ISSN 1845–8319

ORIGIN OF ZEBRA PATTERN IN TYPE IV SOLAR RADIO EMISSION

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Abstract. Strong and weak aspects of different theories of fine structure on solar radio emission dynamic spectra observed as several or numerous quasi-equidistant bands of enhanced and reduced radiation (zebra pattern) are discussed. Most of the works which propose zebra pattern interpretation are based on the plasma mechanism of radio emission generation, which consists of excitation of plasma (electrostatic) waves and their subsequent transformation into electromagnetic emission. Plasma waves arise due to kinetic or hydrodynamic instability at the upper hybrid frequencies at the levels of double plasma resonance in a distributed source. Some works are devoted to considering whistlers as the main reason for stripes in emission and absorption occurring in the dynamic spectra. An alternative theory of zebra pattern origin suggests that of a compact source with trapped plasma waves is present in the corona. Another interpretation is based on special effects that may occur when radio waves propagate through some periodic structure in the corona.

All suggested mechanisms are analyzed with relation to their capability to give the best fit for the observed fine structure features in the framework of the source model with reasonable physical parameters. It is shown that the theory based on the effect of double plasma resonance in a nonhomogeneous coronal loop is the best-developed theory for the origin of zebra pattern at the meter-decimeter wavelengths at the present time.

Key words: solar corona - radio emission - zebra pattern

1. Introduction

Zebra pattern (ZP) is one of the most interesting spectral structures in solar radio emission. It has been recording for more than 40 years by many spectrographs throughout the world at meter, decimeter and (recently) centimeter wavelengths. Despite the fact that the observed properties of ZP are known rather well (see, for example, Elgaroy, 1961, Slottje, 1972, Chernov et

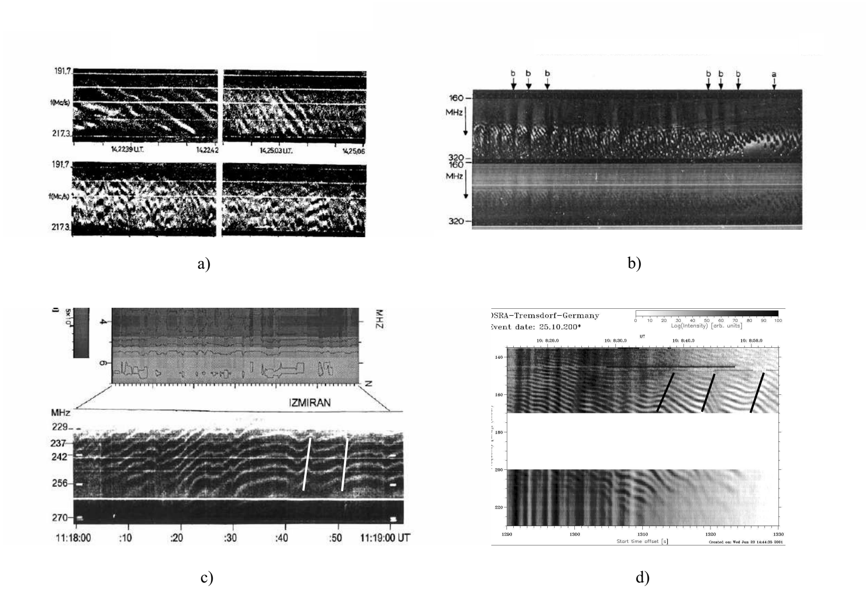

Figure 1: Samples of ZP dynamic spectra: a) Elgaroy, 1961, b) Slottje, 1972, c) Chernov et al., 1999, d) Aurass et al., 2003

al.,1999, Aurass et al., 2003) and the first interpretations of this structure occurred rather long ago (Rosenberg,1972, Chiuderi et al., 1973, Zheleznyakov and Zlotnik, 1975 a,b, Kuijpers, 1975, Fedorenko, 1975) debates on its origin have not calmed down until now. The goal of this review is to compare different mechanisms and source models suggested for ZP origin and to find out which mechanism and model give the best fit for the observed features.

What should a theory explain?

Fig.1 shows typical dynamic spectra of Type IV solar radio emission with ZP [1].

Usually, ZP appears at the post burst stage of a flare. The most distinctive feature of a spectrum is the presence of numerous parallel drifting bands of enhanced emission and absorption in the dynamic spectra superimposed on type IV continuum. It is exactly a feature that should be explained by a

[1]This review does not contemplate to survey totality of ZP observations in the literature. A detailed description of observation data can be found in the paper by Chernov, 2006. We highlight and analyze only the main ZP features to be explained by a theory.

theory first of all. A radiation mechanism and a source model should result in a quasi-harmonic structure of the spectrum with frequency spacing much less than the radiation frequency itself (the stripes are almost equidistant, or the distance between them slightly changes with time and frequency), as well as a parallel frequency drift of stripes and a relatively long lifetime (minutes or hours). Besides, when different theories are compared, we should take into account to what extent the parameters of radiating particles are reasonable and the required physical conditions in the coronal source are realizable.

Below all the theories suggested in the literature to explain the ZP origin are divided into three main groups.

The first and the biggest group presents the mechanisms and the source models providing the formation of a striped spectrum in the radiation source itself due to excitation of longitudinal plasma (electrostatic) waves by non-thermal electrons.

The second group is based on the analysis of low-frequency whistler (transverse electromagnetic) waves which are also generated by non-equilibrium electrons in the coronal traps.

The third group explains the ZP origin as a result of radio wave propagation through some medium with periodically changing parameters. As a consequence of diffraction, the quasi-equidistant stripes of enhanced and lowered emission can appear in the dynamic spectrum instead of the initial smoothed continuum spectrum.

2. Theories based on plasma wave generation

The fine structure of frequency spectrum together with a high brightness temperature implies a coherent radiation mechanism of radio emission. Moreover, the long lifetime of type IV radio emission with ZP signifies that the enhanced radiation (if the harmonic structure is created in the source itself) is provided by electrons having a non-equilibrium distribution over velocities perpendicular to the magnetic field (trapped electrons, so-called ring-type or loss-cone distributions). This differentiates the type IV radiation with fine structure from short-time type III bursts and other fast drifting bursts which are associated with electron beams propagating through the corona along magnetic field lines. Since the longitudinal plasma waves cannot escape from the solar corona because of their strong Landau damping in the rarefied layers on the propagation path, a theory of ZP origin based on plasma wave instability should include the mechanism of plasma wave conversion into electromagnetic radiation leaving the coronal plasma without restraint.

2.1. Bernstein modes

At first glance, the radiation occurs at harmonics of some basic frequency, and the first works devoted to ZP origin (Rosenberg,1972, Chiuderi et al., 1973) developed just this point of view. This basic frequency can hardly be the plasma frequency $\omega_p = (4\pi e^2 N_0/m)^{1/2}$ (where N_0 is the electron number density of the background plasma, and e and m are electron charge and mass, respectively), because the observed frequency spacing $\Delta\omega \simeq 2\pi(2 \div 15)$ MHz matches the electron density $N_0 \simeq (5 \cdot 10^4 \div 3 \cdot 10^6)$ cm^{-3} which is too low for the source of metric and decimetric radiation in the corona. The most probable candidate is the electron gyrofrequency $\omega_B = eB/mc$, where B is the magnetic field and c is the velocity of light. The theory put forward by Rosenberg and co-authors in the seventies, suggested the following scheme of ZP origin. The electrons with non-equilibrium distribution over velocities perpendicular to the magnetic field, are located in a small source where the plasma is weakly magnetized ($\omega_p \gg \omega_B$) and the magnetic field is uniform ($B = const$). These electrons excite longitudinal electrostatic waves at frequencies multiple to electron gyrofrequency, the so-called Bernstein modes (BM) at the frequencies $\omega = s\omega_B$ (s is a harmonic number), and plasma waves at the upper hybrid frequency $\omega_{UH} = (\omega_p^2 + \omega_B^2)^{1/2} \approx \omega_p$. The radio emission recorded is a result of nonlinear coalescence of these waves into electromagnetic emission. The resulting radiation at the summarized frequency

$$\omega = \omega_p + s\omega_B \tag{1}$$

defines the striped form of the spectrum, and the frequency spacing is just the electron gyrofrequency $\Delta\omega = \omega_B$, which is much less than the summarized frequency. Note that in principle it is a direct way to measure magnetic field in the solar corona.

The theory of BM kinetic instability was developed later by Zheleznyakov and Zlotnik, 1975a,b, Fedorenko, 1975, Kuznetsov, 2005. The calculations of frequency dependence of BM growth rates showed that excitation occurs in relatively narrow (compared to gyrofrequency) frequency band, and the maximum increment reaches

$$\gamma_{max}^{BM} \sim 10^{-2} \frac{N_e}{N_0} \omega_B, \tag{2}$$

where N_e is the electron number density of non-equilibrium electrons. Nonlinear coupling of BM and upper hybrid waves, as well as BM with unequal harmonic numbers were investigated by Zlotnik,1976, Mollwo and Zauer,1977, Willes and Robinson,1996, Willes, 1999, Altyntsev, Kuznetsov et al., 2005, Kuznetsov,2005. It follows from estimations given in the above papers that the observed intensity of radio emission in zebra stripes may be reached for reasonable parameters of the background plasma and hot particles.

Thus, the proposed model and mechanism explain quite well the main peculiarities of ZP and can, in principle, be realized under the coronal conditions. The model provides the main ZP feature - separated stripes. It easily explains the synchronous change in frequency in different stripes, since all the stripes are generated in the same source. Moreover, taking into account the relativistic dependence of electron mass and gyrofrequency on velocity allowed Zheleznyakov and Zlotnik, 1975b to give a possible explanation of some exotic kind of ZP - the so-called tadpoles described first by Slottje, 1972 and recorded later by other observers, for example, Magdalenić et al., 2006. No other mechanism explains the bizarre dynamic spectrum of tadpoles so far.

However, the considered scheme of ZP origin may be applied only to a few events. First of all, due to the frequency dependence of BM increment, dispersion properties of BM and peculiarities of BM transformation into electromagnetic radiation, the mechanism under discussion is able to provide only a few (less than 10) harmonics in the resulting spectrum, which means that it cannot be responsible for many events with 20 or more stripes at the decimeter-meter wavelengths. Furthermore, the distance between harmonics is strictly equal to the electron gyrofrequency $\omega_B/2\pi$, i.e., must be equal for all stripes, and it does not fit many observed events where the frequency spacing slightly, but regularly changes with the frequency and the time. The essential disadvantage of this model is the requirement of a uniform magnetic field and, therefore, small size of the source. This results in a necessarily high number density of non-equilibrium electrons in the source.

As for the magnetic field value derived from frequency spacing measurements, the method gives quite reasonable magnitudes for some ZP events. For example, the spectrum recorded by Slottje, 1972 (fig.1b) with $\Delta f \simeq 15$ MHz gives the magnetic field value $B \sim 5$ G in the frequency interval 240 - 320 MHz, which looks quite reasonable. Also, the frequency spacing $\Delta f \simeq 150$ MHz for ZP spectrum recorded in the microwave frequency range 5200 - 6000 MHz (Altyntsev et al., 2005) defines the magnetic field value $B \sim 50$ G, which is acceptable for high frequency sources located in the lower corona (see also Ledenev et al., 2001). However, for many other cases, e.g., for the event recorded by Tremsdorf spectrograph (fig.1d), the frequency spacing 2 MHz corresponds to unreally small values of the magnetic field $B < 1$ G, so the ZP in this, as well in many other cases, cannot be associated with the BM generation. The recent work by Kuznetsov, 2005 shows that the model based on BM can be responsible for ZP at microwaves rather than at the meter or decimeter wavelengths.

2.2. Double plasma resonance effect

An alternative theory of ZP origin is based on the effect of double plasma resonance (DPR) (Pearlstein et al., 1966) in the inhomogeneous flux tube. The idea was put forward and developed by Zheleznyakov and Zlotnik, 1975a,c, and Kuijpers, 1975a and followed later, for example, by Berney and Benz, 1978, Kuijpers, 1980, Winglee and Dulk, 1986, Zlotnik et al., 2003, Yasnov and Karlicky, 2004, Kuznetsov and Tsap, 2007. In the framework of this theory, the enhanced excitation of plasma waves occurs at some levels where the upper hybrid frequency $\omega_{uh} \approx \omega_p$ coincides with the harmonics of the electron gyrofrequency ω_B (fig.2):

$$\omega_{uh} = s\,\omega_B. \tag{3}$$

It is important that in this case the various ZP stripes are excited in distinct regions of a magnetic trap (coronal loop), and the distance between stripes is determined not only by the electron gyrofrequency, but also by the height scales of the magnetic field $L_B = \omega_B\,(d\omega_B/dh)^{-1}$ and the electron number density $L_N = \omega_p\,(d\omega_p/dh)^{-1}$ (see Zheleznyakov and Zlotnik, 1975):

$$\Delta\omega/\omega_B \approx L_B/|L_N - L_B| \approx L_B/L_N. \tag{4}$$

The latter equality is valid if the magnetic field changes with the height faster than the electron number density ($L_B \ll L_N$). In this case, the

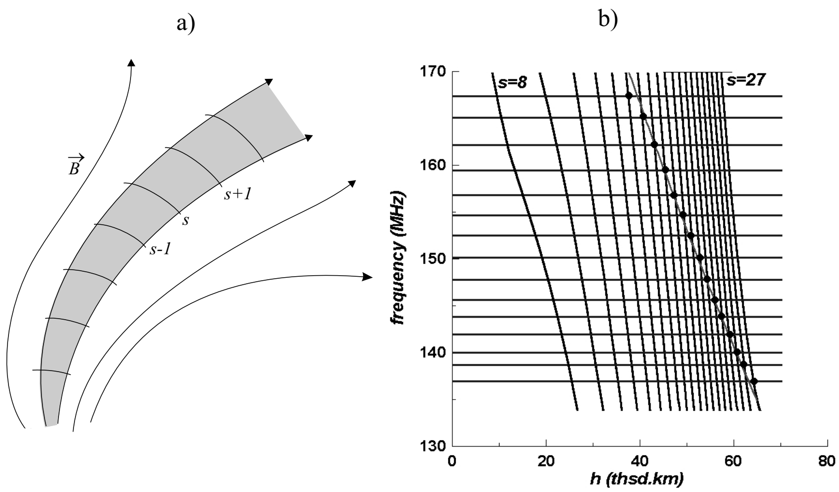

Figure 2: DPR levels in the coronal trap: a) model of the source, b) peak frequencies of the ZP stripes (horizontal lines) and the gyrofrequency harmonics $s\omega_B$ versus the height for the spectrum in Fig.1d; intersections represent the DPR levels, and the line connecting them is the electron number density versus the height.

distance between stripes can be appreciably less than the gyrofrequency ω_B, which eliminates the contradiction with an unrealistically weak magnetic field implied by the point-source BM model. Moreover, in this model, the distance between stripes can change with frequency, which also fits many of the observed cases.

At first, two kinds of DPR instability were considered for ZP interpretation: kinetic instability (Zheleznyakov and Zlotnik, 1975a,c) and hydrodynamic one (Kuijpers, 1975a). However, the hydrodynamic approximation is valid only for sufficiently narrow distributions of hot electrons over velocities. This imposes certain restrictions on the electron number density. Estimations show that even for the most privileged parameters of the source, the electron number density must be incredibly high (see Zheleznyakov and Zlotnik, 1975c, Kuijpers, 1980): $N_e \gg (0.05 \div 0.1 N_0)$.

Calculations show (Zheleznyakov and Zlotnik, 1975 a,c, Winglee and Dulk, 1986, Zlotnik et al., 2003, Kuznetsov and Tsap, 2007) that the maximum value of the kinetic instability increment under DPR conditions is

$$\gamma_{max}^{DPR} \sim \frac{N_e}{N_0}\,\omega_B, \tag{5}$$

which essentially exceeds the BM increment (2). This means that the DPR mechanism imposes quite weak requirements on the non-equilibrium electron number density N_e. Estimates show that at the frequencies $f \sim 100 \div 200$ MHz the condition $N_e > 10^{-6} N_0$ is enough to overcome the collisional damping in the background plasma (with the temperature $T \sim 10^6$ K) and provide enhanced radiation at the frequencies (3). In this case, the bandwidth of the emission "lines" is much less than the gyrofrequency and the distance between the "lines" which give rise to a spectrum with resolved stripes.

Since the DPR levels are certainly present in a non-uniform trap and the instability is excited by a sufficiently small quantity of trapped hot electrons, the DPR mechanism explains, in an easy and natural way, the existence of a fairly large number of stripes in the ZP spectra. Moreover, the frequency spacing, their frequency drift, the change of stripe frequencies, and the value of the magnetic field are in good agreement with other observation data. It is important that the system of DPR levels responsible for a striped spectrum is maintained by the background coronal plasma, not by the parameters of non-equilibrium particles, so it can be preserved or slightly vary for a comparatively long time. This explains the existence of ZP for minutes and hours. Besides, in this model, the source is distributed over the whole trap, which markedly reduces constraints on the non-equilibrium electron number density ensuring the observed intensity of ZP stripes.

Moreover, detailed analysis of the event on 25.10.1994, the spectrum of which is shown in Fig.1d, gives observation evidence for ZP generation at the DPR levels (Aurass et.al., 2003, Zlotnik et al., 2003). For the active region AR 7792, in which, according to the heliographic observations, the ZP source was located, the distribution of the magnetic field over the height was reconstructed using the data of optical measurements at the photospheric level. This made it possible to plot the dependence of the gyrofrequency harmonics $s\omega_B$ on the height shown in Fig.2b. The horizontal lines corresponding to the frequency of ZP stripes in Fig.1d at a fixed instant define the heights of the DPR levels, and the line connecting the points of intersection represents an electron number density distribution over the height in the trap. This distribution coincides surprisingly well with the barometric law $N \sim \exp\left(-2h/10^4 T\right)$ with a quite reasonable kinetic temperature $T = 1.2 \cdot 10^6$ K. It should be emphasized that the density dependence on the height was obtained using two independent sets of data, namely, the peak frequencies of ZP stripes and the extrapolated magnetic field lines. Thus, the coincidence of the obtained law with the most probable (from the physical point of view) density distribution over the height can in no case be considered an aleatory occasion: it is enough to mention, for example, the coincidence of the unequal frequency spacing with the observed ones. Therefore, it undoubtedly confirms the DPR model of ZP origin in the event shown in Fig.1d.

Note that critical remarks by Chernov, 2006 concerning the barometric density distribution and the height magnetic field distribution deduced by Zlotnik et al., 2003 from observation data (as well as other comments) are due to a misunderstanding. The fact that the observed spectrum cannot be explained by other height distributions of the magnetic field and electron number density is not an argument against the DPR origin: the magnetic field was reconstructed just for the active region AR 7792, and there was no need to assume the dipole or some other model. The same concerns the electron density distribution: the barometric law was derived from observation data rather than from a model, and it makes no sense to argue which model is better for this case.

The ability of the DPR mechanism to explain the vast majority of the observed ZP spectra in the meter-decimeter wavelength band is challenged by some authors.

One of the most widespread critical remarks is that the magnetic field value implied by the DPR mechanism is allegedly too small for the actual coronal conditions (LaBelle et al., 2003, Chernov, 2006 and references therein). This wrong argument is based on the assumption that the frequency distance between the ZP stripes is equal to the electron gyrofrequency ω_B. It is right in the case when the ZP originates from Bernstein modes, where indeed, this scheme can be responsible only for the ZP origin with a fairly large frequency spacing. As far as the DPR model is concerned, the frequency spacing is determined not only by ω_B, but also by the height gradients of magnetic field and electron number density (see Eq.(4)), and estimations of magnetic field according to this relation result in quite reasonable values of the magnetic field in coronal loops.

Among the shortcomings discussed in the literature (LaBelle et al., 2003, Chernov, 2006) concerning the DPR mechanism its incapability of explaining the synchronous changes of frequencies in different zebra stripes is mentioned, since these stripes are generated in spatially separated sources (see Fig.2a). However, careful study of the dynamic spectra shows that very often the change in the stripe frequencies only seems to be simultaneous, while actually, the stripes appear with some time lag (see dynamic spectra in Fig.1c,d and straight lines revealing the negative frequency drift of identical features). This means that in the coronal loop acting as a whole, some collective processes take place, and the time delay towards the lower frequencies is determined by the velocity of a signal propagating along the loop. At the same time, the DPR model certainly cannot be responsible for the cases where truly simultaneous changes in the stripe frequencies are recorded (as in the case described by Altyntsev et al., 2005 for one microwave ZP spectrum).

One more weakness of the DPR theory pointed out by some authors (Chernov, 2006 and references therein) is associated with the kind of the distribution function of electrons that are non-equilibrium over velocities perpendicular to the magnetic field and possible overlapping of ZP stripes. Indeed, the results of the DPR theory given above are performed for the so-called ring or DGH - distribution (Dory et.al, 1965), for which the mean electron velocity is equal to zero. From the works by Winglee and Dulk, 1986, Yasnov and Karlicky, 2004, Kuznetsov and Tsap, 2007 it follows that in the case of a more real loss-cone distribution of non-equilibrium electrons, the intervals of enhanced radiation can be overlapped, and the loss-cone distribution function should satisfy some hard requirements in order to provide the resolved stripes in the spectrum. However, numerical calculations in the above papers are based on an incorrect consideration of the dispersion properties of plasma waves propagating across the magnetic field at the DPR frequencies (see Zlotnik and Sher, 2009 for details). Use of exact dispersion relations shows that the constraints on the loss-cone distribution function are not significant, and the resolved ZP stripes are realized for a wide class of trapped electron distributions.

Of course, the DPR theory of ZP origin is far from perfection. A further development requires investigation of the nonlinear stage of instability, including the steady-state level of plasma waves, analysis of transformation of plasma waves into electromagnetic ones, solution of the problem of radiation escape from the corona with a persisting striped spectrum, study and explanation of the polarization of ZP stripes, and consideration of the fine structure in ZP (time behavior). This will enrich our knowledge of the physical processes occurring in the coronal traps, but so far the vast majority of the ZP spectra recorded the meter-decimeter wavelengths are in agreement with the DPR mechanism of radiation.

2.3. Trapped plasma waves

One of quite different mechanisms of ZP origin put forward by LaBelle et al., 2003 uses a similarity of ZP with some spectral features observed in the Earth's magnetosphere. It is based on the effect of the plasma wave trapping in confined plasma density enhancement that provides a discrete spectrum. The authors assume that plasma waves are excited in a small source due to the DPR effect at the second harmonic of electron gyrofrequency $\omega_p = 2\omega_B$.

This mechanism easily explains the main ZP feature - harmonic structure. Besides, it provides the stripe synchronism because the sources of all the stripes are concentrated at the same place. However, adaptability of this model to ZP under the coronal conditions gives rise to doubts.

First, according to the authors' estimations, in order to obtain the observed frequency spacing $\Delta\omega/\omega \sim 1\%$, the size of the region where the electron number density is enhanced (that is the plasma wave trap) must be of meter scale, i.e., much less than the electron free path, which is about a few hundred kilometers. Obviously, the density inhomogeneity of such a scale can hardly exist in the corona for a long time comparable with the ZP lifetime, which is of the order of minutes or hours (cf the electron-ion collisional frequency $\nu_{ei} \sim 10 \div 30\ s^{-1}$). Note that all the consideration is not valid in the meter wavelength band, where the wavelength is of the order of the plasma inhomogeneity (see also Chernov, 2006).

Next, the required relative enhancement of the electron number density given by the authors as $\delta = \Delta N_0/N_0 \sim 20\%$ looks unrealistically high because even in ion-sound solitons which are rated among the most intensive disturbances in the coronal plasma, the density fluctuations are no more than 1%. Moreover, the expected number of stripes is estimated as $m \sim 100$, but under the assumption of density fluctuations $\delta \sim 100\%$. For acceptable values $\delta \sim 1\%$ the number of stripes $m \propto \sqrt{\delta}$ does not exceed $m \simeq 10$. The reasonable value of δ imposes a constraint on a possible frequency interval of ZP observation (see also Chen and Yan, 2007). According to LaBelle et al., 2003, the trapped wave band is $\omega_p^2 + \omega_B^2 < \omega < \omega_p^2(1+\delta) + \omega_B^2$. If ω_2 and ω_1 are the upper and lower spectrum boundaries, then $\omega_2^2 - \omega_1^2 = \delta\omega_p^2$. For frequency boundaries $\omega_1 = 140$ MHz and $\omega_2 = 240$ MHz of the ZP spectrum on 25.10.1994 event given in Fig.1d, the value of δ appears to be incredibly high: $\delta \sim 200\%$. This means that such a mechanism cannot be responsible for broadband ZP spectra.

Another demerit of the mechanism under discussion is the required density number of hot electrons required for provision of the observed ZP intensity. Estimates show that if the ZP is generated in a single trap with the size 1 - 10 m and even if the density of the hot electrons is comparable with the density of the background plasma $N_e \sim N_0$ (that is absolutely impossible), the expected power is many orders of magnitude lower than the observed one. The authors claim that many sources create such a spectrum, their number must be 10^8 and all these 10^8 identical traps must be located at the same height (in order to provide the same frequency stripes) and act coherently. Obviously, such a scheme is not realizable under the coronal conditions.

3. Theory based on whistler generation

The next group of works offering ZP interpretation deals with excitation of low frequency electromagnetic waves, the so-called whistlers, in the solar corona. The generation, propagation and coupling of whistlers with high frequency Langmuir waves was considered for the first time by Kuijpers, 1975b in order to explain the intermediate drift (fiber) bursts. It was assumed that the whistlers (w) and longitudinal plasma waves (l) are excited by electrons with loss-cone distribution over the velocities, and the received radio emission is a result of their non-linear coalescence : $l+w \rightarrow t,\ \ \omega = \omega_p + \omega_w$. The result of such a coupling can be a structure having an instantaneous frequency profile consisting of a depression relative to the ambient continuum on the low frequency side and an enhancement shifted toward the higher frequencies over a distance equal to the whistler frequency ω_w.

The same scheme has been considered as a source of ZP in the numerous papers by Chernov since 1976 up to now (see also Fomichev and Fainstein, 1981, 1988), and the results are summarized in the review Chernov, 2006 . Whistlers look attractive for ZP theory because their frequency $\omega \sim (0.1 \div 0.5)\omega_B$ can easily be conformed with the frequency spacing in the observed ZP spectra. However, the existence of a system of quasi-harmonic stripes is not explainable by whistlers. Indeed, the isolated narrow band fiber burst can appear only in the case where the whistler wave packet extends over the part of the source in which the plasma waves of one frequency are present. Otherwise, coalescence of quasi-monochromatic whistlers with a continuum of plasma waves does not lead to narrow-band features in the resulting spectrum of electromagnetic radiation. In order to obtain a system of resolved ZP stripes, one should assume that whistlers exist at some quasi-discrete levels in the source which are separated from each other by height intervals providing just equal frequency intervals in the dynamic spectrum. Unlike the scheme based on the existence of DPR levels which are due to the loop geometry and do exist in the source with different height gradients of the electron number density and magnetic field, the excitation of whistlers at specially selected heights does not look feasible.

Chernov,2006 (see also the references therein) speculates that the quasi-linear processes accompanying the whistler excitation in a trap and the peculiarities of their propagation along the ducts cause stratification of the trap into layers of enhanced whistler energy and layers of their absorption.

He uses the fact that the quasi-linear interaction of the waves and particles causes distraction of the loss-cone distribution function, quenching of the instability and stopping of the generation. If a permanent source of the hot particle injection exists in the trap, then the distribution function restores after a time, generation is reestablished, and so on. This can lead to a time-periodic excitation of whistlers (Bespalov and Trakhtenherz, 1986).

Such a time-periodic regime is transformed by Chernov into a space distribution of whistlers by assuming that the entire trap is divided into the layers of whistler amplification and absorption. The length of amplification is taken by him as the distance $l^w = \Lambda(c\omega_B/\omega_p^2)(N_0/N_e)$ (where Λ is the Coulomb logarithm) given by Breizman, 1987 for the relaxation path of a relativistic beam which is injected into the trap and excites whistlers. [2] The length of absorption layer is taken as $\Delta l_B = T_c v_{gr}^w$, where $T_c = l_B/2v_e$ is the minimum life time of electrons with velocity v_e in a trap of length l_B, and v_{gr}^w is the group velocity of whistlers. Both distances, according to estimates by Chernov, are less than the trap size, so the trap consists of a number of such intermittent layers, and the whistlers excited in different parts of the trap coalesce with the plasma waves at the corresponding local plasma frequencies, thus allegedly providing the striped structure of the spectrum.

However, the periodic regime of the loss-cone instability considered by Bespalov and Trakhtenhertz, 1986 covers the processes averaged over many passages of an electron and a whistler throughout the trap, that is the oscillation period essentially exceeds both the time of the electron passage T_c and the time of the whistler propagation along the trap $T_w = l_B/v_{gr}^w$. Obviously, in this problem, the distance which is covered by a whistler for one oscillation period is much greater than the trap size, contrary to estimations by Chernov, according to which $l_w \sim \Delta l_B \sim 10^8$ cm$\ll l_B \sim 10^9$ cm. This means that the conclusion on the trap stratification made by Chernov, 2006 with reference to the periodic regime of quasi-linear interaction of whistlers and the loss-cone distributed electrons analyzed by Bespalov and Trakhtenhertz, 1986 is no more than an unwarrantable assumption. Such a statement requires the solution of a complicated nonlinear problem of excitation and propagation of whistlers in a *non-uniform* trap and adjustment of a plenty of parameters. This problem has not been posed or studied so far.

[2] We emphasize that the distance l_w, given by Breizman, 1987 defines the relaxation path of *a relativistic beam*, i.e., bears no relation to the problem of whistler generation by electrons with *the loss-cone distribution*.

Thus, the theory based on the foundational role of whistlers in the ZP origin cannot be considered proved. At the same time, it is not excluded that whistlers are important as a low-frequency component in non-linear interaction with Langmuir waves in the models comprising plasma mechanisms of ZP origin. However, in this case, the striped structure of the spectrum is determined by specific features of the plasma-wave generation mechanism rather than the whistlers.

4. Theories based on the effect of wave propagation through a periodic structure

The next group of works is devoted to explaining the ZP not by the specific generation of emission in the source itself, but by some effects occurring while a wave propagates in the corona. The presence of enhanced radiation with a smoothed spectrum is initially postulated, and then the conditions under which the continuum is transformed into a striped spectrum are looked for.

For example, Ledenev et al., 2006 suppose that the ZP at meter and decimeters wavelengths can be formed as an interference of direct and reflected rays from a small source imbedded in a stratified plasma where the refractive index n depends on the coordinate z along the density gradient as $n^2(z) = 1 - z/L$. Electromagnetic field from the point source located at z_0 consisting of the sum of direct and reflected rays is proportional in the far-field region to $cos\left[(2\omega L/3c)\left(cos^2\theta - z_0/L\right)^{3/2} - \pi/4\right]$, where θ is the angle between the density gradient direction and the line of sight. For the chosen constant z_0 and θ, the authors get the *cos*-"spectrum" with minima and maxima of radiation and claim that it can be qualified as the ZP spectrum. The observed flux of radio emission, according to their concept, is explained by the total fluxes from a great number of such sources. However, it is completely obvious that the sources located at different z_0 give maxima and minima at different frequencies, and the total spectrum of radiation from all the sources filling the non-uniform layer is a smoothed one, no matter the angle θ between the direction z and the line of sight. Thus, the speculation of the authors about a lot (10^6) of "discrete sources corresponding to local density minima with captured Langmuir waves" which are embedded in the non-uniform plasma layer and give just the same interference picture between the direct and reflected rays is not to be noted as a serious mechanism of ZP origin.

Other works from this series consider propagation of the emission with continuum spectrum through some periodic structure that can occur on the propagation path (Barta and Karlický, 2006, Laptuhov and Chernov, 2006). Inspired by the effect that a periodic structure of the crystals of solids has on propagation of the X-ray radiation, Barta and Karlický, 2006 study the interaction of regular structures, such as various kinds of waves in the corona with propagating radio waves, using the well-developed methods of wave optics. They consider both propagation through a single density well and the reflection on the structure in the form of a series of 50 density wells with the final density drop. It follows from their analysis that such a structure can efficiently filter the propagating radio emission forming the frequency windows of transparency and opacity, thus giving rise to a striped spectrum. The modulation of transmission and reflection coefficients that can be conformed with the observed ZP parameters is achieved for periodic structures with a typical size of the order of a few meters and density modulation depth of the order of 10-20%.

Almost the same interpretation of ZP is discussed by Laptuhov and Chernov, 2006 who analyze propagation of an electromagnetic wave through a spatially periodic "nonlinear plasma resonators". They refer to the thermal instability (not explaining this phenomenon) in the corona as the source of periodic change in the electron number density in the wave propagation direction. The size of the discussed periodic structure is $2.5 \div 30$ m for electron number densities $5 \cdot 10^8 \div 10^{11}$ cm^{-3}. It is exactly this spatial period that defines the number and frequencies of harmonics. The high brightness temperature of ZP radio emission is "attributed to coherent emission from a large number of identical small-scale plasma sources".

The influence of the ray-path inhomogeneities on the form of the propagating radio emission spectrum undoubtedly exists. However, their sizes, periodic structure, and long lifetime in unchangeable form, which are required in application to the ZP spectra, can hardly be realized under the solar corona conditions. The nature of such a periodic structure is unclear, and the parameters of all the mentioned structures, whether it be an ion-sound shock or streamer current sheet, a fibrous coronal structure or a thermal instability, are even much less known. Anyway, they cannot be so stationary in time in order to be present for minutes and hours, and the necessary depth of electron number density modulation is too high for real conditions. Moreover, the problem is analyzed only in ID approach for a plane incident wave. If the radiation has a finite angular spectrum, i.e., the waves are incident on the structure at different angles, then the interference pattern becomes fuzzy, since the frequencies of minima and maxima depend on the angle of incidence, and the resulting spectrum can therefore appear to be a continuum one.

Thus, the theories relating the ZP spectrum to the only effect of wave propagation through a periodic structure can be regarded only as a preliminary hypothesis, which is not confirmed by observational details so far. The nature of the periodic structure as well as the origin of the initial radiation incident on a periodic structure are not clarified by those theories. Moreover the parameters of the periodic structures required for conforming to the ZP properties seem to be unrealistic in the solar sources.

5. Conclusions

The theory based on the DPR effect is the best-developed theory for ZP origin at the meter-decimeter wavelengths at the present time. It explains in a natural way the fundamental ZP feature, namely, the harmonic structure (frequency spacing, numerous stripes, frequency drift, etc.) and gives a good fit for the observed radio spectrum peculiarities with quite reasonable parameters of the radiating electrons and coronal plasma.

The theory based on Bernstein modes in a small-size source can be applied to events with few equidistant stripes, but it imposes strong demands on the parameters of hot electrons (high number density) and coronal plasma (uniform magnetic field). Probably, this mechanism is responsible for the origin of ZP in the microwave range.

The theory based on plasma waves trapped by local density enhancements can explain the harmonic structure (with great reserve), but the required parameters of hot electrons and coronal plasma are absolutely unacceptable.

The theory based on whistlers is able to explain only a single stripe (e.g., a fiber burst) and cannot be responsible for the numerous quasi-harmonic stripes.

The theories based on wave propagation effects require specific sources of unknown origin (unknown powerful source, periodic structure, etc.) and face insuperable difficulties with the explaining of the resolved ZP stripes.

They cannot be regarded as worked-out mechanisms.

Acknowledgements

This work was partly supported by the Russian Foundation for Basic Research (Project Nos. 07-02-00157 and 08-02-00119). The author is grateful to V.V.Zaitsev and P.A.Bespalov for valuable remarks.

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