JOINT OBSERVATIONS OF FINE STRUCTURES IN SOME RECENT SOLAR RADIO BURSTS

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Abstract

Some intense and complex type IV bursts were recorded simultaneously by some radio–spectrographs, by the Nançay Radioheliograph and by the Trieste polarimeters at fixed frequencies. For a more detailed analysis optical data were also used, including SOHO and TRACE ultraviolet and Yohkoh/SXT images. The analysis of the complex observations shows that fine structures were observed simultaneously with the appearance of new emerging magnetic loops. The frequency bandwidth of fine structures should be explained by the extension of these new loops in the corona. The continuous conversion of fiber–bursts into zebra–lines with positive frequency drift testifies to a unique origin of both structures, namely the coalescence of plasma electrostatic waves with whistlers.

1 Introduction

Zebra–patterns and fiber–bursts (or bursts with intermediate frequency drift) are well–known fine structures that sometimes are observed on the metric and decimetric continuum emission of type IV Solar radio bursts [Slottje, 1981; Krüger, 1979]. Now the high resolution (10 MHz in frequency and 8 ms in time) of the new microwave spectrometer of NAOC (China, Huairou station) permits the observation of detailed zebra–patterns and fiber bursts also in the microwave range 2.6–3.8 GHz [Chernov et al., 2001].

For the interpretation of such fine structures, the interaction of plasma electrostatic waves (l) with whistlers (w) (both generated by the same fast particles with loss–cone anisotropy) is a well–accepted emission mechanism for fiber bursts: $l + w \rightarrow t$ with freely escaping electromagnetic waves (t) in the ordinary (o) mode [Kuijpers, 1975]. Zebra–patterns show a more complex structure and many mechanisms were proposed

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[Zheleznyakov and Zlotnik, 1975b; Kuijpers, 1975; Chernov, 1976; Mollwo, 1988; Winglee and Dulk, 1986] for its explanation. The majority of them are based on electrostatic emission at double plasma resonance. The most advanced model, proposed by Winglee and Dulk [1986], is based on cyclotron non–saturated maser emission by a loss–cone electron distribution.

However, some difficulties are still present in all these explanations: 1) the frequency separation between zebra–stripes Δf_s corresponds to the cyclotron frequency which is hard to reconcile with the often irregular variation with frequency; 2) the magnetic field deduced from Δf_s seems too low for the flare region and we are faced with the difficulty of having plasma $\beta \approx (v_s/v_A)^2 \ll 1$ (a well accepted value for a magnetic trap in active regions), (v_s and v_A are sound and Alfvén velocities, respectively); 3) all models explain periodic lines in emission, meanwhile we observe lines in absorption also and sometimes absorptions are more pronounced; 4) an important point is missing in most theories: a loss–cone distribution generates whistlers, which in turn affect the electron velocity distribution.

In addition, many features of zebra–stripes and fiber bursts are similar, which led Chernov [1976, 1990a] to propose a common interpretation for both of them based on coupling of plasma waves and whistlers. The whistler instability can be formed in different conditions at the cyclotron resonance: at the normal Doppler effect, when whistlers propagate along magnetic loops against fast particles - for fiber bursts; at the anomalous Doppler effect, when whistlers propagate in the direction of fast particles but under different angles to magnetic force lines - for zebra–stripes [Maltseva and Chernov, 1989; Chernov et al., 1998].

It is known that fine structures do not appear simultaneously at all frequencies from decametric, decimetric to centimetric ranges. Zebra–patterns and fiber bursts are usually appearing in a narrow frequency bandwidth ($\leq$ 50 MHz in the metric range and some hundreds MHz in the decimetric range, $\leq$ 2000 MHz). In this paper we try to compare the parameters of such fine structures at different frequencies and to answer the question of: what defines such a narrow bandwidth. Recent data in X–rays provided by the Yohkoh satellite and images in EUV lines from SOHO and TRACE helped us in the study of the dynamic flare processes in order to answer the above question.

Here we describe and analyse three bursts with fine structures (1998 05 02; 1999 07 28; 1998 09 23). We consider the fine structures as a whistler manifestation. Whistlers yield the principal contribution in the fine structure radio emission by means of the coupling with Langmuir waves as sum and as difference of the frequencies: $\omega_l \pm \omega_w = \omega_t$. [Chernov, 1976, 1990ab].

2 Observations

We performed the analysis of dynamic spectra (IZMIRAN (Moscow), ARTEMIS (Meudon, France) ARTEMIS–IV (Greece) and Tremsdorf (Potsdam)), single frequency polarization data (Trieste Astronomical Observatory (TAO)) and spatial positions

(Nançay Radioheliograph (NRH)) of zebra–patterns in three type IV events. The source positions and the polarization were measured with the NRH at the frequencies of 164, 237, 327, and 407 MHz with the time resolution of 0.25 s. Circularly polarized left– (L) and right–handed (R) emissions were recorded by the radio polarimeter of the TAO at: 237, 327, 408 and 610 MHz with high time resolution (0.02 s). SOHO and TRACE data in EUV lines 195 Å used in this paper were recorded from SOHO and TRACE Synoptic Data Base, courtesy of SOHO EIT, LASCO, MDI consortia. We also used the available SXR data (Yohkoh/SXT) to study the dynamic processes in flares.

Description of events

1998 05 02

In this event for the first time we observed the zebra–pattern at such low frequencies as 22–46 MHz (Figure 1). The radio event started simultaneously with the big flare 3B X1.1 during 13:30 - 15:13 UT in the active region (AR) 8210 located at S15 W15. The LASCO telescope on board of the SOHO recorded a large coronal mass ejection (CME) of halo type traveling out beyond 26 $R_\odot$ (Solar radii).

The radio event in the meter - decimeter range included a group of type III bursts, two type II bursts and a type IV continuum. The global dynamic spectrum in the range 0.05-200 MHz was presented in Leblanc et al. [2000]. The maximum energy release in the corona developed in the decimetric range: 22000 SFU at 606 MHz (Solar–Geophysical Data, N 651, p.II). The event was presented also in the interplanetary space with a very strong type III burst and a type II burst.

The zebra–pattern was observed during an interval lasting about 3 minutes as a structure of a type II burst after a strong type III event. The top panel of Figure 1 shows the zebra–pattern formed by many fragments of lines with different frequency drifts. The most spectacular fragment is the narrowband rope–like fiber lasting about 2 minutes and consisting of zebra–stripes (or repeated short lasting fiber–bursts). This main rope–like fiber represents the low frequency boundary of all fragments of zebra–pattern. Such fragments consist also of rope–like fibers (of different frequency bandwidths) with similar frequency drift.

The frequency drift of the main rope–like fiber was about -0.13 MHz/s (near the frequency $f \approx 37$ MHz, which corresponds, if we use the Newkirk electron density model multiplied by factor 2, to the speed of a disturbance in the corona of about 2200 km/s). The drift of the short isolated elements inside this main rope–like fiber was about -0.04 MHz/s, i.e. a speed of about 700 km/s. Along the decreasing frequency drift of the main fiber from about 43 up to 22 MHz the bandwidth smoothly increased from 0.25 to 0.8 MHz, meanwhile the L–handed polarization decreased.

The frequency bandwidth of the isolated zebra–emission lines was about the same in all fragments $\Delta f \approx 0.08$ MHz and the relative value $\Delta f/f \approx 0.0024$. However, the frequency separation between emission lines was slightly different in different fragments $\Delta f_s \approx 0.08 - 0.17$ MHz and the short fibers inside the main fiber were not strictly periodic in frequency. In some fragments we can see the frequency separation between the emission line and the neighbouring low frequency absorption Δf_{ea}. This value was almost equal to Δf.

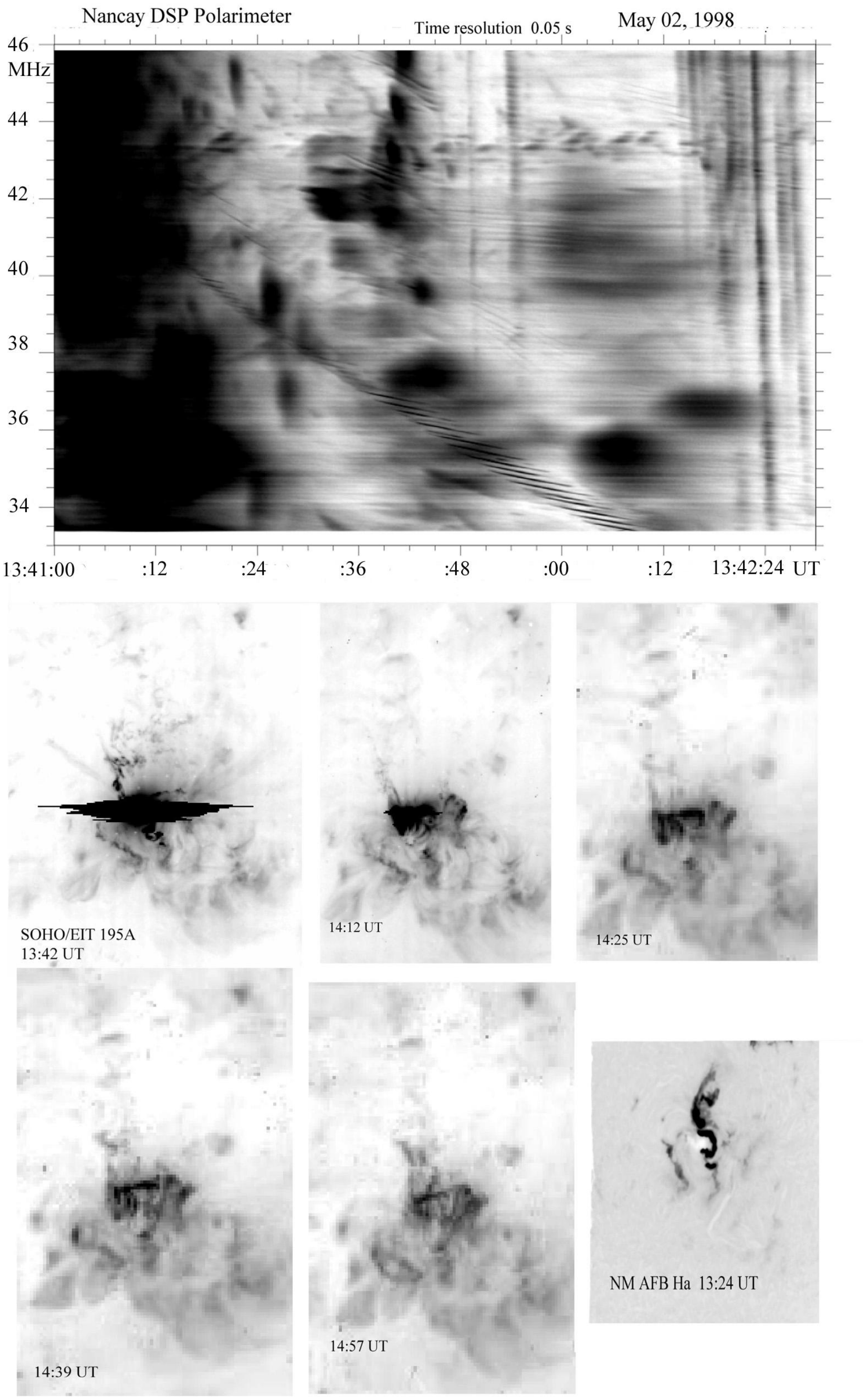

Figure 1: Event 1998 05 02. In the upper panel the dynamic spectra of the Nançay Decameter Spectrometer–Polarimeter are given (summary plot: RH + LH spectral density). In the lower panels the evolution of the flare in the EUV line 195 Å of SOHO/EIT and the H_α image of the flare in NOAA AR 7792 are shown.

The emission of all the elements of type II and type III bursts was almost unpolarized, meanwhile the main rope–like fiber was strongly polarized (L–handed). The other elements of fibers and zebra–patterns (located at lower frequencies of the spectrum) were moderately L–polarized or slightly R–polarized. NRH shows four radio sources above the AR 8210. Therefore the complex behaviour of the polarization of the fine structures should be related to the position of the respective radio sources in different magnetic polarity regions.

Bottom panels in Figure 1 show the evolution of the flare in the EUV line 195 Å (five frames from SOHO/EIT MPEG movie) and the lowest right image shows the beginning of the flare in H_α line. In this last image we can see that at 13:24 the flare presented a helmet–like ejection above the sigmoid flare ribbon. The evolution of such an ejection is clearly seen in the first frame of the EIT 195 Å movie at the flare maximum (13:42). Each subsequent frame contains new fragments of ejected material seen in projection on the disk. It is evident that energy release was present after the escape of the CME in the vertical current sheet with magnetic islands during the restoration of the magnetic structure.

1999 07 28

This event included long–lasting zebra–patterns between 08:15 and 10:30 UT. It was related to the small flare 1B M2.3 (maximum at 08:14) in the AR 8649 at S15 E03. The event was accompanied by the CME of HALO type at 09:06. As concerns fine structures, three main phases can be selected: 08:15–08:30 - impulsive phase, 08:50–09:25 - maximum phase and 10:15–10:30 - decaying phase. During the first two phases zebra–patterns appeared in narrow bandwidths (50–150 MHz) in the frequency range from 200 up to 1500 MHz in intervals of about one minute. During the decay phase fine structures appeared mainly at frequencies 300–400 MHz.

The two top panels of Figure 2 show examples of zebra–patterns during the impulsive phase (left panel shows the IZMIRAN spectrum between 189 and 270 MHz) and during the decaying phase (right panel shows the Phoenix–2 spectrum in the range 320–385 MHz). In the left panel zebra–lines drift towards higher frequencies, meanwhile in the right one zebra–lines display different frequency drifts, however the tendency is towards lower frequencies. In such a case zebra–lines resemble fiber–bursts. A common property of both structures is absorption (of the continuum) at the low frequency edge of each line. This is evident in the L– and R–plots of the TAO (middle panel in Figure 2) at 237 (left side) and 327 MHz (right side). The circular polarization was moderate at the beginning of the event (about 30–40% L–handed), while at the end it strengthened (about 60–80%).

After the event maximum (08:55) some unusual fiber–bursts appeared with absorption at both low and high frequency edges with respect to the emission line. Some lines were observed only in absorption, too. After 10:19 almost all zebra–lines and fiber–bursts showed absorption at the high frequency edge. During that interval zebra–lines formed some cascades with change of the frequency drift from negative to positive (like U–bursts). In such cases fiber–bursts were continuously converted into zebra–lines.

The bottom panels in Figure 2 show the evolution of the flare in the EUV line 195 Å (SOHO/EIT). The flare began above the magnetic neutral line (black spot), zebra–

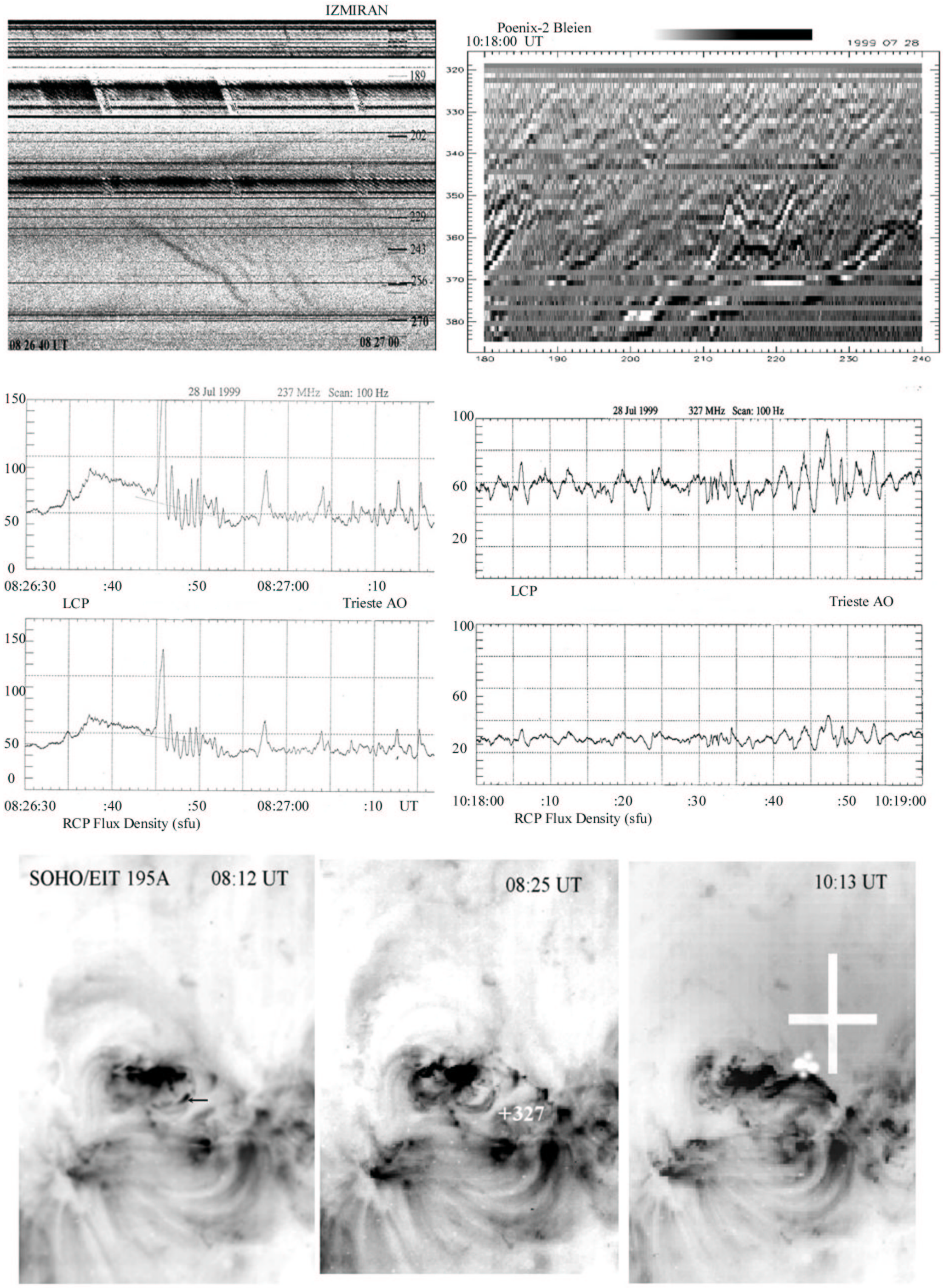

Figure 2: Event 1999 07 28. In the top panel two spectra show zebra–patterns at 08:26 (at the left side the IZMIRAN spectrum between 189 and 270 MHz is shown) and at 10:18 (at the right side Phoenix–2 (Bleien) spectrum between 320 and 385 MHz is reported). In the middle part the time profiles of the TAO polarimeter at 237 MHz (left side) and 327 MHz (right side) are reported. The bottom part shows the flare evolution in EUV line 195 Å (SOHO/EIT). The arrow in the left panel indicates a new rising bright loop. The positions of the radio source centers are shown by crosses (small cross - 327 MHz, big cross - 164 MHz).

pattern appeared at 08:15 after the emergence of a new bright loop in the south–west direction (see the arrow). This loop was raising up to 08:25. The position of the center of the radio source at 327 MHz (NRH) was just above this loop (middle panel). At the maximum of the radio event (08:55) some new bright knots appeared in the north–western part. Afterwards, a new bright loop began to raise above these knots and the radio source position during the zebra–pattern interval (after 10:15) were right above this new loop (small cross - 327 MHz and big cross - 164 MHz in the right panel).

1998 09 23

According to the Solar–Geophysical Data bulletin, the flare 3B M7.1 started in AR 8340 (N18 E09) at 06:40 with its maximum at 07:13. The radio event was observed between 06:45 and 11:00. It included a type II burst (06:52–07:02) and a long–lasting type IV burst with some maxima. Between 08:00 and 08:10 some intervals of fine structure were observed. The top panel of Figure 3 (ARTEMIS–IV) displays a group of fiber bursts (08:03–08:04), zebra–pattern (08:05–08:06) and fast pulsations both in emission and in absorption (08:08–08:09). The main peculiarity of these fine structures was their very low circular polarization (see the L– and R–polarized plots of the TAO polarimeter).

The evolution of the flare is shown in the four bottom panels of Figure 3. Two ribbons in H_α flare were observed for a long time along the eastern and western parts of the neutral magnetic line. Two frames of the TRACE EUV line 195 Å (right panels) show numerous emerging bright loops between the two sides of the neutral line. After 08:00 a new high and bright loop appeared in the southern part of the flaring region. At 08:08 the position of the radio source center at 327 MHz (NRH) overlaid on TRACE image was just localized above this new loop (right bottom panel).

Altyntsev et al. [2001] and Ning et al. [2001] studied many aspects of the radio source structures in the microwave range. In particular, the radio source at 5.7 GHz at Siberian Solar Radio Telescope (SSRT) according to Altyntsev et al. [2001] presented a double structure. At 08:03 the right source (next to the eastern neutral line and to the metric source) was brighter (left bottom panel in Figure 3). However, the maximum energy release was emitted in the decimetric - metric range.

Table 1 summarizes the main parameters of five events with zebra–pattern and fiber–bursts.

In Table 1: $\Delta f_s/f$ - relative frequency separation between zebra–lines; $\Delta f_{ea}/f$ - relative frequency separation between the emission line and the neighbouring absorption; $\Delta f_b/f$ - relative frequency bandwidth of fine structures; $\Delta f/f$ - instantaneous frequency bandwidth of an emission line. In Table 1 we also included the event 1994 10 25 for the completeness of the analysis and the event 2000 10 29 with zebra–pattern at microwaves [Chernov et al., 2001] in order to compare its parameters with those in the metric range. The parameters $\Delta f_s/f$ and $\Delta f_{ea}/f$ increase with frequency; which seems related to the enhancement of the magnetic field strength. $\Delta f_b/f$ decreases with frequency, which signifies a diminishing dimension of the radio source in the lower corona. Only the relative frequency bandwidth of an isolated zebra–line remains rather stable. In four events the radio emission corresponded to the emission in ordinary mode.

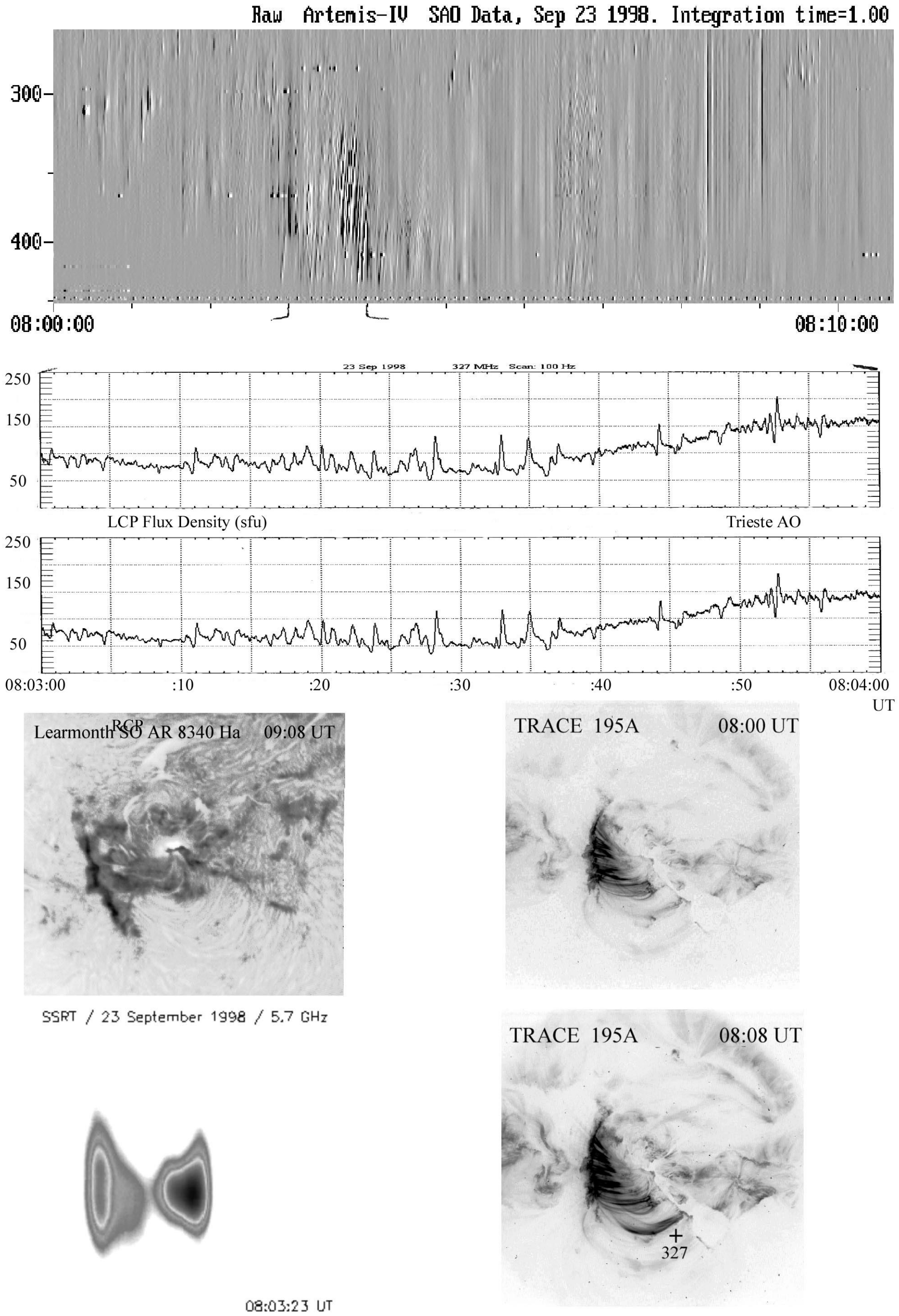

Figure 3: Event 1998 09 23. In the top panel the spectrum in the range 250–450 MHz (ARTEMIS–IV) shows fiber–bursts and zebra–pattern. Below, time profiles of the polarization channels (TAO) are given. The polarization was very weak. The evolution of the flare is shown in the four bottom panels. Two ribbons in the H_α flare were observed in Learmonth SO. Two frames of TRACE EUV line 195 Å (right panels) show many emerging bright loops between the two sides of the neutral line. After 08:00 a high bright loop appeared in the southern part of the flaring region. At 08:03 the position of the radio source center at 327 MHz (NRH), overlaid on the TRACE image, was localized just above this new loop (right bottom panel). In the left bottom panel the brightness distribution of the radio sources at 5.7 GHz is given (SSRT).

Table 1: Parameters of zebra–pattern in 5 events.

Date time UT	f(MHz) range	Flare	$\Delta f_s/f$	$\Delta f_{ea}/f$	$\Delta f_b/f$	$\Delta f/f$	Magn. polar.	Pol. mode
1998 05 02 14:41	35 20-70	3B X1.1 S15W15	0,0036	0,0024	0,88	0,0036	S(N)	L R ?
1994 10 25 10:08	175 100-500	1N C4.7 S09W12	0,015	0,006	0,4	0,0049	S	R O
1999 07 28 08:15	360 45-520	1B M2.3 S15E03	0,014	0,006	0,22	0,0054	N	L O
1998 09 23 08:00	360 100-700	3B M7.1 N18E09	0,064	0,032	0,3	0,014	N	L O
2000 10 29 02:20	3000 1000-3800	2B M4.4 S25E35	0,033	0,015	0,16	0,0059	S	R O

3 Discussion

Three radio bursts with similar fine structures (zebra–patterns and fibers) were closely connected with flares of different importance and type II bursts (shock waves, CME). In all these events the maximum energy release was present in metric and decimetric ranges. The radio sources were probably located high in the corona where the magnetic reconnections develop. The polarization of radio emission was moderate in all events and in three events it corresponded to the ordinary magneto–ionic mode.

The event 1998 05 02

Rope–like fibers shown in Figure 1 are similar to the structure in the frequency range 200–250 MHz reported in Mann et al. [1989] and Chernov [1990a, 1997]. The latter structure was long–lived (more than one hour). The phenomenon was explained considering the theory of whistler instability in a small magnetic trap between magnetic islands with X–points of the magnetic reconnection during long–lasting restoration of the magnetic structure after the escape of a CME. In the frames of EIT 195 Å images we see some ejections in different directions, two of them were the most pronounced: one moving northwards and the other in the south–east direction (slowly moving front). This means that one disturbance (shock front) was propagating towards the observer. Since fine structures were observed only during three minutes when a type II burst was present and since the frequency drift of the main rope–like fiber should be related to the fast shock front (speed $\approx$ 2200 km/s), it is reasonable to consider that radio sources responsible for fine structures were probably located in the shock oscillating front, more exactly between the shock front and the CME. Fast particles accelerated in the shock front were trapped in such a small trap. The periodic whistler instability developed due to the bounce motion of fast electrons with loss–cone distribution between the two maxima of the magnetic field (in the shock front and in the leading edge of the CME).

According to Leblanc and al. [2000] the CME velocity was slightly higher than the speed of the shock front. The increasing distance between them explains the smooth broadening of the main rope–like fiber towards lower frequencies. We must consider that in general the fast shock wave should be propagating obliquely in respect to the magnetic field and in such a case the shock front undergoes oscillating values of magnetic field and density. Such a structure explains also the observation of some other fragments of rope–like fibers and zebra–lines at higher frequencies (in the downstream region).

Whistlers propagate in the same direction as the shock wave. The group velocity of the whistler wave should be about 10^8 cm/s, which explains the smaller frequency drift of fibers inside the main rope–like fiber. We conclude that the unusual rope–like fiber is a manifestation of the simultaneous propagation of a fast shock wave and a CME.

1999 07 28

In Figure 2 we have shown two new bright loops that appeared earlier than two intervals of zebra–pattern structures. The radio sources were localized above these loops. It is evident that the bandwidth of the radio emission is defined by the vertical dimensions of these coronal flare loops. The radio sources were localized above the northern magnetic polarity, as the L–hand polarization corresponds to the ordinary emission mode.

The inverse position of the absorption strip in the zebra–pattern during the decay phase of the event (about 10 minutes long) is a very important fact for theoretical considerations of the emission mechanism. It should be related to the change of the magnetic field gradient in the radio source. A similar behaviour of fiber bursts was considered in Chernov [1990b], where it was shown that in such a case the observed emission is obtained as the difference: $\omega_l - \omega_w = \omega_t$ (the process of decay is: $l \rightarrow t + w$). The continuous conversion of fiber–bursts into zebra–lines with positive frequency drift, when considering that the other parameters of both structures are identical, testifies the common origin of both structures.

1998 09 23

The analysis of the observations shows once more that fine structures were observed simultaneously with the appearance of new magnetic loops. The bandwidth of fine structures between 280 and 450 MHz should be explained by the extension of these new loops in the corona.

4 Concluding remarks

Zebra–pattern and fiber bursts samples were present in a very large range (from 30 to 3000 MHz). Their main spectral parameters and circular polarization were approximately the same. The relative frequency bandwidth of emission lines were similar at all frequencies. The fine structures were observed simultaneously with the appearance of new magnetic loops. The frequency bandwidth of fine structures should be explained by the extension of these new loops in the corona. The continuous conversion of fiber–bursts into zebra–lines with positive frequency drift testifies the common origin of both structures, namely the coalescence of plasma electrostatic waves with whistlers.

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