LANGMUIR WAVE DIAGNOSTICS THROUGH ZEBRA-STRUCTURE IN THE FLARE OF 4 APRIL 2011

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Instrumentation

Siberian Solar Radio Telescope (SSRT)

- 256-element cross-shaped interferometer
- antenna element – 2.5-meter parabolic, step – 4.9 meter
- baseline – 622.3 meter
- central frequency – 5731 MHz
- receiving bandwidth – 120 MHz
- angular resolution:
  - 1-D mode (additive mode) – up to 15"
  - 2-D mode (correlation mode) – up to 21"
- stokes parameters recorded – I, V
- time resolution:
  - 1-D mode – up to 14 msec
  - 2-D mode – up to 1 min
- sensitivity – 0.003 s.f.u.
  (*Grechnev et al., 2003*)

Spectropolarimeter 4-8 GHz

- time resolution 10 ms
- channels number 26
- channel bandwidth 30-60 MHz
- sensitivity 2 SFU
  (Zhdanov, Zandanov, GEAB, 2011)

Intensity (left) and polarization (right) images by SSRT at 5.7GHz

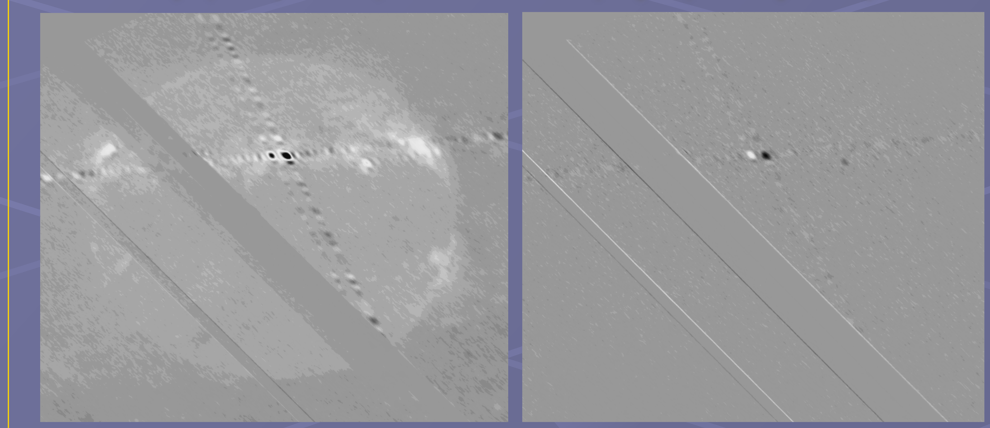
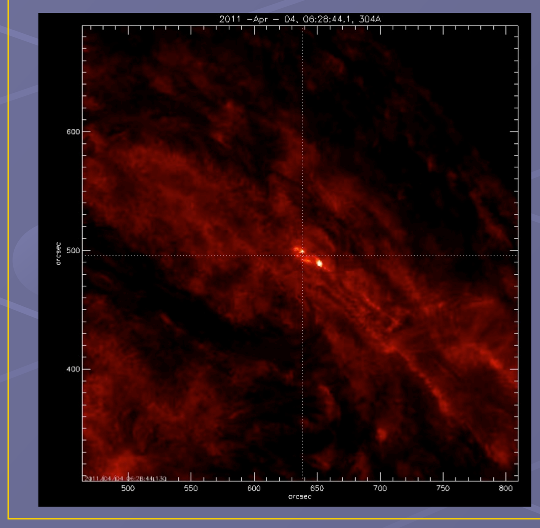


Fig. 1. SSRT image in 5.7 GHz intensity (left) and polarisation (right). The frame indicates the AR where the flare with zebra-pattern occurred. Since there are no displacements between bursts measured by SSRT in two frequencies, so we assume that the source of the two zebra strips is located in the same site correspondent to the centre of the microwave burst. Size of the MW source is about 9".



Frequency gaps between the stripes Δf min-max [GHz] 0.35 – 0.76
Instant frequency width of a stripe [GHz] 0.17 – 1.02

Fig. 2. (left) The exact position of zebra pattern location is shown by the blue cross in the image Fig. 3.

Generation of Langmuir waves by precipitating electrons

Joint Fokker-Plank and wave diffusion equation Zharkova and Siversky, ApJ, 2011

Landau-Fokker-Plank equation for distribution of electrons f:

$$\partial f/\partial t + \upsilon\, \partial f/\partial x - e\varepsilon/m_e\, \upsilon^2 \partial/\partial\upsilon\, (f/\upsilon^2) = e^2\omega^2_p/m_e\, \partial/\partial\upsilon\, [f\, (\ln \upsilon/\upsilon_e)/\upsilon^2] + \pi\omega_p/[m_e n]\partial/\partial\upsilon\, (\upsilon W\, \partial f/\partial\upsilon) + 4\pi e^4 n \ln\Lambda_b/m_e^2\, \partial/\partial\upsilon(f/\upsilon^2),$$

Wave diffusion equation for distribution of waves W:

$$\partial W/\partial t + 3\upsilon_e^2/\upsilon\, \partial W/\partial x = e^2\omega^2_p\, (\ln \upsilon/\upsilon_e)/\upsilon\, f + \pi\omega_p/n\, \upsilon^2 W\, \partial f/\partial\upsilon - \pi e^4 n \ln\Lambda_p/[m_e^2 \upsilon_e^3]W,$$

where n, υ_e, ω_p – density, velocity and plasma frequency of the ambient plasma, Λ_b and Λ_p are Coulomb logarithms for beam and plasma electrons, respectively.

$\varepsilon(t,x) = e/\sigma(x) \int f(\upsilon,x,t)\, \upsilon\, d\upsilon$, -- electric field induced by a beam

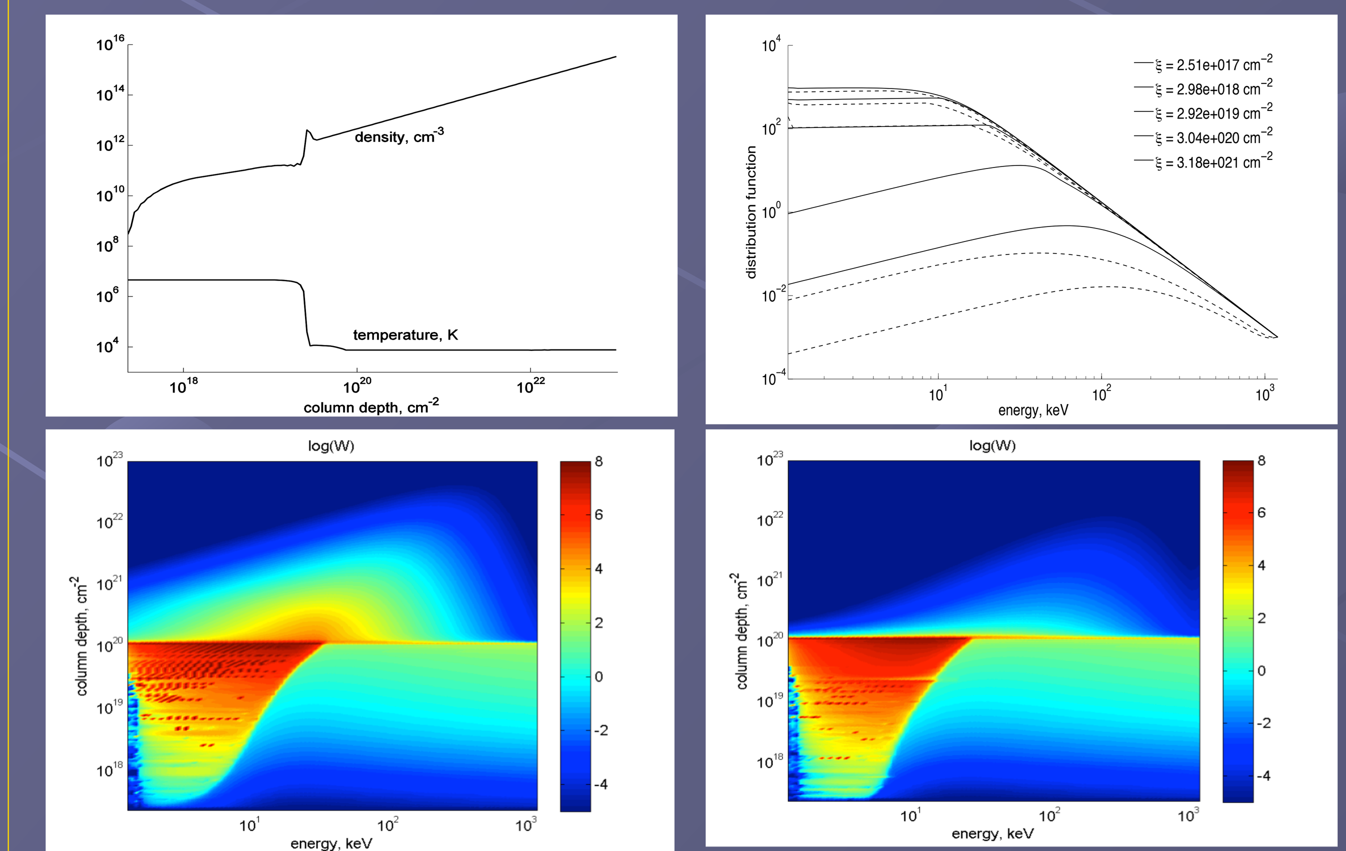


Fig. 6. Top left – HD model of atmosphere, top right – differential spectra of beam electrons with the initial flux of 1012 erg/cm2/s, γ=3.5.
Bottom left – Langmuir wave distribution without return current;
Bottom right - Langmuir wave distribution with return (from Zharkova&Siversky, 2011)

Zebra pattern location on 304A image (top) and MDI magnetogram (bottom)

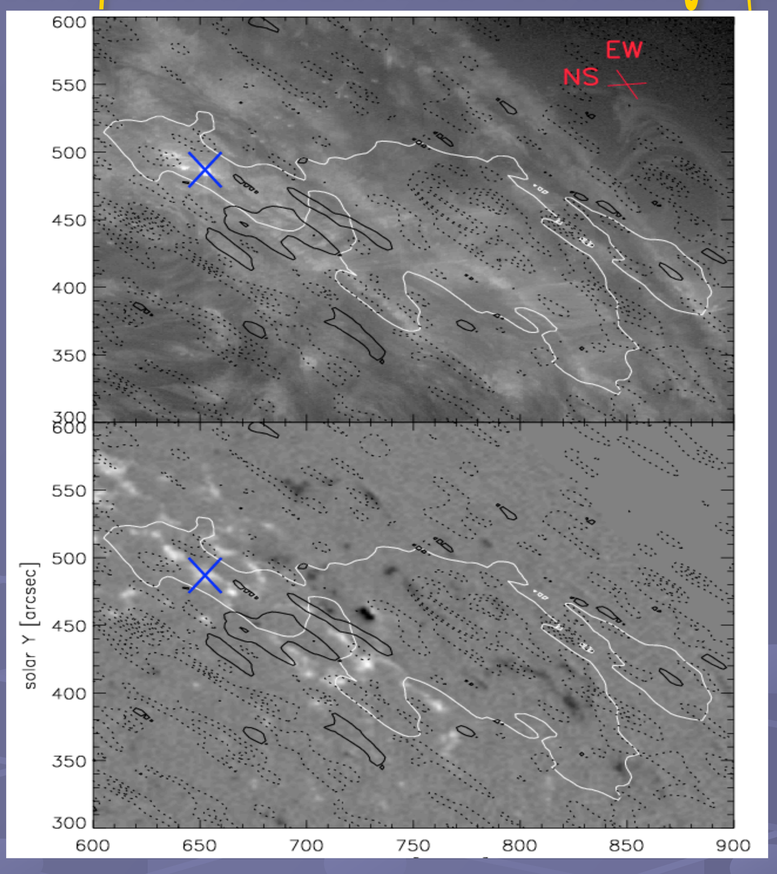


Fig. 3

4 April 2011. Overplotted images – top plot: white contours– SSRT intensity in 5.7 GHz, black contours: – SSRT polarization in 5.7 GHz (dots (LCP) and solid line (RCP)). Background- SDO 304 A (06:28:57UT). Red cross in the right corner show the directions in EW и NS. The blue cross shows a position of the centre of microwave burst in intensity. It is assumed that the location of zebra structure coincides with the location of the blue cross.

Bottom plot: the same contours as above overplotted on MDI magnetogram taken at 06:27:30 UT. Since AR is located close to the limb, a procedure zradialize was applied for correction of magnetic field magnitudes, which reaches in the flare locations about 400 G (at the photosphere).

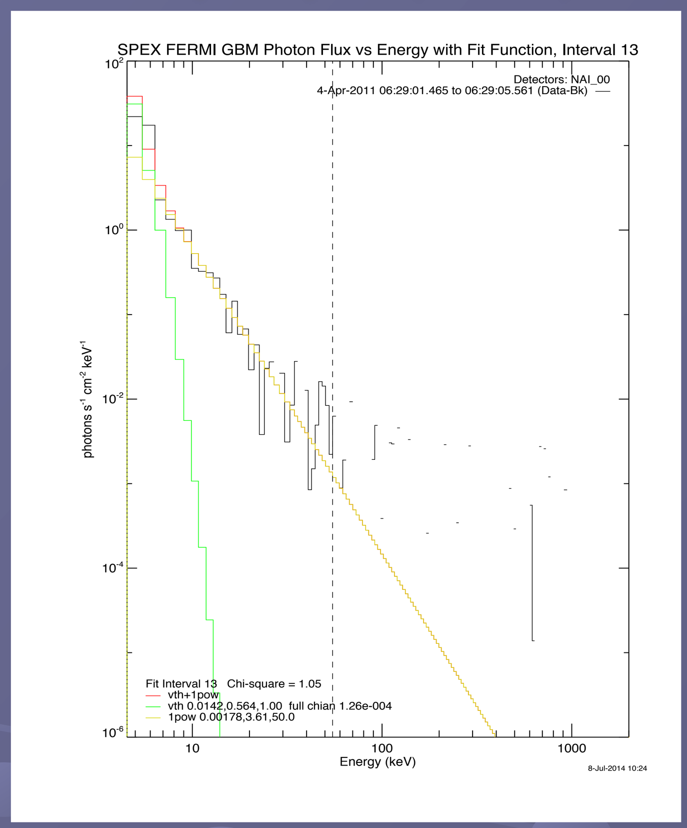


Fig 4. Energy spectrum of energetic electrons obtained from FERMI. Spectral index is 3.61.

Derived parameters of the ambient plasma in the flare of 4 April 2011 (Altyntsev et al, 2012):

Temperature – 43.8 MK
Density - 10^{11} cm^{-3}

Interaction of dense beam electrons with Langmuir waves - beam pinching

Generation of high frequency harmonics of Langmuir waves by anomalous Doppler resonance with beam electrons- Kovalev, Plasma Phys., 2009

$\omega+\omega_B-k_xV_x=0$, $\omega<\omega_B$ – gyrofrequency, V_x- e-velocity

Governing equation:

$$(d^2/\partial\tau^2 +\omega_1^2)\, (d^2/\partial\tau^2 +\omega_2^2)V=0,$$

where

$\omega_1 \approx \omega_p^2 + \omega_B^2\sin^2\vartheta$, $\omega_2 \approx \omega_B^2(1-\omega_B^2/\omega_p^2)\cos^2\vartheta$.
ϑ – pitch angle of electrons

Solution:

$V=a_1\exp(i\omega_1\tau)+a_2\exp(i\omega_2\tau)$ +complex conjugates,
or
$V=a_1 \cos(\omega_1\eta/u)+a_2 \cos(\omega_2\eta/u)$, where
$\eta=x-ut$; $\tau=\eta/u$,
Electron density and electric field
$n_e=n_i/(1-V)$; $\phi'_\tau=4\pi n_i ei[a_1/\omega_1\exp(i\omega_1\tau)+a_2/\omega_2\exp(i\omega_2\tau)$

In the case $V\approx1$ there are many harmonics with close amplitudes exist with their number N defined as

$$N=3/(2^{3/2}(1-a_2)^{3/2}).$$

A number of harmonics is cut off after s > N, because only emission with frequencies $\Omega >= \omega_p$ can leave the volume.

If $a_1 \to 0$ or $a_2 \to 0$ then $N \to 1$,
if $a_2 \to 1$, ratio of amplitudes for s=1,2,3 is 1:0.8:0.7→ N>200
Near critical point $V\to1$
If $a_1\approx a_2$, N => 3.

Space period of this electron wave is $L= 2\pi u/\omega_2$,

it defines a size of the change of denser layers with negative charge and rarefied layers with positive charge seen in simulated waves distributions on the left hand side.

If L is constant and a_2 is increasing then the negative layer becomes narrower while the positive one becomes wider.

At a_2=0.99 electron density changes as
$0.5 <= n_e/n_i <=100$
The width of negative layer is about 0.24 (at n_e/n_i =1) and 6×10^{-4} (at n_e/n_i =50).

Uburst observation

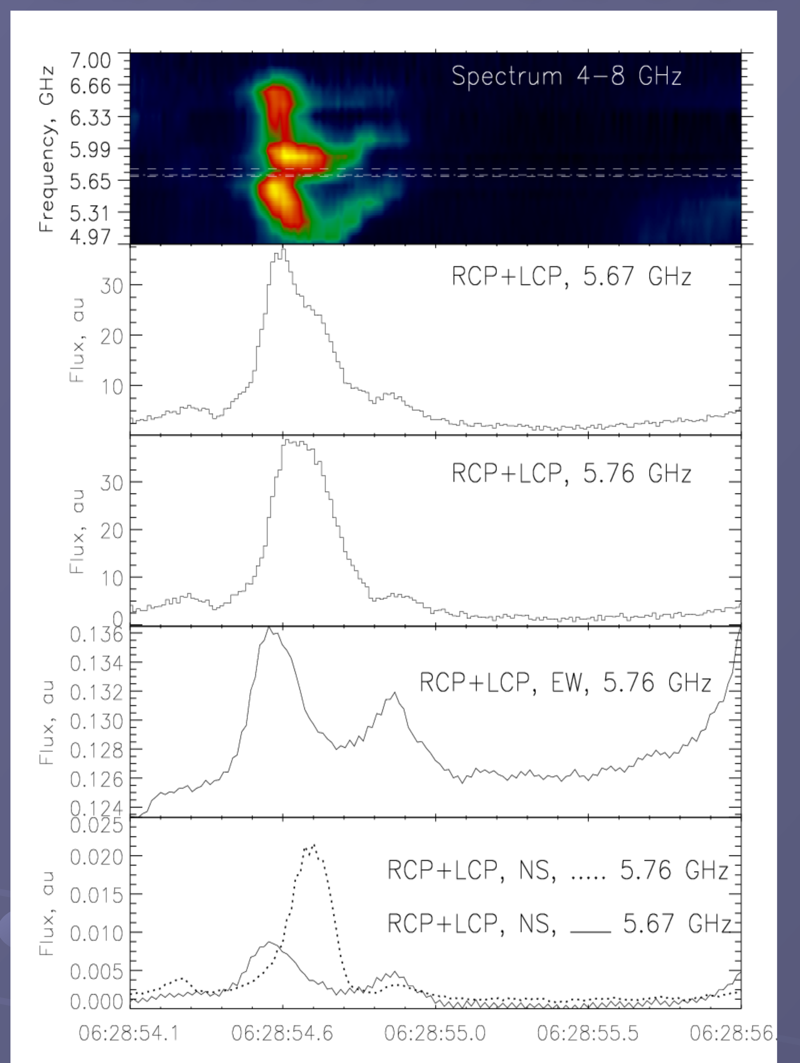


Fig. 5. From the top to the bottom:

- Dynamic spectra of polarimeter in 4-8 GHz.
- Temporal profiles built from the dynamic spectra at 5.7 GHz.
- Temporal profiles in the direction EW, SSRT (5.76 GHz)
- Temporal profiles of zebra pattern in direction NS (5.67 5.76 GHz).
- The bottom band of zebra pattern corresponds to the curve 1 order of NS (5.67 GHz)
- The top zebra band corresponds to the 2 order of NS (5.76 GHz)

The NS interferometer observed the 04 Apr 2011 flare region contemporary in two high-order fringes; thus, two 1D scans were recorded simultaneously within the two frequency intervals (orders) centered at about 5.67 and 5.76 GHz.

Proposed interpretation of the observed zebra patterns and u-burst in the flare

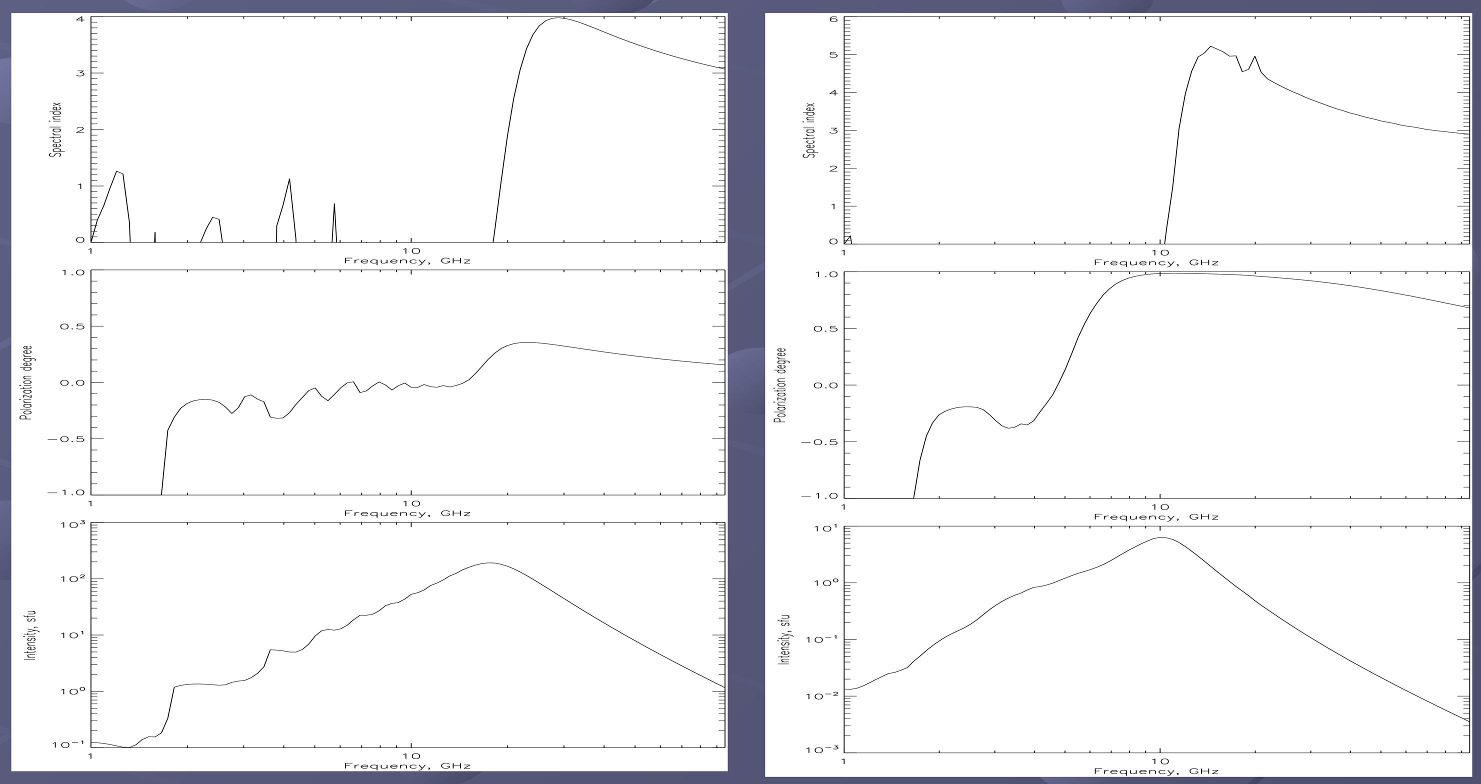


Fig. 7. Simulated MW spectral index (top), MW polarisation (middle) and MW intensity (bottom), viewing angles 110° (left) and 170° (right)

Evaluation of flare and beam parameters

For the ambient plasma density in a flare of 10^{11} cm^{-3}, $T=4.8\times10^7$ K ($V_T=3\times10^9$ cm/s) and B = 50G (close to the model), velocity of electron beam $V^*\approx10^{10}$ cm/s (100 keV) the size of electron condensation caused by pinching is ($7 \cos^{-1}\vartheta<< L <70$) cm.

Increment of these wave generation: $\gamma=(n^*/n_i)(u/V^*)\, \omega_B^2\cos^2\vartheta$.

In flare with these parameters $\gamma>>\nu_{ei}$ (ν_{ei}- frequency of electron-ion collisions).

Let us evaluate the electric field ϕ'_τ in this wave.
Ignoring decay processes energy density of this wave $E_w=(\phi'_\tau)^2_{max}/4\pi$ should not exceed the thermal energy of the ambient plasma W_T.

$$W_T = 2n_ik_BT \approx 10^2\ erg/cm^3; \quad \to \phi'_{\tau\, max} \approx 10^4\ v/cm.$$

Kinetic energy of accelerated electrons $W^* \approx N^*m_eV^{*2}$ is comparable with thermal energy only at densities of $N^* \approx 10^8$ cm^{-3} (initial energy flux $F_0 \approx 10^{11}$ erg/cm²/s).

This can be achieved if $a_2 \approx 0.50$ (N=3). Only radiation with frequencies $\Omega >= \omega_p$ can leave the atmosphere, i.e. the emission at lower frequencies $s\omega_2 < \omega_p$ cannot be emitted. We observe only N=2.

Two possible ways to see zebra patterns in MW emission:

1) Propagation through these patterns of the initial MW emission emitted from flaring atmosphere during generation of Langmuir waves. Although the initial electromagnetic wave with amplitude lower than the potential wave does not affect the original EM wave.
2) Own emission of the plasma ambient plasma modulated by these non-linear waves in electron charge pinching producing from 1 to 200 patterns

Intervals $\Delta\Omega = \omega_2 \approx \omega_B\cos\vartheta$, so that $\Delta\Omega/\Omega$ =1/s. If ω_p/ω_B= 3, we observe harmonics with s>=3. The ratio of components 3 and 4 should be E(3)/E(4)=1:0.7.

U-burts reflect propagation of MW emission htrough negative charge patterns (Altyntsev et al, 2005).

References

Altyntsev et al, 2005, A&A, 431, 1037; Kovalev, 2009, Plasma.Phys., 35, 1; Zharkova and Siversky, 2011, ApJ, 731,33, Zharkova et al, 2015 (in prep).