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ON THE ZEBRA STRUCTURE IN MICROWAVE BURSTS

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Abstract. We presented nineteen cases of zebra pattern structure (ZPS) and fiber bursts (FB) in four radio bursts at the frequency range about 3 GHz, using the new microwave spectrometer of NAOC between 2.6-3.8 GHz (China, Huairou station) with high resolution (10 MHz and 8 ms). FB and ZPS have about the same spectral parameters, and the main one -the frequency separation between the emission and the neighbouring low frequency absorption ~30 MHz. Therefore we consider both fine structures as whistler manifestation. New calculations show an increase of the whistler growth rate with the increase of temperature near flare region, a decrease of electron cyclotron damping and a decrease of whistler frequency up to 0,1 of electron cyclotron frequency. The duration of fiber bursts about 2 sec corresponds to the whistler waves propagating undamped at about 2 sec, which requires the whistler increment <0,5 1/s. This finding is used to obtain the magnetic field strength in the generation region. For reasonable value of electron temperature (2-20 MK) B=125-190 G for regions, where the electron density is (8-18) $\times 10^{10}$ cm^{-3}.

INTRODUCTION

Zebra-pattern structure (ZPS) and fiber-bursts (FB) (or bursts with constant intermediate frequency drift) are well-known fine structures in the meter and decimeter continuum emission of type IV solar radio bursts (Slottje, 1981). But now with new microwave spectrometer of NAOC (China, Huairou station) with higher resolutions (10 MHz and 8 ms) one can observe detailed zebra pattern and fiber bursts at high frequencies (see Chernov et al. in this issue for references).

The majority of theories of zebra-pattern is based on an electrostatic wave emission from non-homogeneous source at double plasma resonance, when the upper hybrid frequency (ω_{UH}) is equal to some harmonics of electron cyclotron frequency (ω_{Be}): $\omega_{UH} = (\omega_P^2 + \omega_{Be}^2)^{1/2} = s\omega_{Be}$ with electron plasma frequency $\omega_P >> \omega_{Be}$. (Zhelznykov & Zlotnik, 1975, Kuijpers, 1975 Mollwo, 1983, Winglee & Dulk (1986). But recent TRACE data in EUV images show that the magnetic trap (radio source) consists usually of many thin (~ 10^8 cm) magnetic loops with almost constant magnetic field strength and electron density along loops (see e.g. Figure 2 in Messmer et al. in this issue). In such a case we are faced with the difficulty of having double plasma resonance levels in the radio source. To avoid some difficulties with the model at double plasma resonance and taking into account a similarity of main features of zebra stripes and fiber bursts, we consider both fine structures as whistler manifestation, namely the interaction of plasma electrostatic waves *(l)* with whistler waves *(w)* (generated by the same fast particles with loss-cone anisotropy) $l + w \rightarrow t$ (Chernov, 1976).

OBSERVATIONS

Here we describe and analyze four bursts with fine structures (1998 , April 15; 1998, June 12, 1999, August 25 and 2000, October 29). Their dynamic spectra are similar to the zebra pattern structures (ZPS) in metric type-IV bursts. There were nineteen ZPS and FB cases in four flare events observed by broadband radio spectrometer at Huairou, Beijing of National Astronomical Observatories, and two remarkable events (1998 04 15 and 2000 10 29) are discussed here in more detail. If we compare positions of new arising bright magnetic loops at SOHO images in 195A with SOHO MDI magnetograms during the fine structure, then the strong right-hand polarization of both remarkable events corresponds to ordinary radio magneto-ionic mode. For the event 2000 10 29 we used the radio source position at 17 GHz of Nobeyama radio heliograph. All the variety of ZPS and FB known in metric range is also characteristic at microwaves around 3 GHz. ZPS and FB are not always strictly periodic, and stripes in emission and in absorption are often observed as isolated ones.

The event 2000 10 29 is the most rich of fine structure. During about 20 minutes ZPS and FB were following by pulses of some seconds intermitting one another. The evolution of ZPS and FB is shown in the Figure 1. FB have a maximum of value Δf-band ~1,3 GHz, and ZPS – only 0,42GHz, but we have a frequency gap in the recording spectra between 2,6-2,0 GHz. This event was connected with H_α 2B M4.4 flare in AR NOAA 9209, located at S25E35. The fine structure was observed in numerous emission pulsations of some second duration. ZPS show different frequency drift: slow negative, positive or some wiggles. Fiber bursts overlap often zebra pattern, and the emission frequency band is about the same for both structures. After some wiggles of ZPS a strong series of FB with different periodicity on time and constant frequency drift ~ -244 MHz/s was observed. FB and ZPS have about the same spectral parameters, e.g. the frequency bandwidth of emission stripes Δf ~ 20 MHz. Detail analysis of multi-channel time profiles shows, that the intensity level in black stripes (between emission stripes) could be higher of the emission level of main continuum (without ZPS). Thus, black zebra-stripes are visible not due to the absence of bright stripes, but due to an absorption of the main continuum emission (a modulation effect). In this connection the main parameter of ZPS and FB is not frequency separation between emission stripe ($\Delta f_s \approx$ 60-70 MHz on an average), but the frequency separation between the emission and the neighbouring low frequency absorption with a mean value $\Delta f_{ea} \approx$ 30-40 MHz. Therefore we could consider both fine structures in a unique model, as whistler manifestation.

DISCUSSION

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In the whistler model the frequency separation $\Delta f_{ea} \approx f_w \approx (0{,}1\text{-}0{,}25) f_{Be}$ in the metric range 300 to 100 MHz (Chernov et al. 1998). So, we can find whistler frequency from observations and determine f_{Be}. On the other hand the duration of a ZPS series is defined by the time interval of whistler propagation without damping t_d, therefore it should be necessary to verify the value f_{Be} using a damping factor: $exp(-\gamma t)$, which requires the whistler increment $\gamma < 1/t_d$. In our event 2000 10 29 the value of $t_d \approx 2\ s$. All previous studies of whistler generation and propagation in the solar corona were made for low frequency range (≈100~300 MHz). For our observations we have made more detailed simulations for frequencies about 3 GHz.

For a Maxwellian plasma the permittivity of whistler waves propagated along the external magnetic field is (Scharer and Trivelpiece, 1967)

$$\varepsilon = 1 + \frac{\omega_P^2}{\omega_w \sqrt{2} \mathrm{v}_t k_w} Z\left(\frac{\omega_w - \omega_B}{\sqrt{2}\mathrm{v}_t k_w}\right), \qquad (1)$$

where k_w - the wave number of the whistler waves, v_t - the thermal electron velocity, Z - the plasma dispersion function (Fried and Conte, 1961)

$$Z(z) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-t^2} dt}{t - z}$$

With real k the relation (1) provides a complex $\omega_w = \omega_{wr} + i\gamma$ (ω_{wr} is the real part of ω_w)

As $\gamma << \omega_{wr}$, $\gamma << \omega_B - \omega_{wr}$ and $|\omega_{wr} \operatorname{Re} Z| >> |\gamma \operatorname{Im} Z|$ we can solve relation (1) for γ

$$\frac{\gamma}{\omega_{wr}} = \frac{y^2 \operatorname{Im} Z\left(\dfrac{(x-1)c}{\sqrt{2}\mathrm{v}_t x\sqrt{1+\dfrac{y^2}{x(1-x)}}}\right)}{2\sqrt{2}\mathrm{v}_t \dfrac{x^2}{c}\sqrt{1+\dfrac{y^2}{x(1-x)}} + y^2 \operatorname{Re} Z\left(\dfrac{(x-1)c}{\sqrt{2}\mathrm{v}_t x\sqrt{1+\dfrac{y^2}{x(1-x)}}}\right)} \qquad (2)$$

where $y = \frac{\omega_P}{\omega_B}$, $x = \frac{\omega_{wr}}{\omega_B}$. The influence of fast electrons on the electron cyclotron damping is considered to be weak. The duration of ZPS bursts is about 2 sec. If the whistler waves propagate undamping about 2 sec, then accordingly to a damping factor of $\exp(-\gamma t)$ that requires $\gamma < 0.5\,\mathrm{s}^{-1}$, respectively $\frac{\gamma}{\omega_w} < 10^{-9}$ for $\omega_w \approx 2\pi \cdot 35 \cdot 10^6\,\mathrm{s}^{-1}$ ($\omega_w \approx 2\pi \cdot \Delta f_{ea}$ – is taken from observations). We solved the Equation (2) relatively ω_B for different values of electron temperature and for values of $\frac{\gamma}{\omega_w} \approx 10^{-9}$. These data give us an opportunity to get the value of the magnetic field strength in the generation region, where $\omega_P = 2\pi \cdot 3.6 \cdot 10^9\,\mathrm{s}^{-1}$. We have: B=85 G, B=110 G, B=130 G, B=170 G correspondingly for T=2 10^6K, 5 10^6 K, 10^7 K, 2.2 10^7 K. The magnetic field strength depends weakly from the electron temperature. We observe ZPS in the C8.8/SN flare and consequently the temperature of flare generation region may be enough large. The middle temperature of flare loops is 2.2 10^7 K (Doschek, 1990). Hence we suppose that the magnetic field strength for our case is about 170 G.

These estimations are coincided with the value, derived using the frequency drift velocity of fiber bursts, simultaneously observed with ZPS at the same frequency range. The frequency drift is defined by the whistler group velocity, then in the Newkirk model for the electron density multiplied by a factor 60, we got the same estimations with the formula $\boldsymbol{B \approx 15{,}43(\ln f - 3)^{-2} \times df/dt}$.

We must else verify the reality of whistler generation by fast particles near a hot flare region. In the whistler model the loss-cone fast electron distribution is assumed. The loss-cone distribution generates the Langmuir and whistler waves (Kuijpers , 1975). There are two possibilities to explain the narrow band emission, when the electrons resonance velocity $\mathbf{V_z}$ parallel to the ambient field is determined by: $\boldsymbol{\omega - k_z V_z \pm \omega_B = 0}$ .This is the resonance at the normal Doppler effect (-) and at the anomalous Doppler effect (+).

We suppose that the radio source of fine structure was located near the place of fast particle acceleration. And in such a case the distribution function of fast particles may be a beam including an anisotropy on perpendicular velocities, which could generate whistlers as at normal Doppler effect as anomalous one almost simultaneously. The frequency

position of ZPS on the spectra at high frequency edge (even as a high frequency limit of whole burst emission at all events) supports such a proposal.
The increment of whistler instability is defined by the expression (Benz, 1993):

$$\gamma / \omega_B = \pi \cdot sign(k_z) \cdot x\left(1 \mp \frac{1}{x}\right)^2 \eta(\upsilon_R^{n,a})\left\{A(\upsilon_R^{n,a}) - \frac{1}{\pm\frac{1}{x} - 1}\right\}, \quad (3)$$

where $\eta(\upsilon_R^{n,a}) = \frac{\upsilon_R^{n,a}}{n}\int 2\pi\upsilon_\perp d\upsilon_\perp f(\upsilon_\perp, \upsilon_z = \upsilon_R^{n,a})$

define a ratio of electrons in the resonance with whistler waves (i.e. $v_R^{n,a}$) to the total number of electrons – n; the function $A(v_R^{n,a})$ takes into account the pitch angle anisotropy; v_z , $v_\perp$ - velocity components along and perpendicular magnetic field; upper signs correspond to the resonance at the normal Doppler effect (n) and bottom signs – to the resonance at the anomalous (*a*) one. Let us adopt the distribution function of fast electrons in a view of a beam with loss-cone *(j)* and temperature *(a)* anisotropy:

$$f(\vec{\upsilon}) = \frac{n\upsilon_\perp^{2j}}{(\pi)^{3/2}\upsilon_{t,z}\upsilon_{t,\perp}^{2j+2}(j+1)}\exp\left[-\frac{(\upsilon_z - \upsilon_b)^2}{\upsilon_{t,z}^2} - \frac{\upsilon_\perp^2}{\upsilon_{t,\perp}^2}\right], \quad (4)$$

where $v_{t,z}$ $v_{t,\perp}$ - mean thermal velocities in the electron beam, the parameter $a = 1 - v_{t,z}^2 / v_{t,\perp}^2$.
Calculations were made for $\omega_P = 2\pi \cdot 3{,}6 \cdot 10^9$, $v_b = 0{,}3c$, $B = 170\ G$ and three values of electron temperature: T= $2 \cdot 10^6$ K, 10^7 K, $2 \cdot 10^7$ K. The result at anomalous Doppler effect ($a = -0{,}5$, $j = 0{,}2$), responsible for ZPS is shown at the Figure 3.

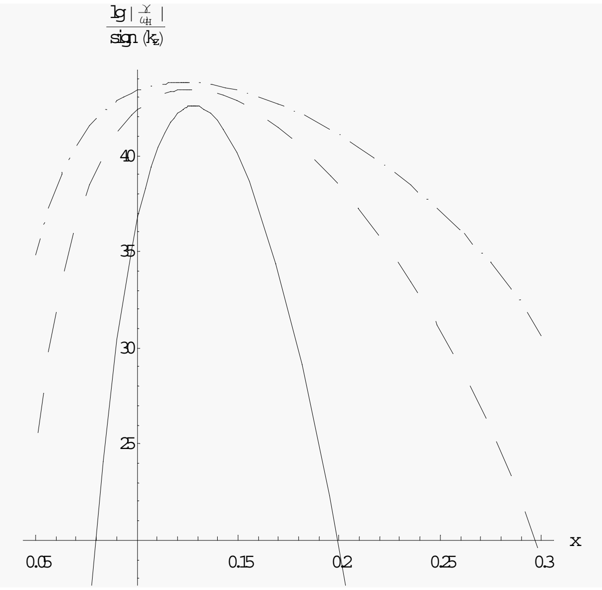

Fig. 3. Increment of the whistler instability relative to ω_B on the dependence of x = ω_{wr} / ω_B for three values of the coronal temperature (from below to upward) T= $2 \cdot 10^6$ K, 10^7 K, $2 \cdot 10^7$ K.

We can see, the whistler growth rate increases with T and the maximum in this case takes place on x ≈ 0,1, just the same value was used with the evaluation of B.
In the Figure 2 we try to get levels of double plasma resonance in the alternative model of ZPS for realistic distribution models of magnetic field, received by Dulk and McLean (1978) using radio data, and electron density model of Newkirk, multiplied by a factor 60-90.
The main disagreement with the observation is too strong dependence of the frequency separation between levels on the frequency (i.e. between crossing of two curves: ω_{UH} and harmonics (s) of B).

CONCLUSION

The analysis of 19 cases of zebra-patterns near 3 GHz in four radio events shows full variety of fine structures similar to the metric range. FB and ZPS have about the same spectral parameters, therefore we consider these fine structures as whistler manifestation, namely the interaction of plasma electrostatic waves with whistler waves (generated by the same

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fast particles with loss-cone anisotropy) $l + w \rightarrow t$. New simulations of whistler instability in conditions of hot flare regions yield moderate values of magnetic field strength B ~ 170 G near the 3 GHz plasma level.

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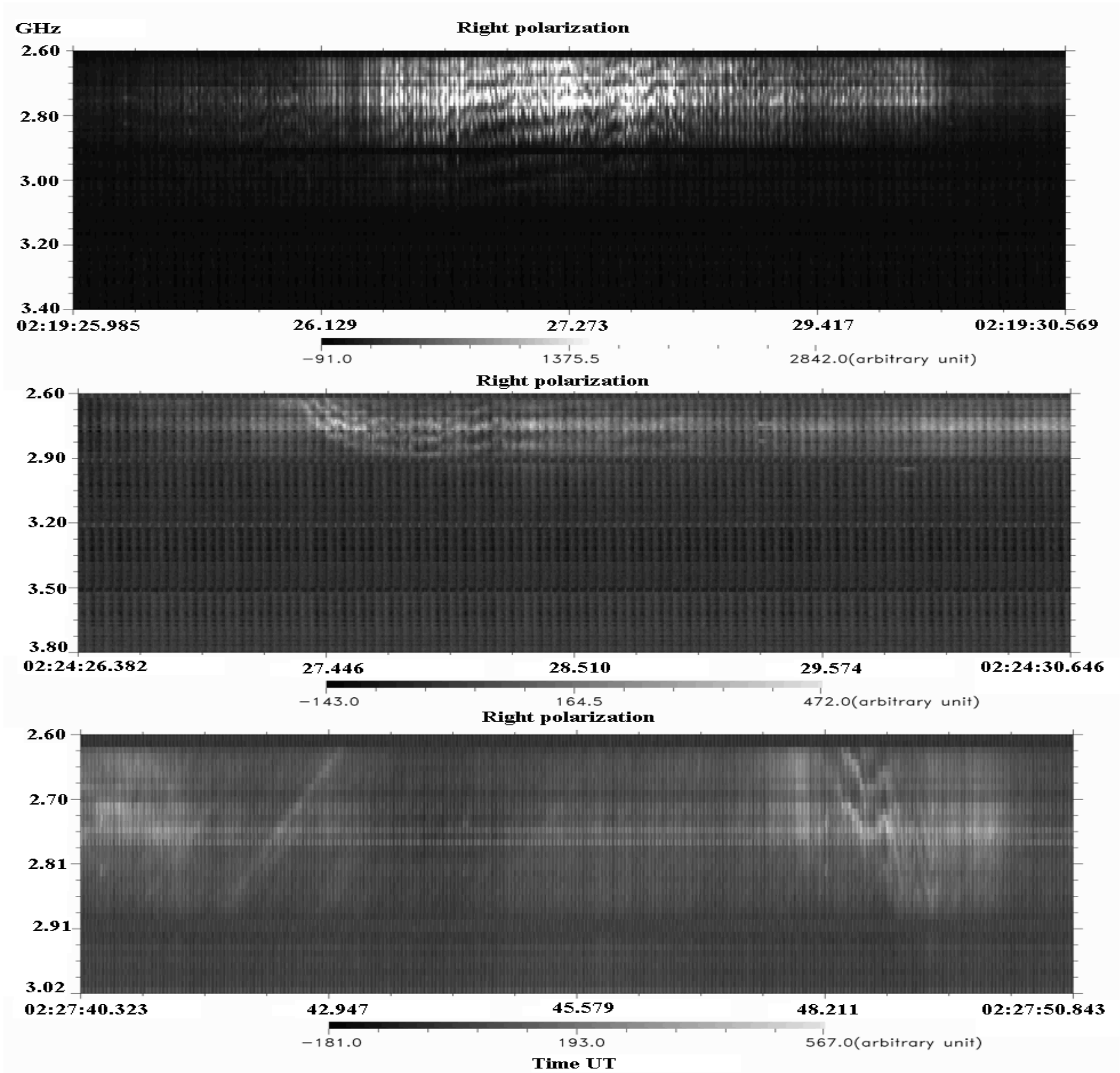

Fig. 1. Radio spectrograms of zebra-patterns and fiber bursts during the evolution of the event 29 October 2000 between 02:19-02:28 UT in right polarization recorded by the spectrometer of NAOC (2,6-3,8 GHz. The frequency difference between 5 regular zebra stripes at the top panel depends weekly on the frequency.

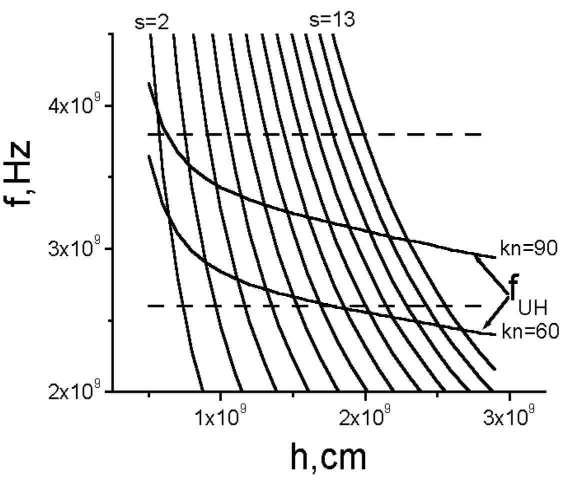

Fig. 2. Dependences of upper hybrid and cyclotron frequencies on the height in the corona in the magnetic field model of Dulk & McLean, 1978 and electron density model of Newkirk, multiplied by kn. The main disagreement with the observation is too strong dependence of the frequency separation between levels of double plasma resonance on the frequency.