

INTERPRETATION OF FINE STRUCTURE IN SOLAR NON-THERMAL RADIO EMISSION (ZEBRA-PATTERN AND BROAD-BAND PULSATIONS) AND DIAGNOSTICS OF POST-FLARE CORONAL PLASMA

E. Ya. Zlotnik* and V. V. Zaitsev*

Abstract

Observations of Solar radio bursts accompanying Solar flare yield a valuable information about parameters of plasma in the region of energy release, properties of particles accelerated during a flare, and non-thermal processes in the source of radiation. An example of relatively easy diagnostics of post-flare plasma is a fine structure on dynamical spectra of type IV bursts, namely, zebra-pattern and broad-band quasi-periodic pulsations. In this contribution harmonic bands of zebra-pattern are interpreted as a result of plasma wave generation at the levels of double plasma resonance in trap-like sources (followed by wave transformation into electromagnetic emission escaping from the corona), and broad-band pulsations (breakdown and resumption of generation) are assumed to be due to the process of excitation of magnetic flux tube oscillations. Based on suggested interpretation and combining the observational data on both kinds of fine structure, we retrieve the physical conditions in trap-like sources to find the parameters of particles accelerated during a flare and which provide the observed fine structure in Solar type IV radio bursts.

1 Introduction

We discuss some features of the fine structure of dynamic spectra of Solar meter wave radio bursts originating from trap-like sources in the corona, mainly so-called zebra-structure and quasi-periodic pulsations. Our goal is to show ways to retrieve physical conditions in the sources and parameters of non-thermal particles providing the observed characteristics of radio emission.

A zebra-structure (parallel drifting bands) superimposed on type IV continuum was described rather long ago [see, for example, Elgaroy, 1961; Slottje, 1972a,b; Bernold, 1980] and now is recorded by many spectrographs.

**Institute of Applied Physics, Russian Academy of Sciences, 46 Uljanov St., 603950 Nizhny Novgorod, Russia*

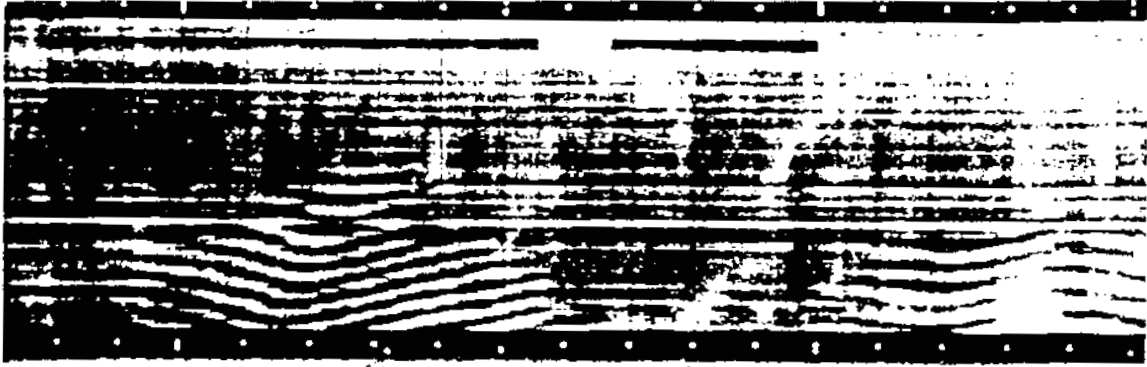


Figure 1: Dynamic spectrum of zebra-pattern and broad-band pulsations [Slottje, 1972b]. Frequency band is $217 \div 253$ MHz. Dots on the time axis mark second intervals.

Figure 1 shows an example of zebra-structure [Slottje, 1972b]. The parallel drifting lanes are often equidistant, but sometimes the distance between lanes increases with the frequency. Often the zebra-pattern is superimposed by broad-band quasi-periodic pulsations of radio emission – enhancements and reductions of brightness with typical period of one or few seconds. Both kinds of fine structure are often observed independently, but their simultaneous recording, as it will be shown below, yields especially valuable information about parameters of the radiation source. An impressive sample of zebra-pattern with numerous parallel drifting lanes (up to 20) and broad-band quasi-periodic pulsations (in the frequency interval 140–300 MHz) was recorded on September 25, 1994, in the Observatory of Solar Radio Astronomy in Tressdorf (Astrophysical Institute Potsdam); it is important that the distance between zebra lanes on that spectra increases with frequency at a fixed moment of time and increases with time as moving towards the end of the event; this will be discussed somewhere else.

2 Interpretation of fine structures

To explain the zebra-pattern structure a few theories were put forward. The most prominent feature of these parallel drifting bands is the presence of numerous radiation bands, and the distance between them is much less than the frequency itself. This fact implies the generation at harmonics of some frequency, most probably the electron gyrofrequency. One of the possible reasons of such spectrum is an excitation of Bernstein modes at the gyrofrequency harmonics in a quasi-homogeneous compact source and then non-linear coalescence of these waves with high-frequency plasma waves into electromagnetic emission [Zheleznyakov and Zlotnik, 1975a,b]. Another version is the kinetic instability of plasma waves in the inhomogeneous flux tube at the levels of so-called double plasma resonance with subsequent transformation into radio emission due to the same non-linear process [Zheleznyakov and Zlotnik, 1975a,b]. Some authors discussed non-linear interaction of whistlers (as a low-frequency partner) and plasma waves [Chernov, 1990a].

As for pulsating structure, there are two possible explanations. The first is MHD-

oscillation of the trap or coronal loop [Zaitsev and Stepanov, 1975; Edwin and Roberts, 1983], when due to a change of the magnetic field, say, at the top of the loop, the mirror ratio also changes, resulting in a change of a number of trapped non-equilibrium particles and correspondingly to periodic change of radio brightness. The second way to explain periodic structure is a non-linear pulsating stage of instability [Trahtengertz, 1968; Zaitsev, 1970] when the dominant part in forming the plasma wave level is played by ion-induced scattering. Under the action of induced scattering the plasma waves go out of the resonance with particles, and are repumped into the nonresonant part of the spectrum with high phase velocities, where they dump because of absorption by hot particles; then the energy density of plasma waves in the resonance region begins to grow and they dump again and so on.

In this contribution we try (based on suggested interpretations of zebra-pattern and quasi-periodic pulsations) to show what information about the physical conditions in sources we can extract from observations of fine structures.

2.1 Zebra-structure

When interpreting zebra-pattern we bear in mind a big number of bands in many events, and by this reason we choose the version of its generation in a non-homogeneous source (Figure 2) in the regions of double plasma resonance at $f_B \ll f_p$ [Zheleznyakov and Zlotnik, 1975b]:

$$f_{uh} = \sqrt{f_B^2 + f_p^2} \approx f_p; \quad f_p = s f_B \quad (1)$$

Here $f_B = eB/2\pi mc$ and $f_p = (e^2 N/\pi m)^{1/2}$ are electron gyrofrequency and plasma frequency, e and m are electron charge and mass, c is the light velocity, N is the electron density, B is the magnetic field strength.

The kinetic instability under such conditions is known to have the lowest threshold relative to the number of hot particles (nonequilibrium over the velocities transverse to magnetic field), which are able to provide the observed brightness temperatures. In the framework of such a scheme the distance between the zebra lanes

$$\Delta f \approx \frac{2f_B L_B}{|L_N - L_B|} \quad (2)$$

is determined not only by the gyrofrequency, that is the magnitude of the magnetic field B , but also by the height scales of the magnetic field L_B and the electron density L_N . Here the factor 2 appears due to the suggestion that the observed radio emission is a result of combinational scattering or non-linear coalescence of two plasma waves. If L_N is much less than L_B , then the distance Δf is equal to twice the electron gyrofrequency,

$$L_N \ll L_B, \quad \Delta f \approx 2f_B, \quad (3)$$

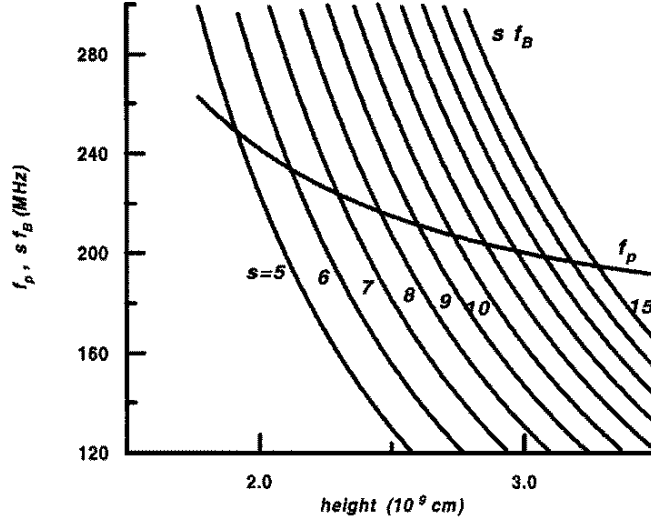


Figure 2: Model of distributed source of zebra-pattern extended along magnetic flux tube: levels of double plasma resonance.

and in this case we can at once find the magnetic field in the source. But if we apply such approach to, for example, a Trensorf spectrum at a frequency of about 200 MHz and Δf about 2 MHz we obtain $s \sim 100$, that is hardly realized. More probable is an inverse case, when the magnetic field changes with height more quickly than the electron density. It is just the case shown in Figure 2. It is important that in the framework of such a model the often observed increase Δf with frequency is easily explained. In this case Δf is less than twice the gyrofrequency,

$$L_N \gg L_B, \quad \Delta f \approx 2f_B \frac{L_B}{L_N}, \quad (4)$$

so we can't directly find the magnetic field, because it depends on one more parameter - the ratio of the magnetic field and the electron density scales. In principle the magnetic field could be found, if the numbers of excited harmonics were known. But they are not determined; so using only the zebra spectrum it is impossible to find the magnetic field.

However, if the zebra-pattern is superimposed by broad-band pulsations, we can get additional information about the magnetic field and the electron density in the source.

2.2 Quasi-periodic broad-band oscillations

It is well-known that Solar radiation in different wavebands contains different oscillations. The measured oscillation periods cover some orders of magnitude ($T \approx 10^{-2} \div 10^3$ s) and are likely to be associated with different physical oscillation mechanisms. The majority of these oscillations have been attributed to global modes of MHD oscillations in coronal

loops: a symmetric (or sausage mode) of global MHD oscillations modulates the cross sections and thus the density of the plasma and the radiating particle number. It is this mode which is usually applied to oscillations in radio emission (other modes (for example, kink mode) are applied to oscillations in UV band with much longer periods). Some other oscillations are due to peculiarities of the non-linear stage of plasma instabilities responsible for quasi-periodic pulsations: this mechanism is associated with shorter (milliseconds) periods [Zaitsev and Zlotnik, 1988].

In type IV we see, most probably, a standing fast MHD mode, and the possibility to explain the presence of both structures with reasonable parameters of the loop and radiating particles confirms such a suggestion.

Investigations of eigen-oscillations of coronal loops have been performed by many authors [see, for example, references in Priest, 1987]. The coronal loop is usually approximated by a symmetrical homogeneously filled cylinder with frozen footpoints. From the resonance conditions one can get free modes of standing MHD waves, where the loop volume oscillates as a whole. The period of symmetric or sausage type or fast standing MHD mode is determined by the cross size of the loop $L_{\perp}$ and the Alfvén velocity V_A :

$$T_{fast} \sim \frac{L_{\perp}}{V_A}, \quad V_A = \frac{B}{\sqrt{4\pi m_i N}} = c \sqrt{\frac{m}{m_i}} \frac{f_B}{f_p} \quad (5)$$

(m_i is proton mass). A typical period of oscillations [according to Slottje, 1972a; Bernold, 1980; and Tremsdorf data] is about one or few seconds. If we accept for a cross size of the loop the typical value $L_{\perp} \sim 10^8$ cm, then

$$\frac{f_p}{f_B} \sim T \cdot \frac{c}{L_{\perp}} \sqrt{\frac{m}{m_i}} \approx 7 \div 10. \quad (6)$$

This estimation is made for a homogeneous plasma cylinder, so to our essentially non-homogeneous flux tube, where the ratio f_p/f_B changes along the loop, this result may be applied rather carefully. Actually such an estimation gives a mean or some effective value, and we may accept that in our sources harmonic numbers are in the interval $5 \div 15$. For $s = 10$ we obtain from the condition $f_p = s f_B$ (at some mean frequency, for instance, $f = 250$ MHz) the gyrofrequency $f_B \approx 25$ MHz and the magnitude of the magnetic field $B \approx 9$ G.

Further, using the data on the distance between the zebra lanes we can estimate a ratio of the magnetic field and the electron density scales along the flux tube. For adopted parameters and $\Delta f \sim 2.5$ MHz we obtain the following value:

$$\frac{L_B}{L_N} \sim 5 \cdot 10^{-2}. \quad (7)$$

If we accept $L_N \sim 10^{10}$ cm, then the magnetic field scale is $L_B \sim 5 \cdot 10^8$ cm, that is reasonably slightly above the cross size of the fluxtube.

2.3 Parameters of hot particles

According to theoretical estimation [Zheleznyakov and Zlotnik, 1975a,b] the best conditions for a kinetic instability at the double plasma resonance are realized if the mean velocities v_e of nonequilibrium electrons (with distribution function of loss-cone or ring type) are of the order $v_e \sim 20 v_T$ (v_T is the thermal velocity). In this case the increment

$$\gamma \sim 2\pi \frac{N_e}{N_0} f_B. \quad (8)$$

Here N_0 and N_e are electron numbers of background and nonequilibrium plasmas, correspondingly. At $N_0 \sim 5 \cdot 10^8 \text{ cm}^{-3}$, $f_B \sim 25 \text{ MHz}$, and effective collisional number $\nu_{eff} \sim 35 \text{ s}^{-1}$ the hot electron number $N_e \sim 300 \text{ cm}^{-3}$ is enough to overcome collisional damping. It is a rather small part of electron density of background plasma ($N_e \sim 10^{-6} N_0$) and it is some orders of magnitude less than the values necessary for the Bernstein mode instability as a source of zebra-pattern. In order to know if this number of nonequilibrium electrons is enough to provide the observed intensity of radio emission, a non-linear problem of forming of steady state level of plasma waves must be solved. This problem has not been considered yet. But the problem of non-linear coalescence of plasma waves with the given energy was investigated, and its solution helps to make some conclusions on the level of plasma waves and hot particle number. In particular, for zebra-pattern recorded by Slottje [1972b] for observed intensity $I_\omega \sim 10^{-7} (\text{erg/s}) \cdot \text{cm}^{-2} \cdot \text{Hz}^{-1}$ we can estimate required plasma wave spectral energy density $W_{k_{pl}} \sim 10^{-4} \text{ erg}$ (k_{pl} is the wave number of the plasma wave).

Comparison of the energy density of electrons generating plasma waves in the double plasma resonance regions

$$N_e \frac{mv_e^2}{2} \approx 4 \cdot 10^{-6} \text{ erg/cm}^3, \quad (9)$$

where the threshold density $N_e \sim 300 \text{ cm}^{-3}$, with the total energy density of these waves in the interval $(\Delta k_{pl})^3$

$$W_{pl} \sim W_{k_{pl}} (\Delta k_{pl})^3 \sim 2 \cdot 10^{-7} \text{ erg/cm}^3, \quad (10)$$

shows that here only a small part of the energy of nonequilibrium particles must be given to plasma waves. This is an additional argument in favor of reality of such scheme of zebra-pattern origin.

3 Conclusion

Thus, from rather rough theoretical approximation we can estimate some physical parameters of the source. It is important that we considered two simultaneously recorded kinds

of fine structures: zebra-pattern and broad-band oscillations. It is this fact which permitted us to find the magnetic field and the height scales of the electron density and the magnetic field. It should be noted that any additional information about the fine structure features is very useful in selecting the proper mechanism responsible for observed radiation and in retrieving the physical conditions in the radiation source. For example, if the data on zebra lane polarization had been available, we would have been able to determine which mechanism of non-linear transformation of plasma waves – scattering on ions (coalescence with low frequency waves) or combinational scattering (coalescence of two high frequency plasma waves) – is predominant, and it would have answered the question, which harmonic of the plasma frequency (fundamental or the second harmonic) is observed, that, in its turn would have given a more exact measurement of the magnetic field. It goes without saying that at present using the digital spectrographs with a high frequency and time resolution gives us a chance to look deeper into the sources of non-thermal radiation containing fine structures of frequency spectra.

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References

- Bernold, T., A catalogue of fine structure in type IV Solar radio bursts, *Astro.Astrophys.Suppl.Ser.*, **42**, 43–58, 1980.
- Chernov, G. P., Whistlers in the Solar corona and their relevance to fine structures of type IV radio emission, *Solar Phys.*, **130**, 75–82, 1990a.
- Edwin, P. M., and B. Roberts, Wave propagation in a magnetic cylinder, *Solar Phys.*, **88**, 179–191, 1983.
- Elgaroy, O., Studies in high-resolution spectrometry of Solar radio emission, *Astrophys. Norvegica*, **7**, 123–261, 1961.
- Priest, E. R., Solar Magnetohydrodynamics, Reidel Publ. Co., Dordrecht, 1987.
- Slottje, C., Peculiar absorption and emission microstructures in the type IV Solar outburst of March 2, 1970, *Solar Phys.*, **25**, 210–221, 1972a.
- Slottje, C., Zebra-pattern in type IV radio bursts, *Proc. of the 2nd Meeting of the CESRA*, Ed. A. Abrami, 88–93, Triest, 1972b.
- Trahtengertz, V. Yu., About possible origin of aurorae fine structure, *Geomagnetism and Aeron.*, **8**, 966–972, 1968.
- Zaitsev, V. V., On stabilization of beam instability, *Izv. VUZ - Radiofizika*, **13**, 837–843, 1970.
- Zaitsev, V. V., and A. V. Stepanov, On the origin of pulsations in type IV Solar radio bursts: oscillations of plasma cylinder, in *Issledov. on Geomagnetism, Aeronomy and Solar Physics*, **37**, 3–10, 1975.

- Zaitsev, V. V., and E. Ya. Zlotnik, On the origin of S -trains in the Solar radio spectra, in: *Solar Maximum Analysis, Add. Issue (Proc. Int. Workshop SMM, June 1985)*, edited by V. E. Stepanov et al., 346–350, Novosibirsk, Nauka, 1988.
- Zheleznyakov, V. V., and E. Ya. Zlotnik, Cyclotron wave instability in the corona and origin of Solar radio emission with fine structure, Bernstein modes and plasma waves in a hybrid band, *Solar Physics*, **43**, 431–451, 1975a.
- Zheleznyakov, V. V., and E. Ya. Zlotnik, Origin of zebra-pattern, *Solar Physics*, **44**, 461–470, 1975b.