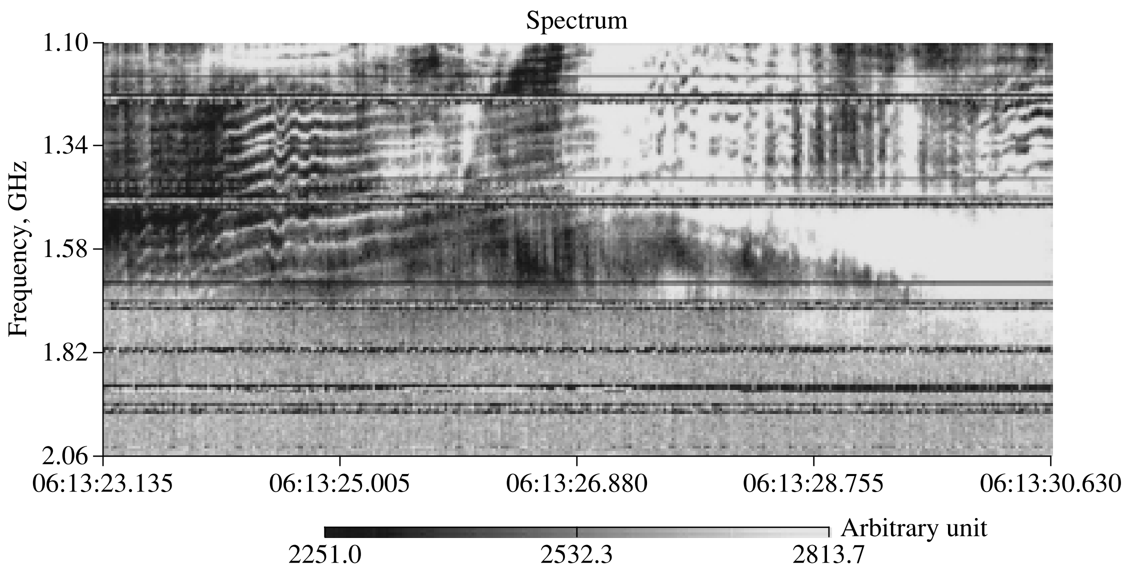

Fig. 5. The first ZP fragment that lasted 7.5 s against the background of fast broadband pulsations during the phenomenon of October 26, 2003.

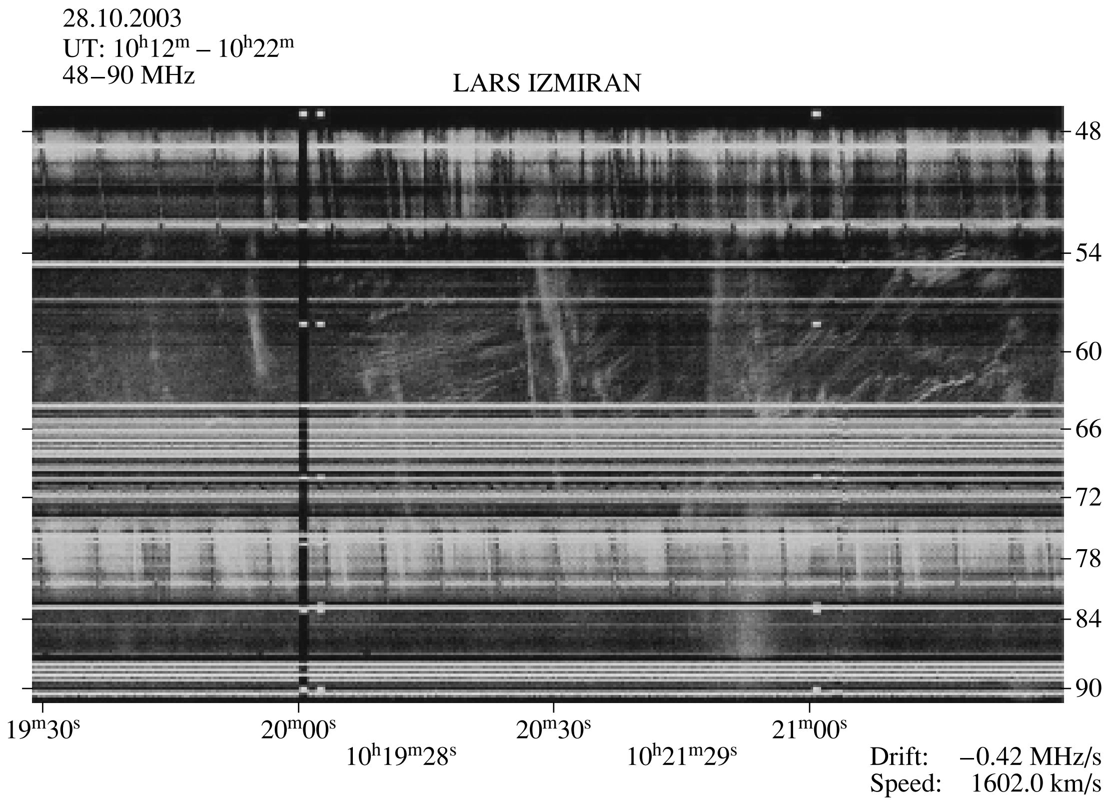

Fig. 6. The ZP fragments at a very high level of the flare continuum observed by the IZMIRAN spectrograph on October 28, 2003, before a type II burst. The ZP stripes in the range 55–65 MHz, with the negative frequency drift against the background of other rapidly drifting bursts, were gradually transformed into twisted ZP (braided or lace bursts according to Karlicky et al. (2001)).

corresponding shock velocities are almost identical for both bursts (~630 km/s). For the electron density, we used the Newkirk model in the meter range and the known reference model (Avrett, 1981) in the centimeter range. A stripe similar to a type II burst terminates in two ZP stripes.

Numerous groups of fiber bursts against a background of fast pulsations lasting more than 15 min were observed in the decimeter range simultaneously with this unusual burst. Figure 9 demonstrates the series of fiber bursts (lasting 2–3 s each) against a background of irregular fast pulsations in emission. Two wave-like ZP stripes against the background of a more powerful pulsating emission appeared at the end of the spectrum. All of these FS elements showed a strong right circular polarization. In this case, the other family of fiber bursts, possibly from the adjacent double source, was observed in the left polarization at the HF edge of the spectrum. Up to 40 fiber bursts, more prolonged than previous bursts but not always regular in frequency, are observed against the background of fast pulsations in absorption (or sudden reductions) in the range 1–2 GHz in Fig. 9b. The time profile of the intensity at a frequency of 1.848 MHz (Fig. 10) indicates deep absorptions of the continuum in dark fiber bursts. At that time, isolated elements of fiber bursts and ZP were also observed around 3000 MHz, but these elements were not harmonically related to fiber bursts at a half-frequency. Note that the intersections of the fiber bursts and fast pulsations on the spectrum did not result in changes in the frequency drift on the entire interval of the fiber bursts. At frequencies higher than 5.2 GHz, FSs were not observed.

DISCUSSION

ZPs and fiber bursts have close spectral characteristics; therefore, we consider both structures as a manifestation of whistlers in a radio source as a result of their interaction with plasma electrostatic waves $l + w \longrightarrow t$, when both waves are generated by the same fast particles with the anisotropic distribution of a loss-cone type in hot flare loops.

The observations indicated many new effects in FS. We now try to interpret these effects within the scope of known theoretical models. Figure 5 demonstrated the interaction between agents in a radio source: the frequency drift of the ZP stripes abruptly changes during their intersections. Such an interaction agrees with the theory of the scatter of fast particles (responsible for the pulsation emission) on whistlers (Chernov, 1996). These new fast particles sharply change the distribution function of the particles responsible for the generation

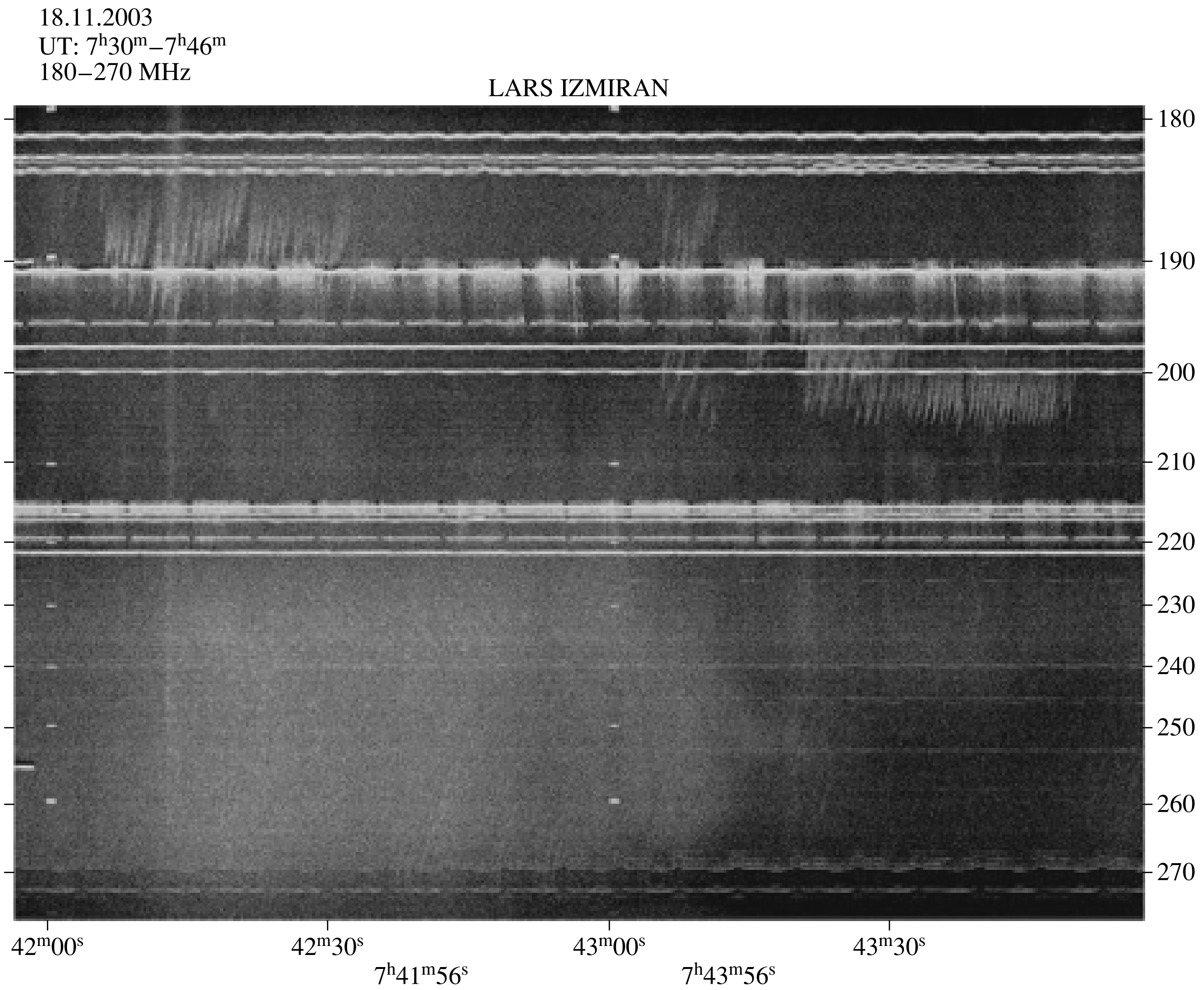

Fig. 7. Unusual fiber bursts rapidly drifting in the narrow frequency range during the phenomenon of November 18, 2003, on the IZMIRAN spectrum (180–270 MHz). Weak usual fiber bursts are observed at the HF edge of the spectrum against the background of a strong continuum.

of whistlers. Whistlers can be generated in the regions of normal Doppler cyclotron resonance and anomalous resonance. Changes in the stripe frequency drift in the whistler model are related to the transition of instability from one resonance to another. In this case, the whistler group velocity changes its direction, which causes a change in the ZP stripe frequency drift.

The intersections of the fiber bursts with pulsations in the emission and absorption (sudden reductions) shown in Figs. 9 and 10 did not cause changes in the frequency drift of the fiber bursts. In such cases, fast particles and waves diverge in space (in the same or even different sources), and the quasi-linear diffusion on whistlers does not result in a change of resonances. Simultaneous fast pulsations in the emission and absorption with a millisecond period and numerous fiber bursts with a narrow instantaneous band indicate that both structures are probably emitted from one source. The identical polarization of emission confirms such an assumption. In this case, we can anticipate that each beam of fast particles causes one pulsation and whistler wave packet. The irregularity of the pulsations and fiber bursts also corresponds to this assumption when each fiber looks like an isolated burst with its own frequency range (up to 40 fiber bursts at 1–2 GHz). Whistlers are generated in the regions of normal resonance, when particles and waves move against one another and a quasi-linear effect does not operate. However, these effects can start operating at the whistler propagation trajectory when new particles overtake a wave. This is probably observed in the case illustrated in Fig. 10, when fiber bursts acquire deep absorptions from the LF edge, which also indicates that the diffusion of fast particles on whistlers is strong (Chernov, 1996).

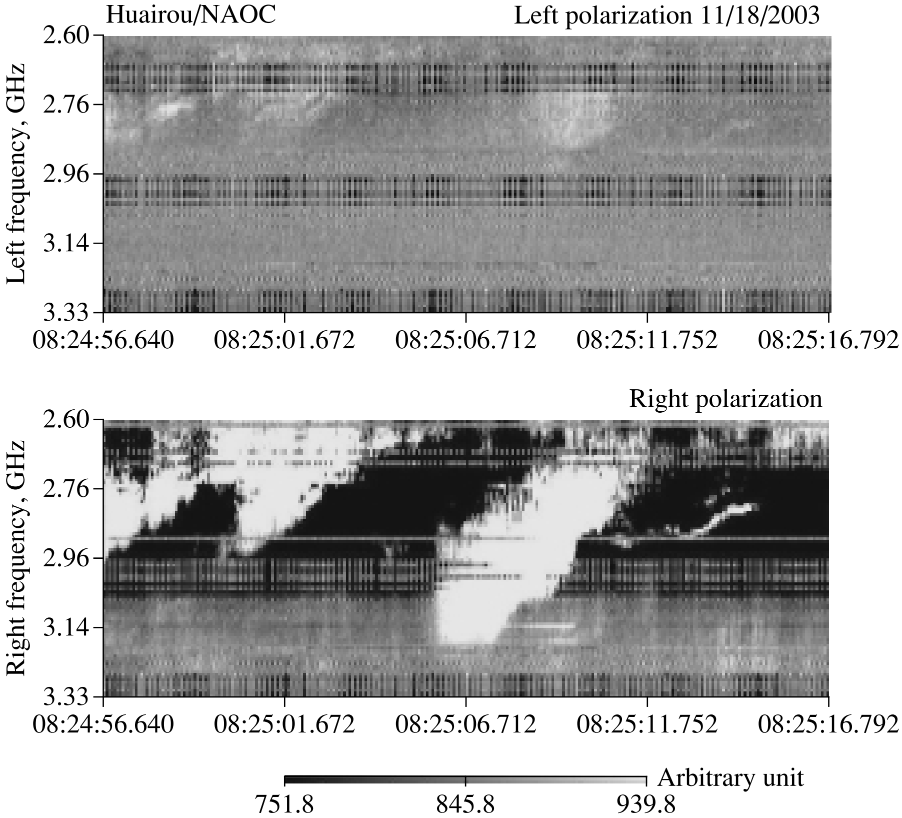

Fig. 8. Drifting stripes in the range 2.6–3.3 GHz (NAOC spectrometer) similar to type II bursts in the meter range.

Event of April 21, 2002

Two important conclusions follow from an analysis of all of the experimental data. First, the entire interval of the ZP occurrence exactly coincided with a new burst of hard X rays in the 44–67 keV channel (MTI/HXRS), and two instants of the strongest ZP coincide with the appearance of new HXR sources (RHESSI), the position of which coincides with two polarized radio sources at 5.7 GHz (SSRT). Second, according to the TRACE data, the appearance of the ZP in the 195 Å line also coincided with the maximum phase of dark matter precipitation from above. Thus, the formation of ZP is closely related to the acceleration of fast particles in an arcade, more precisely, at two X points of the magnetic reconnection mentioned above.

The emission in the Fe XII line (195 Å) is observed in the form of only bright loops with a temperature of about 1.8 MK. Against the background of this emission, the dark matter precipitating from above is superheated plasma (to ~50 MK) propagating downward from the region of magnetic reconnection high in the corona since the energy release was maximal at altitudes of decimeter radiowaves. According to the CORONAS-F data (Grechnev et al., 2006), the source of superheated plasma was actually located in this region, although this holds true for the source in the Mg XII line which is excited at a temperature higher than ~10 MK. The tail particle velocity distributions, generating electrostatic plasma waves and whistlers (the bump in the tail instability) should originate in the regions where superheated plasma contacts with plasma in flare loops with a moderate temperature (1.8 MK).

A detailed analysis of the multichannel time profiles indicates that the emission level in the dark ZP stripes between light stripes can be lower than the background burst level (see the profiles at several fixed frequencies in the lower panel of Fig. 3). Thus, the presence of dark stripes is related to the absorption of the background microwave emission rather than to the absence of light stripes (in the emission). Therefore, the frequency separation between adjacent emission and absorption peaks (~50), rather than such a separation between emission bands (Δf_s), should be considered as the main characteristic parameter of the ZP. If Δf_{ea} depends (e.g., in the ZP model in the regions of double plasma resonance) on relative variations in the plasma frequency and electron gyrofrequency harmonics at different heights in the corona, then Δf_{ea} is determined immediately by the mechanism of the formation of stripes in the emission and absorption. Although the ZP stripes vary, the average Δf_s value in all phenomena is about 60–80 MHz in the range 2.6–3.8 GHz, and the average Δf_{ea} value is about 30–40 MHz for the ZP and fiber

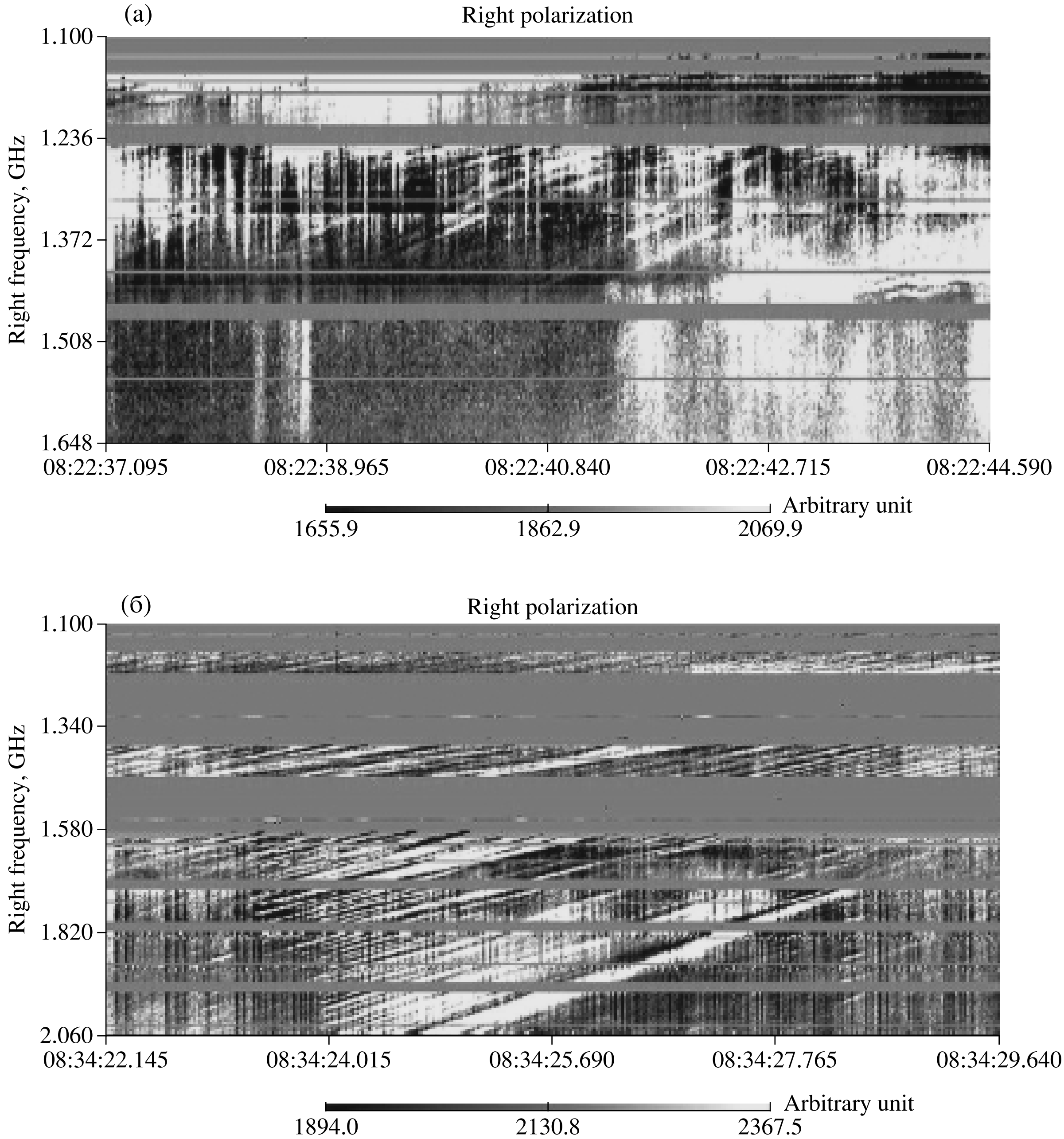

Fig. 9. (a) The series of short-term fiber bursts against the background of fast pulsations in the emission in the range 1.1–1.6 GHz (November 18, 2003; NAOC spectrometer). Wave-like ZP stripes appeared at the end of the spectrum as a continuation of the fiber bursts. (b) The continuation of the phenomenon of November 18, 2003. Numerous fiber bursts with different instantaneous frequency ranges (to 40 fiber bursts in the range 1–2 GHz) are observed against the background of fast pulsations in the absorption (sudden reductions). Both spectra are shown in the right polarization, which was predominant.

bursts. Fiber bursts do not always have regular frequencies; each fiber burst most often appears as an isolated burst, but the parameter Δf_{ea} indicates that the stripes of the ZPs and fiber bursts are of a similar origin.

In the whistler model, the magnetic field strength estimates obtained based on the Δf_{ea} frequency separation can be compared with the field estimates obtained, based on the velocity of the frequency drift of the fiber bursts simultaneously observed at the same frequencies, using the formula

$$B = 15.43(\ln f - 3)^{-2}\, df/dt \qquad (3)$$

(Elgaroy, 1982), obtained for the 60-fold Newkirk model and for the whistler frequency $\omega_w = 0.1\ \omega_{Be}$. These estimates usually coincide and give realistic field values ($B \sim 160$ G) at altitudes of the plasma level in the corona near 3 GHz (for further details, see (Chernov,

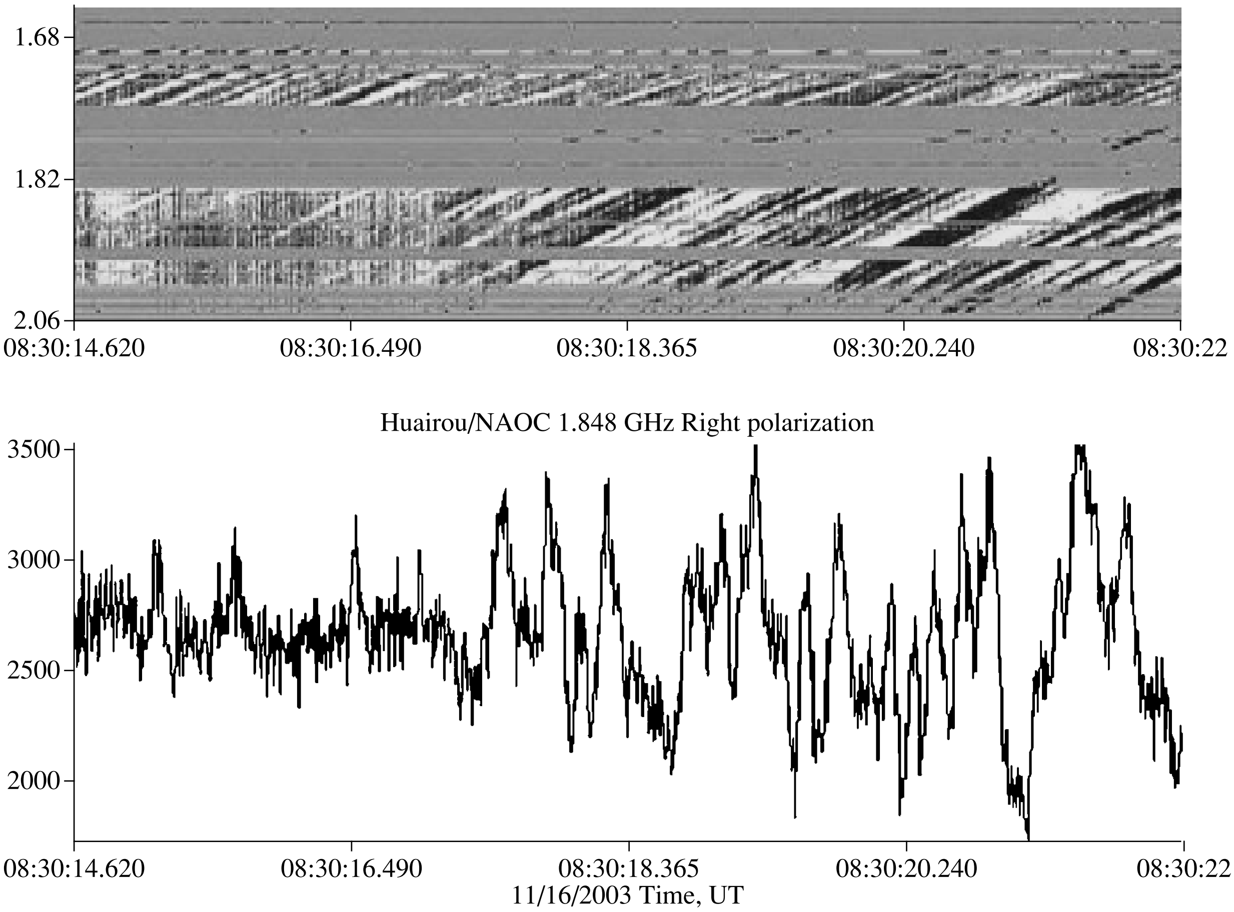

Fig. 10. The fragment of fiber bursts with a variegated instantaneous frequency band in the range 1.5–2.0 GHz against the background of very fast pulsations in the emission. The intensity profile at a frequency of 1.848 GHz indicates that the gradual disappearance of pulsations is accompanied by deep absorptions of fiber bursts from the LF edge of the spectrum.

2004)). If the B value is estimated according to the new model (LaBelle et al., 2003) assuming that the frequency separation between adjacent stripes is $\Delta f_s \approx 0.02 f_{Be}$, the B values obtained for $\Delta f_s = 80$ MHz are too large (about 1500 G) and close to the photospheric values.

An alternative model, based on the plasma wave generation at the upper hybrid frequency under the conditions of double plasma resonance, was also considered for ZP. The main disadvantage of this model consists in that the frequency separation of the Δf_s emission stripes increases with an increasing frequency from 60 MHz at 2.7 GHz to ~450 MHz at 3.8 GHz, which is usually not observed. As a rule, the frequency separation imperceptibly increases with the frequency. An example of the ZP shown in Fig. 3 is interesting in this respect. This example also indicates that the double plasma resonance model cannot explain the simultaneous emission of 34 stripes in the 2.6–3.8 GHz range of an almost identical intensity at any distributions of the density and magnetic field in the corona. At the same time, such a case is quite real in the whistler model, where a strict periodicity of the stripes is specified by the whistler generation mechanism due to instability fluctuations under the action of quasi-linear effects independently from the models of the density and magnetic field in the corona.

The frequency profiles in Fig. 3 show the fast pulsations in light ZP stripes with a distinct period of 30 ms. Hence, these new observations confirm the conclusions (Chernov et al., 2003) that the ZP in the microwave range always has a fine spike structure, which is adequately explained by the whistler model. The stable appearance of the ZP series in a pulsating regime as well as the large number of ZP stripes cannot also be related to a new model (LaBelle et al., 2003) because the frequency separation and the number of ZP stripes strongly depend on the parameters of the inhomogeneities within the scope of this model, whereas this separation imperceptibly increases with the frequency. LaBelle et al. (2003) explain all of the ZP parameters, but the parameters of such inhomogeneities as a propagating ion acoustic wave cannot be so close in a wide frequency (altitude) range during a long period; i.e., the spectrum of the stripes should, most probably, merge into the continuum.

CONCLUSIONS

Using all of the available data, we considered several recent phenomena with the ZP in light of the complex approach to the analysis of flare processes. The ZPs and fiber bursts were observed at frequencies of 50 to ~3800 MHz. At higher frequencies, the emission of the electrostatic plasma waves is apparently suppressed in a dense flare plasma. The main relative spectral parameters and the degree of circular polarization of the ZPs and fiber bursts are almost identical. New data on the ZPs and fiber bursts in the microwave range indicate that these structures are analogous with similar formations in the meter range. The coincidence in time and space of the sources of hard X rays and radio sources of the FS indicates that the ZPs and fiber bursts are related to the prolonged acceleration of fast particles in an arcade of flare loops. The real values of the magnetic field strength ($B \approx 160$ G) at a plasma level of about 3 GHz are obtained within the scope of a common model for the ZPs and fiber bursts with whistlers. The fine structure was observed simultaneously with new hot magnetic loops ascending into the corona, and the frequency range occupied by the FS on the dynamic spectrum depends on the extension of these new loops in the corona. The continuous transformation of the fiber bursts into ZP and inversely indicates that both structures are of a common origin. All of the main properties of the stripes in the emission and absorption are explained within the scope of the mechanism of the interaction between plasma and electrostatic waves and whistlers, if the quasi-linear diffusion of fast particles on whistlers, deforming the particle velocity distribution function, is taken into account.

The dependence of the frequency separation between stripes on the frequency, obtained within the scope of the model of ZP in the regions of double plasma resonance, is too sharp and disagrees with observations. Note that the double plasma resonance mechanism was successfully used to explain large-scale stripes in the emission, which lasted during a considerable part of the phenomenon, as was indicated, e.g., by Chernov et al. (1998) for a wave-like fiber burst lasting more than 2 h.

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