NEW FEATURES IN TYPE IV SOLAR RADIO EMISSION: COMBINED EFFECTS OF PLASMA WAVE RESONANCES AND MHD WAVES

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Abstract

The solar radio event of 1992 February 17, 0800-1150 UT, exhibits extraordinary fine structure and a wealth of new features: (1) fine structure of zebra-patterns (sudden frequency shifts, bandsplitting of individual zebra stripes, bright dot-like emission modulated in phase with ∼0.2 s pulsations), (2) pulsations at three different time scales from ∼0.2 s to ∼3 min, and (3) a narrow-band "spaghetti" emission line, slowly oscillating in frequency. "Spaghetti" has a bandwidth of ∼10 MHz and produces a high-frequency cutoff of the continuum emission; it oscillates between 400 and 500 MHz in phase with 3 min pulsations. Also, we observed for the first time a change of the sign of circular polarization during a zebra-pattern. This event was simultaneously recorded with the *ARTEMIS* spectrograph in *Nançay* (100-500 MHz), in *Tremsdorf* (200-400 MHz), and in *IZMIRAN* (180-270 MHz). Positions of the radio sources were measured with the *Nançay radioheliograph* at four frequencies. This intense, long-lasting, and very complex event was accompanied by only two small H_α flares and an active dark filament; it was not accompanied by any microwave bursts.

We discuss various physical processes that may play a role in the generation of the radio emission during this unusual event, such as electron cyclotron maser emission at multiple gyroharmonics, whistler waves, magnetoacoustic waves (kink and sausage modes), and magnetic reconnection.

1 Introduction

Metric and decimetric type IV bursts occur usually after big flares. Particles injected in a magnetic trap give rise to different plasma instabilities which show up as fine structures on dynamic spectra: pulsations with different time scales (from ms up to some min), fiber

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bursts (or intermediate drift bursts) and zebra-patterns [Kuijpers, 1975, 1980; Slottje, 1981; Chernov, 1976a,b]. But occasionally strong radio events were also observed in the absence of any big flare, such as 1990 0605 [Chernov et al., 1994]. The interpretation of these "quiet" events present additional difficulties.

So far the best observed "quiet" type IV occurred in 1992 on 0217 at 0800–1150 UT. This event exhibited extraordinary fine structures and a wealth of new features: superfine zebra-pattern elements, a "spaghetti" emission line slowly oscillating in phase with broadband pulsations. It was recorded by three spectrographs simultaneously: in Nançay (ARTEMIS, 100–500 MHz, [Maroulis et al.,1993]), in Tremsdorf (200–400 MHz, [Mann et al., 1992]) and in IZMIRAN (180–270 MHz). Positions are available from the Nançay Radio Heliograph (NRH) at four frequencies (164, 237, 327, 407 MHz). This intense, long-lasting and very complex event in metric and decimetric ranges was accompanied by very weak flare activity.

By showing us features which have been unnoticed so far in other big events, without interferences from flare activity, this exceptional event will help us study purely coronal activity, and understand the major physical mechanisms at work in type IV radio sources.

2 General description of the event 1992 02 17

The smoothed dynamic spectrum from ARTEMIS, presented in Figure 1, offers a general view of the event. It lasted 4 hours, and extended from 100 to 500 MHz. The event began by a diffuse drifting continuum emission band in the range 300–150 MHz with frequency drift df/dt$\approx$0.14 MHz/s, similar to type II drift rates (but no type II burst occurred during the whole day). The intense part of the event consisted of a radio continuum containing numerous strong pulsations approximately from 0900 to 1100, in the range 150–450 MHz. At lower frequencies, in the range $\approx$100–190 MHz, a developed noise storm persisted during the whole event.

According to Solar Geophysical Data, the only accompanying activity consisted of three small H_α flares (SF C 4.1, 1N, SF C 3.6) in the active region (AR) NOAA 7058 (N13 W40) over the time period 0817–1008 UT, three very small X-ray peaks in the range 1-8 A (GOES-7 X-ray detector), and an active dark filament near the south of AR NOAA 7056 (S08 W39) after 1110 UT. According to IZMIRAN's 10 cm data, there was no significant microwave burst, only a small increase of the quiet level by 7 sfu at 0847 UT.

So this event had only meter and decimeter (wavelength) components, with a sharp high frequency boundary oscillating between 450–480 MHz. We conclude that it was related to active processes high in the corona.

Pulsations over a wide range of time scales were recorded in full detail thanks to the high intensity resolution and the high time resolution of the ARTEMIS digital multichannel spectrograph.

Three different characteristic periods show up in the data:

— pulsations at ≈3 min lasting during the whole event (Figures 1 and 2);

— pulsations with a fluctuating period of ≈20 s (time derivative at the bottom of Figure 2) from the beginning of the event until about 1014 UT;

— pulsations at ≈0.2 s (Figures 3 and 4) similar to sudden reductions; these pulsations persist during the "spaghetti" emission and exhibit a remarkable frequency drift of ≈ -1000 MHz/s.

Strong and exceptionally long-lasting zebra-patterns were observed by the 3 spectrographs. The detailed coincidence of all the fine spectral elements in three very distant observatories proves the solar origin of these structures. The zebra-pattern had about the same low frequency limit as sudden reductions, namely ≈190 MHz. The high frequency boundary oscillated between 250 and 350 MHz.

The first elements appeared at ≈0830 UT and continued up to ≈1120 UT. During the course of the event, the zebra patterns developed from a very non-stationary phase with numerous sharp kinks to almost straight lines parallel to the time axis after 1037 UT.

Combining the IZMIRAN and Tremsdorf spectra we find that the frequency separation Δf between zebra-lines changes irregularly with frequency in the range 233 and 267 MHz between 5.6 and 8.5 MHz. (The same effect was mentioned by Slottje, 1981). But Δf exhibits a better defined dependence on time: during one hour from 1000 to 1100 UT, it increases from ≈5 to ≈8 MHz.

Position, brightness and polarization are given in Figure 5 as a function of time during the central part of the event for two frequencies of NRH. For all the four frequencies of NRH the source positions coincide with the positions of the 3 small flares in the north AR. The source of zebra-lines as well as the source of pulsations (peaks intensity contours at 237 MHz) coincide with the continuum during the whole event. But four sources of the "spaghetti" at 407 MHz between 1058 and 1107 UT (Stokes I in Figure 5) are shifted northward, and their centers nearly coincide with the position of the principal continuum source at 237 MHz.

3 New features in a type IV event

3.1 "Spaghetti" emission line

Pulsations have a rather sharp high frequency boundary around 400 MHz; at a frequency about 10–15 MHz higher than the latter one we see an unusual emission line of instantaneous bandwidth b_t ≈10 MHz, which looks like a spaghetti in the dynamic spectrum (Figures 1 and 2): its frequency exhibits an almost sinusoidal oscillation of 20 to 60 MHz amplitude, with the same ≈3 min period as the pulsations and in phase with them: pulsation intensity maxima correspond to the "spaghetti" frequency maxima and vice versa.

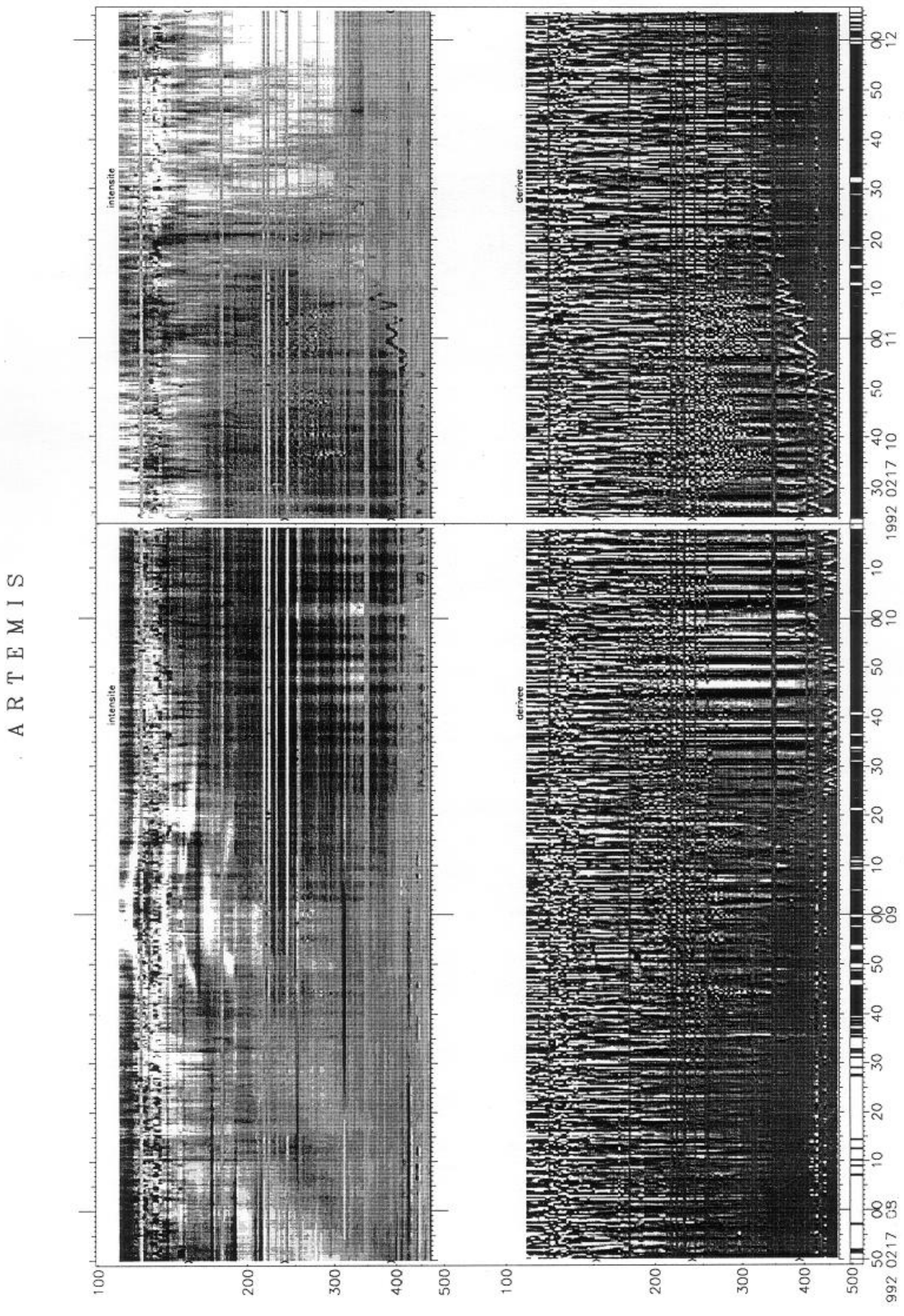

Figure 1: ARTEMIS dynamic spectrum. In the top part - intensity, in the bottom - derivative. The structure seen in the spectrum consists of: broadband 3 min pulsations in phase with oscillations of the "spaghetti" emission line at ≈ 400MHz. White arched bands between 100 and 200 MHz around 09 UT are rather due to a local interference, because they are absent at dynamic spectra in Tremsdorf and IZMIRAN.

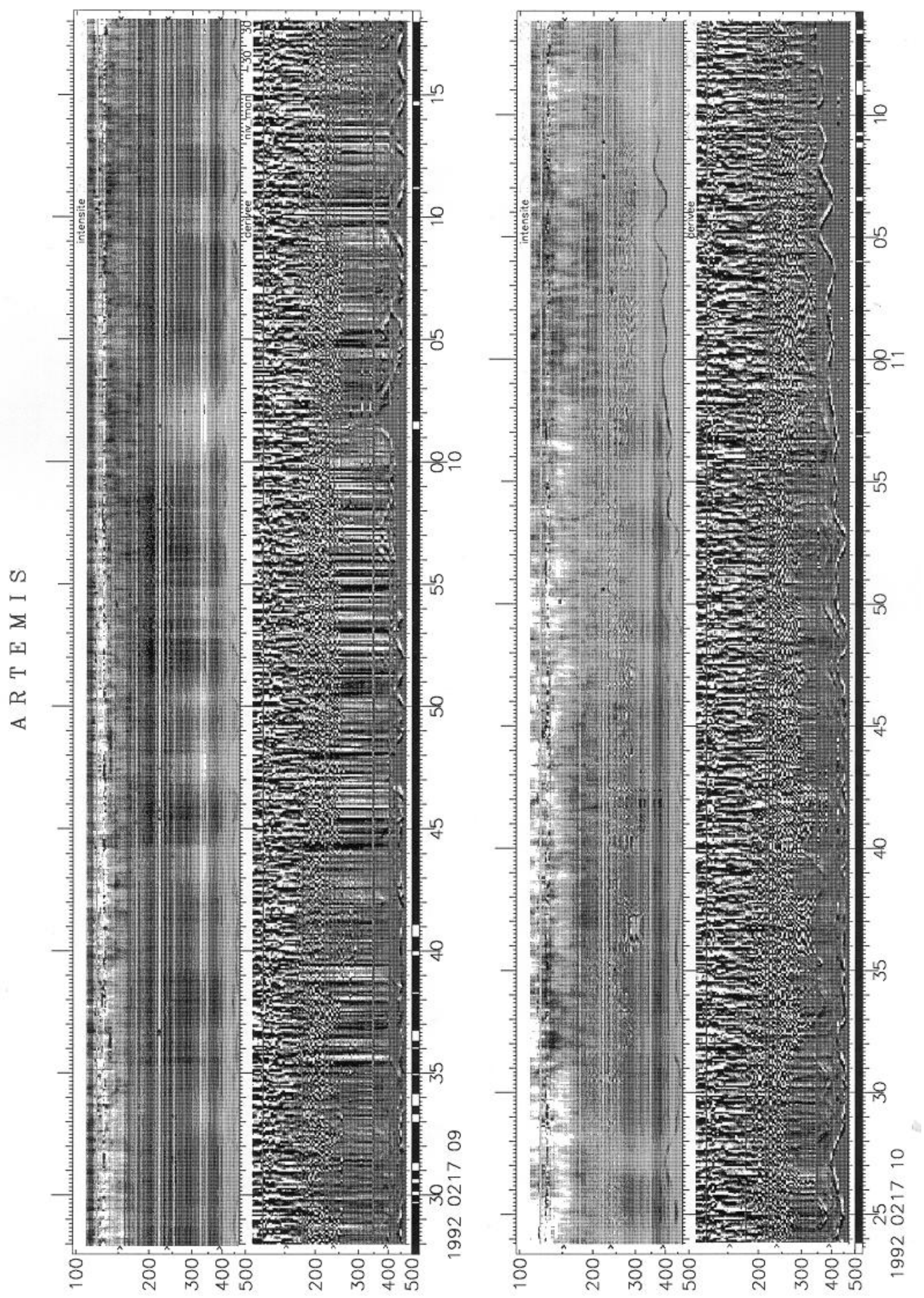

Figure 2: ARTEMIS dynamic spectrum between 0928–1114 UT. The time scale has been enlarged by a factor of five with respect to the one in Figure 1. Besides 3 min pulsations (in phase with the "spaghetti") we can also see at their background a pulsation with a period of about 20 s, a zebra-pattern (point-like structure) between about 190 MHz and a high frequency boundary oscillating between 250–350 MHz, and a noise storm at the low frequency edge.

The "spaghetti" emission appears at ≈0920 UT as the background type IV emission becomes intense. As the latter fades away and its high frequency boundary slowly drifts towards lower frequencies, the spaghetti follows the same frequency drift: from approximately 1050 to 1120 its average frequency shifts approximately from 440 to 330 MHz.

In addition, weaker emission bands appear episodically at the low frequency edge of the "spaghetti", with a frequency separation varying from 20 to 80 MHz; they follow the main "spaghetti" in its frequency oscillations (Figure 2).

This "spaghetti" emission is very distinct from zebra-patterns: one main emission line persists during more than two hours, with a relative bandwidth $b_t/f \approx 1/45$ about four times larger than zebra lines.

Using the full time resolution of the data (0.01 s), we discovered the most unexpected effect (Figure 4): the "spaghetti" emission consists of a succession of bright points (black) on its low frequency edge, and of nearly simultaneous short absorptions (white) on its high frequency edge. It turns out that these emission–absorption dots occur in phase with the fast (0.2 s) pulsations: this dotted very fine structure is just another manifestation of these pulsations. The duration of each point is about 0.12 s, corresponding to the periodicity of sudden reductions ≈0.25 s. Sudden reductions (fast pulsations) on the whole frequency range of type IV emission take place only at times of increased "spaghetti" emission; they disappear when the "spaghetti" fades into the background.

3.2 Zebra pattern superfine structure

During this event IZMIRAN's spectrographs uncovered new features in the frequency structure of zebra patterns.

Throughout the event we observe many sudden frequency shifts of the whole zebra pattern. The upper spectrum of Figure 3 shows several such instances, especially at 0958 11.2 and 20.8. All zebra lines are displaced by about half their frequency separation, so that right after they are just between the positions of the lines before. The frequency shift does not occur simultaneously for all the lines; it exhibits a frequency drift $df/dt \approx -50$MHz/s, typical of type III bursts at these frequencies. As a matter of fact, we do note the presence of diffuse, type III-like structures with similar drift rates in the low frequency part of the spectrum (Figure 4). These sudden frequency shifts seem to occur at random in the zebra pattern, over periods of one second to one minute.

The bottom spectrum of Figure 3 shows the most surprising phenomenon: after a kink at 1058 21.0–22.0, each zebra-line splits into two lines. It is the first time we see that. The splitted lines can be followed for several minutes, with chaotic frequency drifts, sometimes leading to lines crossing one another.

Right after line splitting, the low frequency line is continuous, while the high frequency line consists of points regularly spaced with a period of ≈0.25 s. After a minute or so the dotted lines turn back to continuous emission lines.

The bright points take place almost simultaneously in different zebra lines and it appears that they are just part of the fast (0.2 s) pulsations, along with the dots making up the "spaghetti" emission line. Intervals between bright points of zebra-lines correspond to absorption of the "spaghetti" and to sudden reductions of the type IV continuum.

3.3 Polarization reversal

Another exceptional effect is presented in Figure 5. The circular polarization of the principal continuum and of all the peaks (fine structure) changes sign during the event: Stokes V goes from < 0 (right hand polarization) to > 0 (left hand polarization), as evidenced by dashed contour lines changing into solid lines. At 237 MHz the reversal takes place from 1000 to 1010 UT, spreading gradually from the south-east part to the north-west part of the source. At 407 MHz the reversal takes place much later, at ≈1058 UT (just at the time new substructures appear in the zebra-pattern around 200–265 MHz); and it affects the continuum only, while the "spaghetti" emission (six peaks between 1055 and 1106 UT) maintains the previous polarization. Meanwhile, at lower frequencies, the polarization of the noise storm (164 MHz) keeps the same sign (left hand) during the whole event.

4 Interpretation: source model

The absence of a strong flare or cm emission shows that the energy is released high in the corona.

The time variation of the frequency separation between zebra lines shows that the magnetic field in the source varies. More specifically, the change of polarization observed in the middle of the event, as well as the activation of a dark filament at the same time (cf. Figure 1 in Steele and Priest, [1989]), are both indicative of magnetic reconnection.

It is tempting to relate the unique occurrence of the "spaghetti" emission line to the unusally small size and high density of the source. The "spaghetti" line being the highest frequency emitted, it is also tempting to locate it in the densest part of the source, that is inside the current sheet where magnetic reconnection proceeds. This may account for the small bandwidth of the emission.

4.1 Emission mechanism

The classical picture of a metric and decimetric type IV burst is that energetic electrons trapped in a closed magnetic structure give rise to electrostatic loss-cone and Cerenkov instabilities, followed by conversion into electromagnetic (transverse (t)) waves [Stepanov, 1973; Kuijpers, 1975], which show up as the different details of the fine structure.

Fiber bursts (or intermediate drift bursts) are explained by the widely accepted non-linear mechanism - the coupling of Langmuir waves (l) with whistler waves (w): $l + w \Rightarrow t$ [Kuijpers, 1975; Chernov, 1976b; Fomichev and Fainshtein, 1988] and in different aspects of a strong whistler turbulence [Bernold and Treumann, 1983; Mann et al., 1987; Treumann et al., 1990].

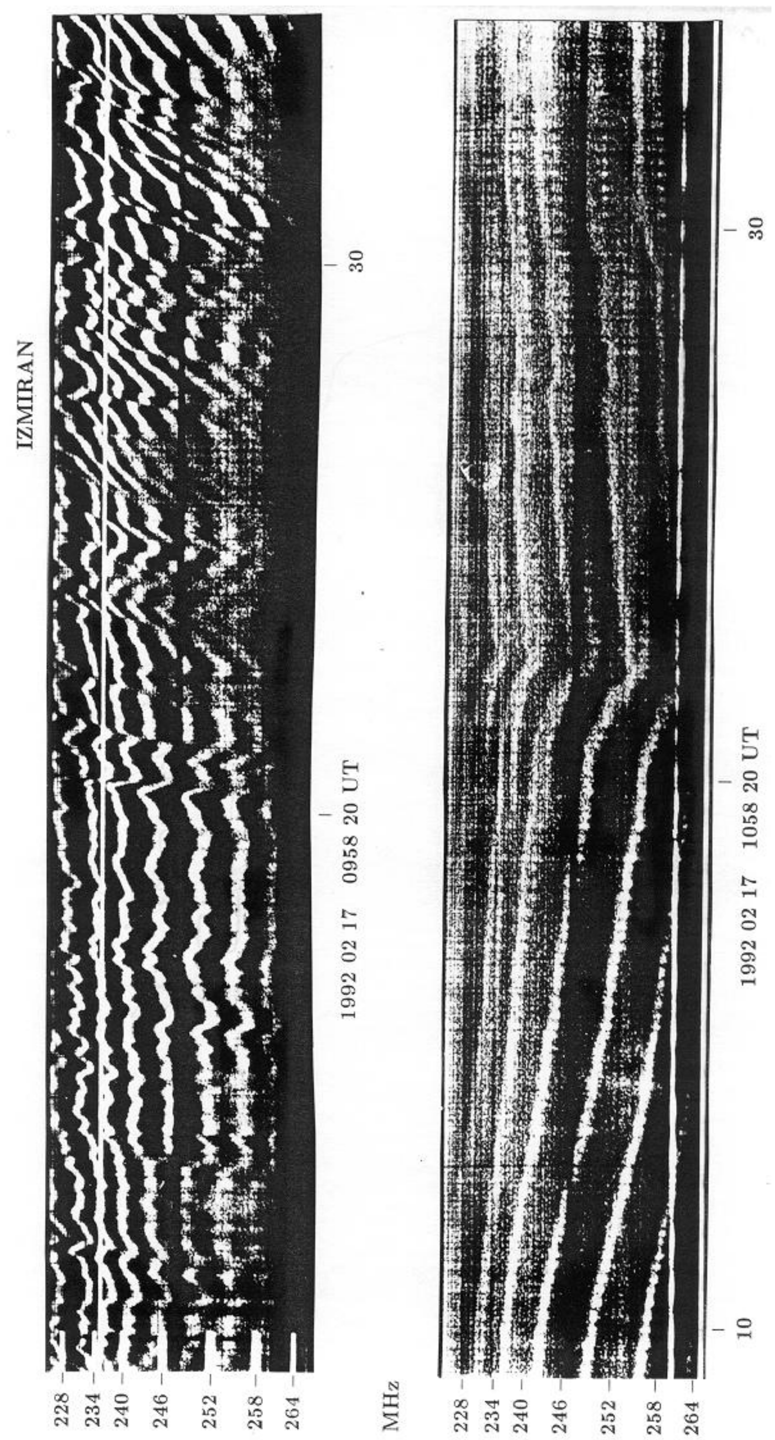

Figure 3: Two parts of zebra-pattern with IZMIRAN spectrograph with high resolution in the frequency range 226–265 MHz. The top part presents clearly numerous sharp displacements (shifts) on frequency of zebra-lines; in the bottom panel we observe that each zebra-line splits into two lines, where one of those consists of points.

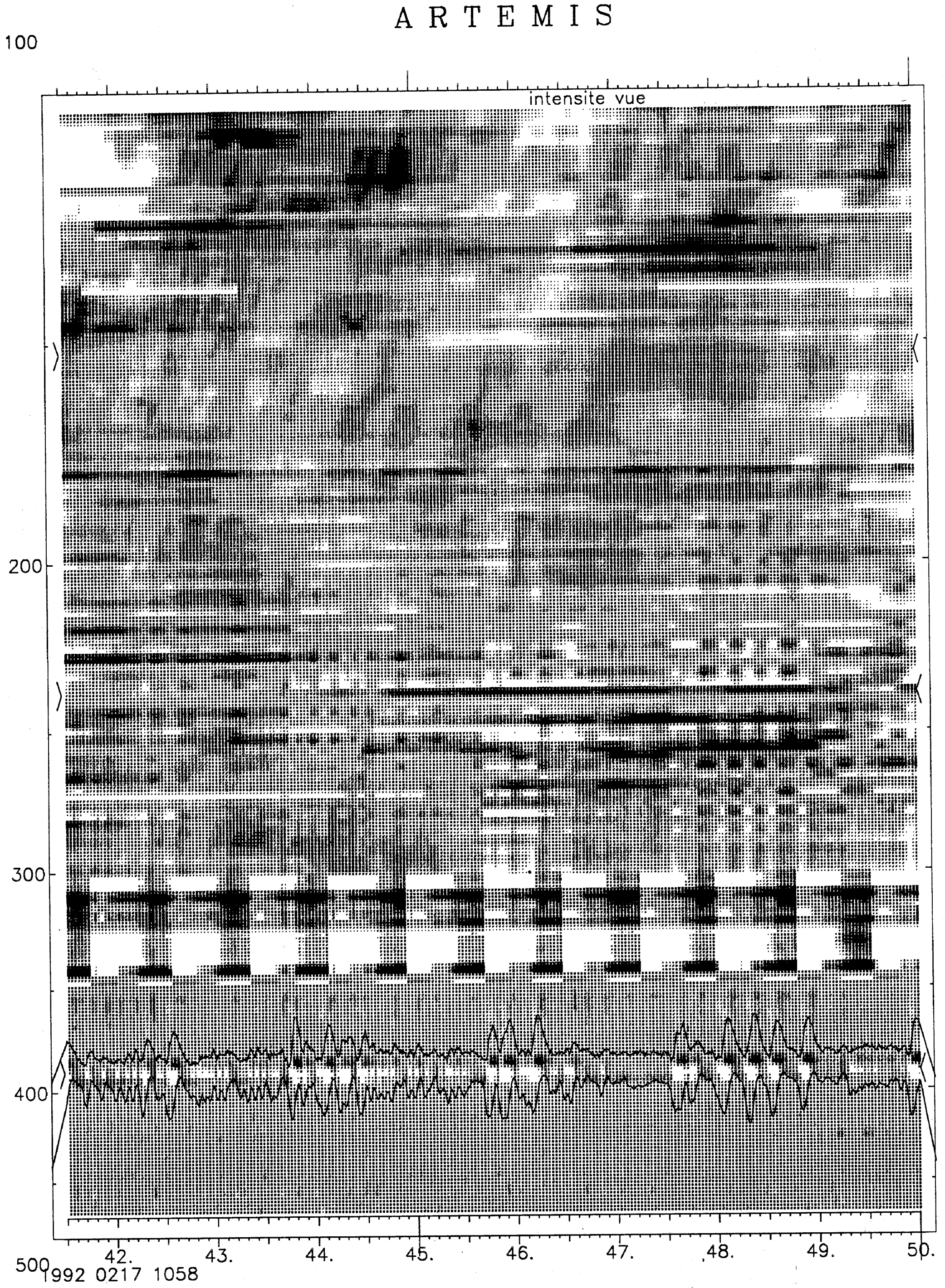

Figure 4: ARTEMIS spectrum in intensity with maximal time resolution in the moment of substructure of zebra-pattern. Overlapping the spectrum intensity profiles of the two channels at frequencies around 400 MHz. We discover that the "spaghetti" emission line consists of emission points (black) and absorption points (white) which is confirmed by overlaying the time profiles of the two channels near 400 MHz. Those points coincide with sudden reductions of the period about 0.25 s.

Zebra-patterns are more complicated structures, and many different mechanisms were proposed: Chiuderi et al., [1973]; Zheleznyakov and Zlotnik, [1975 a,b,c]; Fedorenkko, [1975]; Kuijpers, [1975, 1980]; Berney and Benz, [1978]; Fomichev and Fainshtein, [1981]; Mollwo, [1983, 1988]; and may be the most attractive one, Winglee and Dulk, [1986], based on a non-saturated maser mechanism with a loss-cone distribution function. The majority of these are based on the electrostatic emission at double plasma resonance:

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

(ω_{Pe}, ω_{Be} - electron plasma and cyclotron frequencies).

However many difficulties remain with all these versions:

— the density ratio of energetic to cold particles $n_h/n_c \approx 10^{-2}$ is too high

— the frequency drift is explained by fast changes of the magnetic field, but the frequency separation between zebra-lines (Δf) yields too weak a magnetic field: $\Delta f \approx (2\pi)^{-1}\omega_{Be}$, with chaotic dependence on f_{Pe} (or on height in the corona) and plasma $\beta > 1$

— there is no explanation for zebra-stripes in the intense continuum in the presence of a strong modulation (absorptions)

An important point missing in previous theories is that a loss-cone distribution generates whistlers which in turn affect the electron velocity distribution [Omura and Matsumoto, 1987]. In addition, many features of zebra lines and fiber bursts are similar. This led Chernov [1976a,b] to propose a unique interpretation for fiber bursts and zebra patterns, based on Langmuir wave and whistler coupling: $l + w \Rightarrow t$. In this model, the frequency separation between emission and neighbouring low frequency absorption in the zebra-pattern is related to the magnetic field strength B by $\Delta f_{ea} \approx 0.1 \cdot f_{Be}$ [Chernov, 1990]. In the present event, we have $\Delta f_{ea} \approx 3 - 4$ MHz at a frequency ≈250 MHz, which gives quite a reasonable value $B \approx 11 - 14$G.

We will use the specific new features observed during the present event to confront further this model to the Winglee and Dulk [1986] model in section 5.

4.2 Pulsations

The nature of radio pulsations of different time scale is usually divided on three groups: 1) magnetic flux tube oscillations, when the emissivity of trapped particles is modulated by a standing or propagating MHD wave; 2) cyclic self-organizing systems of plasma instabilities (wave- particle, wave-wave interactions); 3) modulation of acceleration of particles into the source [Aschwanden, 1987]. Along these lines, the various periodicities observed in the present event may be explained as follows.

The ≈3 min pulsations may be due to standing waves of the fast magnetosonic mode, trapped in the magnetic arch where the source is located.

According to Roberts et al. [1984] and Aschwanden [1987] a disturbance at the foot of the loop can provide such oscillations due to the kink instability. MHD wave can be trapped in the loop with small Alfvén speed inside the loop due to a strong density enhancement.

For that long period rather a standing mode of fast magnetoacoustic wave takes place in the loop with the length L $\approx 3 \times 10^9$cm. It should be oscillating with the time period:

$$\tau_f \approx \frac{2L}{jV_{Am}}, \qquad (2)$$

where j gives the number of nodes along the loop (for a standing mode we would rather have $j = 1$) and V_{Am} is a mean Alfven speed ($V_{Am} \approx 3.5 \times 10^7$ cm/s). Then for usual values of $T_{e,i} \approx 10^6$K and for the ratio $\omega_{Pe}/\omega_{Be} \approx 20$ we can estimate $\tau_f \approx 171$ s, that is very near to the observed period.

The ≈20 s pulsations may be due to travelling waves of the same fast magnetosonic mode, generated by sausage instability during magnetic reconnection; as soon as reconnection stopped, at the end of the polarization reversal around 1014 UT, these pulsations stopped, too.

The ≈0.2 s pulsations may be due the intermittent acceleration of electrons inside the current sheet. As newly accelerated electrons flow along the magnetic field, they fill up the loss-cone distribution in velocity space, quenching the loss-cone instability, which show up as sudden reductions on the background emission [Benz and Kuijpers, 1976; Zaitsev and Stepanov, 1975].

The fine structure of the "spaghetti" reflects this mechanism: the bright points take place between sudden reductions; therefore the emission mechanism of the "spaghetti" must also be due to the loss-cone instability at the upper hybrid frequency at double plasma resonance (Figure 1). The disappearance of the "spaghetti" during minima of the 3 min pulsations may be due to the breaking down of the double plasma resonance. The appearance of two or three additional emission bands (Figure 3) may be connected with a simultaneous emission at some cyclotron harmonics when the double plasma resonance is fulfilled at some levels during enhancement of the magnetic field during maximal intensity of 3 min pulsations.

5 Discussion

We discovered two new properties of the zebra-pattern:

- occasional and sudden frequency shifts of zebra stripes;

- occasional splitting of a zebra stripe into two differently structured lines.

Let us see how well these properties can be accounted for in either of the two main alternative models for zebra generation.

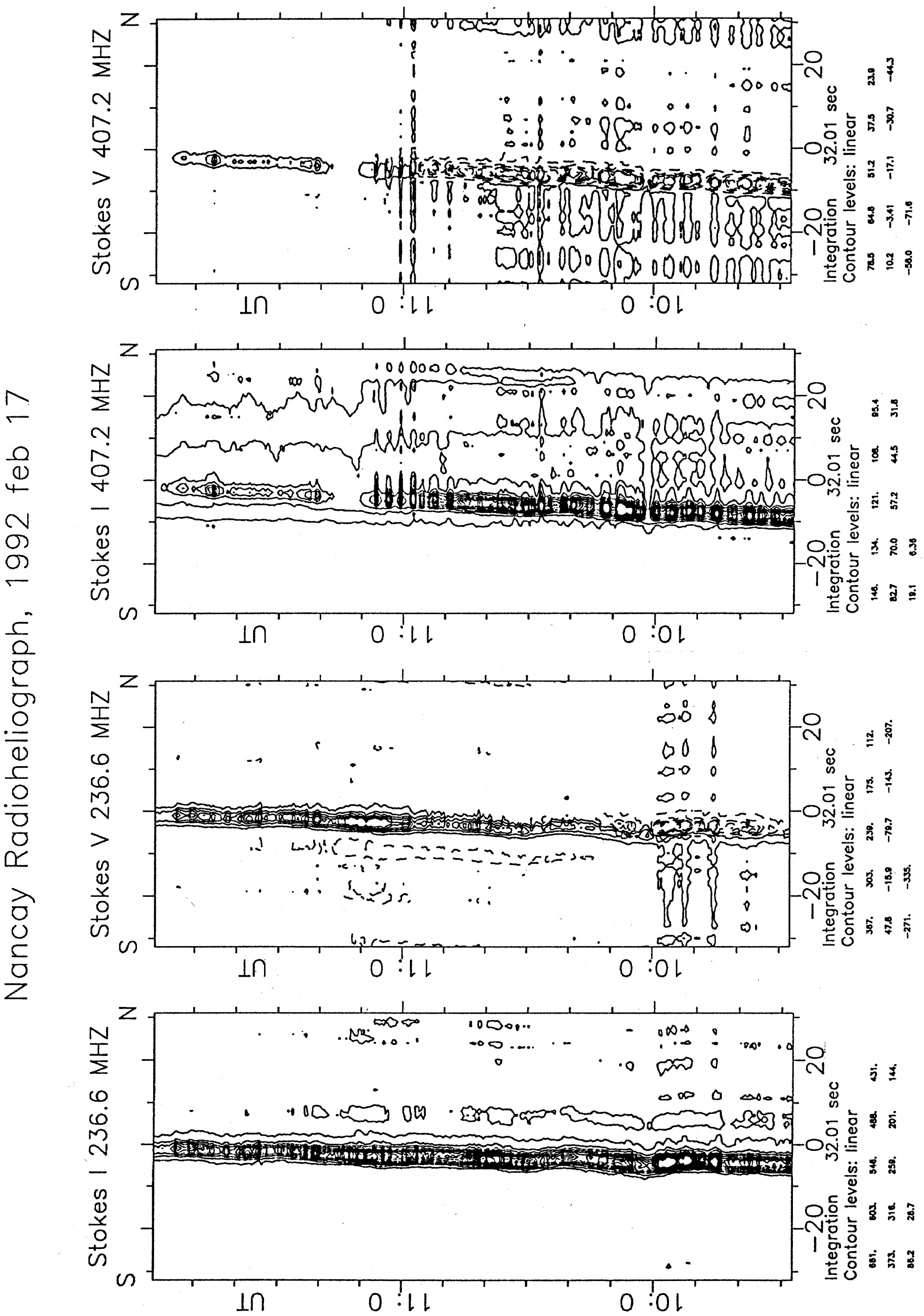

Figure 5: Contours of source positions measured by NRH at frequencies 236.6 and 407.2 MHz; in abscissa: channel number in the south-north direction in intensity (Stokes I) and circular polarization (Stokes V); in ordinates: time. The polarization reversal from RH (dashed contours) to LH (solid lines) takes place at 236.6 MHz between 1000 and 1010 UT, and at 407.2 MHz at about 1058 UT, moreover we can see that the sources of the "spaghetti" at 407.2 MHz between 1058 and 1107 UT (with centers smaller displaced to the north of the main continuum source) maintain the previous RH sign of polarization.

The first model is the electron cyclotron maser mechanism of Winglee and Dulk [1986] in which double plasma resonance takes place at cyclotron resonance:

$$\omega - k_{\|}v_{\|} - s\omega_{Be}/\gamma = 0 \qquad (3)$$

($k_{\|}$, $v_{\|}$ - wave number and speed of fast electrons both parallel to the magnetic field, γ - Lorentz factor) provided that: $v_{\|} \ll v_{\perp}$, s is high enough ($\approx$ 15....17) and $k_{\perp}v_{\perp} \approx s\omega_{Be}$ with a positive derivative of the distribution function, i.e., $\partial F/\partial v_{\perp} > 0$.

A general difficulty with this model is that the loss-cone distribution must be saturated rather at meter wavelengths. Further difficulties arise with explaining the new features dicovered in the present event.

Sudden frequency shifts of zebra-stripes can be the result of sharp changes of $v_{\|}$ or of B. If $v_{\|}$ increases, both following conditions would break down:

$$v_{\|} \ll v_{\perp} \quad \text{and} \quad \partial F/\partial v_{\perp} > 0, \qquad (4)$$

and the instability would switch off. On the other hand, magnetic field perturbations propagate at the Alfvén speed V_A, which is much too slow to account for the sudden frequency changes observed.

Stripe splitting implies that the growth rate in one hybrid band presents two maxima; this is impossible according to the calculations by Winglee and Dulk, [1986].

We will now try to explain these particular features in the model of plasma wave coupling with whistlers: $l + w \Rightarrow t$.

Fast particles filling the entire magnetic trap interract with standing whistler waves at the cyclotron resonance:

$$\omega_w - k_{\|}v_{\|} - s\omega_{Be} = 0, \qquad (5)$$

with the conservation laws:

$$\omega_w + \omega_l = \omega_t, \quad k_w + k_l = k_t, \qquad (6)$$

where k_w is the whistler wave number $\approx 2 \times 10^{-2} cm^{-1}$ [Kuijpers, 1975; Fomichev and Fainshtein, 1988; Chernov, 1990].

Depending on the form of the distribution function the instability can develop with s=+1 (normal Doppler effect) or s=-1 (anomalous Doppler effect) [Maltseva and Chernov, 1989]. Maximum whistler amplification is localized in narrow zones of characteristic size $l_w \approx 10^8$cm, producing the different zebra lines [Chernov, 1989].

Sudden frequency shifts and splitting of zebra lines occur during periods of enhanced sudden reductions, that is in the midst of repeated injections of electron beams with high $v_{\|}$. The structuration of some splitted zebra lines in dots is even synchronized with the sudden reductions. Moreover frequency shifts and splitting exhibit drifts similar to type III bursts.

If a new beam of particles is injected ω_w changes suddenly; conservation equations (6) break down locally, but are quickly restored at nearby plasma levels with a different value of ω_l. This will result in a sudden shift of the frequency ω_t, propagating from one zebra line to the next one at the speed of the beam; this is precisely what we observe in Figure 3.

Another consequence of the injection of a new beam is that the velocity distribution is suddenly filled up with high velocities parallel to the magnetic field, which tends to turn on the instability on the anomalous Doppler resonance [Gendrin, 1981].

This offers a natural explanation for splitted zebra stripes in terms of a simultaneous whistler instability at normal Doppler resonance: $\omega_{w,s=1} = k_\| v_\| + \omega_{Be}$ and at anomalous Doppler resonance: $\omega_{w,s=-1} = k_\| v_\| - \omega_{Be}$ at slightly different plasma levels. For $(\omega_{w,s=1} - \omega_{w,s=-1})/2\pi \approx$2 MHz we need $v_{\|,s=1} \approx 1.6 \times 10^9$cm/s and $v_{\|,s=-1} \approx 2.6 \times 10^9$cm/s, which are quite possible velocities in the source.

Additional beams with a narrow velocity dispersion (high $v_\|$) do not change the conditions of instability for the normal Doppler effect (high $v_\perp$); therefore only the high frequency component of a splitted zebra line will be structured by these beams into a succession of emission dots.

6 Conclusion

Thus the radio event 1992 02 17, wealthy of fine structures, helped us to verify two alternative zebra-pattern models. The main new observational substructure of a zebra-line (splitting into two independent lines) was well explained by the the model $l + w \Rightarrow t$ due to the simultaneous whistler instability at normal and anomalous Doppler cyclotron resonances during periodic injections of new particles, providing fast pulsations (sudden reductions).

In the model of the electron cyclotron maser mechanism it is impossible to get two growth rate maxima in one hybrid band necessary to explain such a splitting.

At the same time the latter mechanism explains well the long-lasting oscillating fiber like "spaghetti" in the frequency range 350–450 MHz.

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