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Instability of Electrons Trapped by the Coronal Magnetic Field and Its Evidence in the Fine Structure (Zebra Pattern) of Solar Radio Spectra

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Abstract Solar radio emission is a significant source of information regarding coronal plasma parameters and the processes occurring in the solar atmosphere. High resolution frequency, space, and time observations together with the developed theory make it possible to retrieve physical conditions in the radiation source and recognize the radiation mechanisms responsible for various kinds of solar radio emission. In particular, the high brightness temperature of many bursts testifies to coherent radiation mechanisms, that is, to plasma instabilities in the corona.

As an example, the fine structure of solar radio spectra looking like a set of quasi-harmonic stripes of enhanced and lowered radiation, which is observed against the type IV continuum at the post-flare phase of activity, is considered. It is shown that such emission arises from a trap-like source filled with a weakly anisotropic equilibrium plasma and a small addition of electrons which have a shortage of small velocities perpendicular to the magnetic field. For many recorded events with the mentioned fine spectral structure the instability processes responsible for the observed features are recognized. Namely, the background type IV continuum is due to the loss-cone instability of hot non-equilibrium electrons, and the enhanced striped radiation results from the double-plasma-resonance effect in the regions where the plasma frequency f_{p} coincides with the harmonics of electron gyrofrequency f_B; $f_{\mathrm{p}} = sf_B$. Estimations of the electron number density and magnetic field in the coronal magnetic traps, as well as the electron number density and velocities of hot electrons necessary to excite the radiation with the observed fine structure, are given. It is also shown that in some cases several ensembles of non-equilibrium electrons can coexist in magnetic traps during solar flares and that its radio signature sensitively depends on the parameters of the distribution functions of the various ensembles.

Keywords Corona · Radio emission · Energetic particles · Electrons · Instabilities · Waves · Plasma

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1. Introduction

Solar radio emission is a source of rich information regarding the processes in the solar corona which accompany any kind of solar activity including solar flares. It is well known that electrons are accelerated during flares in such a way that some of them propagate along the open magnetic field and others are trapped by magnetic configurations in the form of bipolar or more complicated structures. These electrons have a non-equilibrium velocity distribution and can excite different kinds of plasma instability. Since the electron number density in the coronal plasma determines the radio frequency band, such instabilities result in coherent radio emission, which appears in the whole radio band from centimeter and millimeter waves up to decameters.

Plasma instabilities manifest themselves in solar radio bursts in various ways. The most spectacular evidence of plasma instability are type III radio bursts, which are also the best understood. They are fast drifting bursts with the frequency decreasing with time. Such a spectrum is a radio image of the electron beam escaping from the energy release region and penetrating the solar corona; the fast electrons excite plasma waves due to the Čerenkov instability and the frequency of these waves, increasing with electron number density, decreases as far as the electrons are moving from more dense to more rarefied regions of the solar corona, providing us with the usually observed negative frequency drift.

More energetic flares are often accompanied by powerful type II slowly drifting bursts. They indicate the propagation of a shock wave through the solar corona and a plasma instability excited around the shock front. The type II bursts are often followed by a broadband type IV continuum, which exists, as a rule, for a relatively long time. It is type IV solar radio emission which the present paper mainly deals with.

First of all, its long duration points to the fact that it cannot be associated with the transient electrons, but with electrons trapped by the magnetic field, which can live and radiate in the source for a long time. However, the continuum itself does not concede unambiguous interpretation; it may be either due to synchrotron radiation of relativistic electrons accelerated during the flare or a plasma instability of trapped electrons. Both mechanisms can provide the broadband long-lived continuum at meter and decimeter wavelengths. A highlight here is the appearance of a fine structure in the form of narrow-band details against the background continuum. The synchrotron mechanism does not permit the existence of narrow-band features in the spectra, and the fine structure can originate only due to plasma instability mechanisms.

The most interesting and informative kind of fine structure in type IV bursts is the so-called zebra pattern (ZP), recorded as quasi-equidistant parallel drifting bands of enhanced intensity (see, for example, Altyntsev *et al.*, 2005; Aurass *et al.* 1999, 2003; Chen and Yan, 2007; Chen *et al.*, 2011; Chernov *et al.*, 1999; Chernov, 2006; Elgaroy, 1961; Kuznetsov, 2008; Slottje, 1972). Figure 1 shows two impressive examples of zebra structure that will be analyzed in the present paper. It will be shown how one can use the observed fine structure to understand the mechanism of the plasma instability, which is responsible for such spectral features, and to explore the parameters of coronal sources.

2. Theory for Zebra Pattern Origin

First of all, the presence of narrow-band features and a high brightness temperature of ZP indicate that the cause of the above-mentioned fine structure is a coherent mechanism, which is most likely a plasma instability. A fairly long lifetime of ZP (from tens of seconds up to

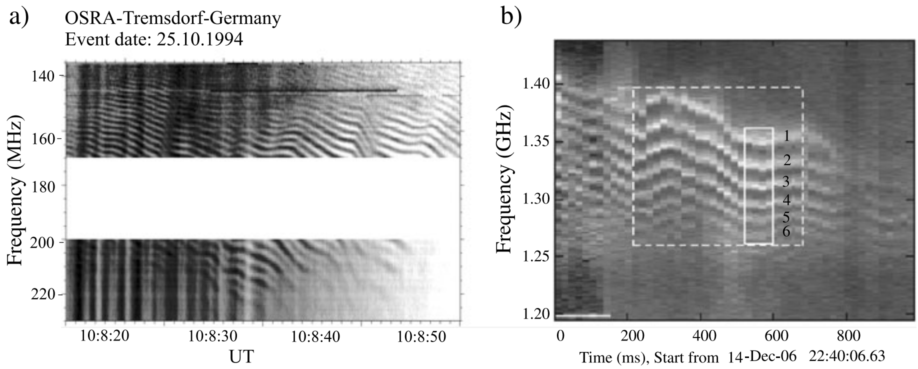

Figure 1 Examples of the zebra-pattern in solar spectra: (a) ZP recorded by the Tremsdorf radio spectrograph for the event on 25 October 1994 at meter wavelengths (see Aurass *et al.*, 2003), (b) ZP recorded by the *Frequency Agile Solar Radiotelescope Subsystem Testbed* and the *Owens Valley Solar Array* for the event on 14 December 2006 at decimeter wavelengths (Chen *et al.*, 2011).

a few hours) indicates that the instability is not caused by transient particles, which quickly leave the acceleration region, but instead by the electrons captured in a magnetic trap in the solar active region. These electrons are in non-equilibrium with respect to velocities transverse to the magnetic field. Therefore, the ZP source must be located in some kind of magnetic trap in the corona in order to keep the electrons, accelerated during the flare, radiating at the-post flare stage during the type IV events.

The most adequate theory for the origin of ZP is based on the effect of double plasma resonance (DPR) in an inhomogeneous flux tube. The idea was put forward and developed by Zheleznyakov and Zlotnik (1975a, 1975b) and Kuijpers (1975) and followed later, for example, by Berney and Benz (1978), Kuijpers (1980), Winglee and Dulk (1986), Zlotnik *et al.* (2003), Kuznetsov and Tsap (2007), Zlotnik and Sher (2009) and others. In the framework of this theory, the enhanced excitation of plasma waves propagating perpendicularly to the magnetic field occurs at some levels where the upper-hybrid frequency f_{uh} coincides with the harmonics of the electron gyrofrequency f_B (Figure 2):

$$f_{\mathrm{uh}} = s f_B. \tag{1}$$

Here, $f_{\mathrm{uh}} = (f_{\mathrm{p}}^2 + f_B^2)^{1/2}$ is the upper hybrid frequency, $f_B = (eB/2\pi mc)$ is the electron gyrofrequency, $f_{\mathrm{p}} = (e^2 N_0/\pi m)^{1/2}$ is the plasma frequency, N_0 is electron number density, B is the magnetic field, e and m are the electron charge and mass respectively, c is the light velocity, and s is harmonic number. The DPR effect appears in a mixture of weakly anisotropic background equilibrium plasma ($f_{\mathrm{p}} \gg f_B$) and a small number of hot electrons with a non-equilibrium distribution over the velocities perpendicular to the magnetic field. In this case, the dispersive properties of the plasma are determined by the background component, while the instability is due to the non-equilibrium electrons. Calculations showed (Zheleznyakov and Zlotnik, 1975a, 1975b; Winglee and Dulk, 1986; Zlotnik *et al.*, 2003; Kuznetsov and Tsap, 2007) that under the most favorable DPR conditions the maximum value of the kinetic instability growth rate is

$$\gamma_{\max}^{\mathrm{DPR}} \sim \frac{N_{\mathrm{e}}}{N_0} 2\pi f_B \tag{2}$$

(N_{e} is the hot electron number density), which essentially exceeds the growth rate on Bernstein modes far from the DPR region (Zheleznyakov and Zlotnik, 1975a; Kuznetsov, 2005)

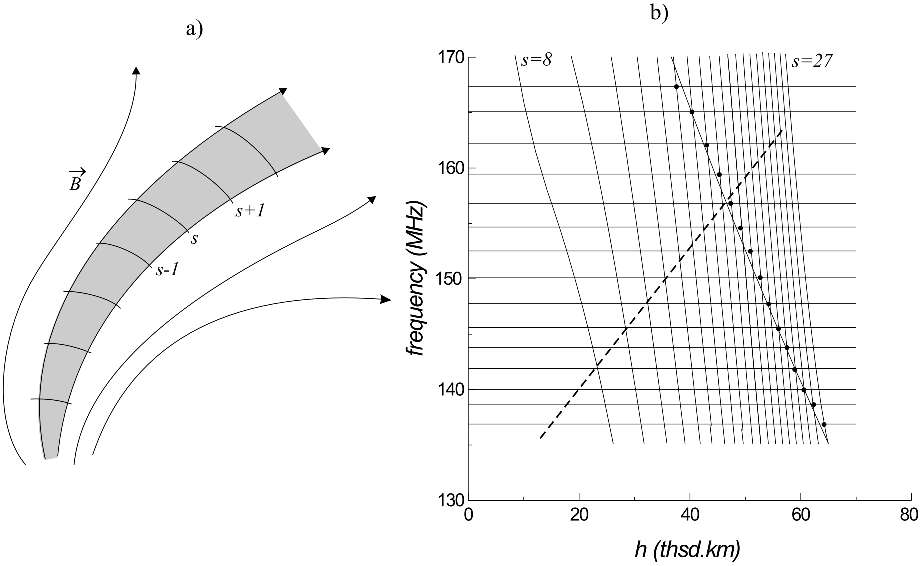

Figure 2 DPR levels in the coronal trap: (a) model of the ZP source, (b) peak frequencies of the ZP stripes at 10:08:23 UT (horizontal lines) and the gyrofrequency harmonics sf_B versus the height for the spectrum in Figure 1a; intersections (black circles) represent the DPR levels and the solid line connecting them is the electron number density versus height (see also Zlotnik *et al.*, 2003). The dashed line is the imaginary electron number density versus height, which indicates the unobserved decrease in distance between the stripes with the frequency in the case where the gradients of the magnetic field and electron number density have opposite sign.

and the loss-cone instability increment for inclined waves (Zaitsev and Stepanov, 1975; Zlotnik *et al.*, 2009). It is very important that the enhanced radiation arises in a comparatively narrow-band interval (Zheleznyakov and Zlotnik, 1975a); thus, the mechanism leads to the existence of resolved ZP stripes.

It is important to mention that in this case the various ZP stripes are excited in distinct regions of a magnetic trap (coronal loop), and the distance between the stripes is determined not only by the electron gyrofrequency, but also by the height scales of the magnetic field $L_B = f_B(\mathrm{d}f_B/\mathrm{d}h)^{-1}$ and the electron number density $L_N = f_\mathrm{p}(\mathrm{d}f_\mathrm{p}/\mathrm{d}h)^{-1}$ (see Zheleznyakov and Zlotnik, 1975b; Winglee and Dulk, 1986):

$$\Delta f/f_B \approx L_B/|L_N - L_B| \approx L_B/L_N. \tag{3}$$

The latter equality is valid if the magnetic field changes with height faster than the electron number density ($L_B \ll L_N$), which is quite common for active regions. In this case, the distance between the stripes can be appreciably less than the gyrofrequency f_B.

Evidently, the DPR effect may occur only if the height gradients of the electron number density and the magnetic field are different. Moreover, it is easily seen in Figure 2b that the frequency spacing changes with the harmonic number and frequency; namely, for the event on 25 October 1994 (solid line in Figure 2b) Δf increases with the frequency, which fits the bulk of the observed ZP events. Temporal variations in the magnetic field or electron number density result in the DPR point shift and change the corresponding frequency of zebra stripes, which causes the frequency drift of ZP. It is clear from Figure 2b that the frequency drift is negative if the electron number density decreases with time (the line f_p

moves downwards) or the magnetic field increases with time (the harmonic net shifts upwards and the points of intersection move downwards). Conversely, the drift is positive if the electron number density decreases or the magnetic field increases with time.

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 observational 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 the non-equilibrium particles, so it can be preserved or slightly varied 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 the constraints on the non-equilibrium electron number density ensuring the observed intensity of ZP stripes.

Moreover, a detailed analysis of the event on 25 October 1994, the spectrum of which is shown in Figure 1a, gives observational evidence for the ZP generation at the DPR levels (Aurass *et al.*, 2003; Zlotnik *et al.*, 2003). For active region AR 7792, in which, according to the heliographic observations, the ZP source was located, the distribution of the magnetic field with 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 $s\omega_B$ with height shown in Figure 2b. The horizontal lines corresponding to the frequency of ZP stripes in Figure 1a 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 with height in the trap (solid line in Figure 1a). This distribution agrees surprisingly well with the barometric law $N \sim \exp(-2h/10^4 T)$ with a quite reasonable kinetic temperature $T = 1.2 \times 10^6$ K. It should be emphasized that the density dependence with 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 with height can in no case be by chance; 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 for ZP origin in the event shown in Figure 1a.

The second and even more convincing evidence of the DPR origin of ZP is the measurements made by Chen *et al.* (2011) for the event shown in Figure 1b. It is the first observation of ZP emission that combines the simultaneous high spectral and time resolution data with interferometric observations over the entire bandwidth. The authors managed to obtain the absolute locations of ZP stripes and showed that the sources of different zebra stripes are spaced apart. These first measurements of ZP stripe absolute location are a very important, and doubtlessly decisive argument in favor of the DPR mechanism for the ZP origin.

3. Retrieving the Physical Conditions in ZP Sources

Thus, we have high-quality observations of the zebra structure and an adequate theory of its origin. So, what can we learn about the physical parameters of the ZP source and the processes resulting in the occurrence of the striped spectrum? We will consider first constraints on the physical conditions in the background plasma in the coronal trap (magnetic flux tube) where the ZP sources are located, and then discuss the parameters of the hot electrons responsible for the DPR instability.

3.1. Background Plasma

- It is necessary for the DPR effect that the plasma in the source is weakly anisotropic,

$$f_B \ll f_{\mathrm{p}}; \tag{4}$$

otherwise, the DPR condition in Equation (1) cannot be fulfilled for the numerous harmonics. In coronal loops, this condition is easily realized.
- The height gradients of magnetic field and electron number density must be of different value but must have the same sign:

$$|L_B| \neq |L_N|, \quad \mathrm{sgn}(L_B) = \mathrm{sgn}(L_N). \tag{5}$$

The first inequality is necessary to provide the numerous points of intersection of the dependence $f_{\mathrm{p}}(z)$ with the harmonic set (see Figure 2b). The same sign of the gradient is also an imperative requirement for the ZP source; only in this case the observed increase in the frequency spacing with frequency can be achieved. To the contrary, for example, if the magnetic field decreases, but the electron number increases with height (as is shown by the dashed line in Figure 2b), the frequency spacing decreases with frequency, which contradicts the observations.
- The observed frequency spacing is, as a rule, much less than the local gyrofrequency. If the frequency spacing was comparable with the gyrofrequency, we would have obtained a too low value of the magnetic field in the source (for the event shown in Figure 1a the frequency spacing $\Delta f \simeq 2$ MHz gives an unrealistically small value, $B < 1$ G). This means that the magnetic field should change faster with height than the electron number density:

$$L_B \ll L_N. \tag{6}$$

- Within the frame of a DPR origin of ZP, the observed frequency of a stripe is the local plasma frequency f_{p}, which unambiguously determines the electron number density.
- A very important parameter is the frequency spacing between zebra stripes. As follows from Equation (3), it depends on two factors: magnetic field and ratio of gradients L_N and L_B. Hence, the frequency spacing does not permit a direct measurement of the magnetic field. However, having at hand some additional information regarding the source properties, we can find both the magnetic field B and the gradient ratio L_B/L_N (see examples below).

We demonstrate the points mentioned above retrieving the physical conditions in the ZP sources for the two events shown in Figure 1. In both cases the magnetic field measured at the photospheric level was extrapolated to the solar corona in order to get the best fit with the observed features of the corresponding active regions. This enables one to recognize the harmonic numbers of zebra stripes and, hence, to measure the magnetic field in the sources. Thus, for the event on 25 October 1994 (Figure 1a) recorded in the frequency band (130–220) MHz, the electron number density of the background plasma is $N_0 \approx (2.1-5.9) \times 10^8$ cm^{-3}, the harmonic numbers are $s = 13-27$, the magnetic field is $B \approx (3-10)$ G and the ratio of gradients is $L_N/L_B \approx 10$. The same parameters for the event on 14 December 2006 (Figure 1b) in the frequency band (1.25–1.4) GHz are $N_0 \approx (1.9-2.4) \times 10^{10}$ cm^{-3}, $s = 8-13$, $B \approx (34-62)$ G, and $L_N/L_B \approx 4$.

Except for the main parameters of the background plasma in the ZP source, the analysis of specific spectral features permits us to study more complicated properties of the source. For example, the wave-like change of the ZP stripe frequencies shown in Figure 1a directly points to the location of the ZP source in an oscillating magnetic flux tube (Zlotnik, Zaitsev, and Aurass 2011a, 2011b). The value of the period, which is 5 s, implies that the only mode which can be responsible for such oscillations is the fast magneto-acoustic mode (Aschwanden, 2005). Moreover, the spectrum shows oscillations for which the maxima and minima lag in time towards the lower frequencies. It means that the oscillations at the greater heights (corresponding to the higher harmonics and lower frequencies) occur later than at the lower heights, which causes the frequency drift of maxima and minima in the oscillating structure. Besides, the time delay increases with time. The simplest explanation for this effect is the increase in the oscillation period with harmonic number (or frequency decrease). Analysis shows that the observed oscillation period indeed increases with the harmonic number. For example, for the harmonics with numbers 18 – 20, the relative change in the period is about 5 %. For the fast magneto-acoustic mode, the oscillation period T is determined by the loop diameter d and Alfvén velocity V_{A}:

$$T \simeq \frac{d}{V_{\mathrm{A}}}. \tag{7}$$

In turn, the Alfvén velocity is proportional to the ratio of the plasma frequency and electron gyrofrequency:

$$V_{\mathrm{A}} = \frac{B}{\sqrt{4\pi m_{\mathrm{i}} N}} = c\sqrt{\frac{m}{m_{\mathrm{i}}}}\frac{f_B}{f_{\mathrm{p}}} = \frac{c}{s}\sqrt{\frac{m}{m_{\mathrm{i}}}} \tag{8}$$

(m_{i} is the ion mass), and in the DPR regions depends only on the harmonic number s. Correspondingly, the oscillation period is proportional to the harmonic number:

$$T \simeq \frac{d}{c} s \sqrt{\frac{m}{m_{\mathrm{i}}}}. \tag{9}$$

Thus, for the considered spectrum with harmonic numbers 18 – 20 the relative change in the period is just 5 %:

$$\frac{\Delta T}{T} \simeq \frac{\Delta s}{s} \approx \frac{1}{20} = 5\ \%, \tag{10}$$

which is the same as the observed value. Therefore, the wave-like dynamic spectrum of ZP is the radio image of fast magneto-acoustic oscillations of the coronal loop.

3.2. Non-equilibrium Electrons

Detailed study of ZP also permits one to obtain information regarding the energetic electrons and the type of instability resulting in the occurrence of the spectrum with resolved stripes of enhanced and lowered radiation.

- First, the electrons responsible for ZP must be in non-equilibrium relative to the velocities perpendicular to the magnetic field. This can be a distribution of the ring-type or DGH-type (Dory, Guest, and Harris, 1965),

$$f \propto v_\perp^2 \exp\left\{-v_\perp^2/(\Delta v_\perp)^2\right\}, \quad \overline{v_\parallel} = 0, \tag{11}$$

  or a loss-cone distribution,

$$f \propto \begin{cases} \exp\left\{-\left(v_\perp^2 + v_\parallel^2\right)/2(\Delta v)^2\right\}, & \theta \geq \theta_0, \\ \sin^N(\pi\theta/2\theta_0)\exp\left\{-\left(v_\perp^2 + v_\parallel^2\right)/2(\Delta v)^2\right\}, & \theta < \theta_0 \end{cases} \tag{12}$$

  (θ is the angle between the magnetic field and the electron velocity). It is important that there is a lack of electrons with small perpendicular velocities and the mean velocity along the magnetic field is equal to or close to zero. Such distributions are unstable relative to the longitudinal plasma waves propagating perpendicularly to the magnetic field, and it is these waves which can provide the DPR effect.

- The mean transverse velocity of the non-equilibrium electrons should at least be an order of magnitude greater than the velocity of the thermal electrons in the background plasma (Zlotnik, 2009; Zlotnik and Sher, 2009). This is necessary, first, to overcome the cyclotron absorption by the thermal electrons in the background plasma, and, second, to get into the DPR region. This effect arises if the instability region is located at the branch of the positive dispersion of plasma waves. For rather large velocities, the instability threshold gets exactly into this branch. But for the smaller velocities, the instability boundary is located in the region of abnormal dispersion of electron cyclotron waves where the increments of the instability are not as high.
- The next parameter is the energetic electron number density. The growth rate shown in Equation (2) at the DPR levels is fairly high, and in order to overcome the collisional absorption, only a small part of the non-equilibrium electrons is necessary. In particular, at meter wavelengths for the event on 25 October 1994 the requirement $\gamma^{\mathrm{DPR}} > \nu^{ef}$ is satisfied for the hot electron number density $N_{\mathrm{e}} > 3 \times 10^{-6} N_0$. Estimations also show that such a number is quite enough to provide for the observed intensity of the ZP radiation.

  It is worth noting that such a low threshold for the number of energetic particles is provided only by the kinetic DPR instability. In order to realize the hydrodynamic approximation for the DPR instability (Kuijpers, 1975), a much greater hot electron number density, namely $N_{\mathrm{e}} \gg (0.05 - 0.1) N_0$, is necessary.

One more example of specific ZP showing that it is possible to reconstruct even a more complicated composition of energetic particles is described by Zlotnik *et al.* (2009). It concerns the ZP which appears only in the fast drifting envelopes similar to type III bursts. It is rather an enigmatic phenomenon because the presence of electron beams along the magnetic field can only destroy and diffuse the discrete stripes of ZP, but in that event they conversely appear. The analysis showed that this structure can be explained only by the presence of several components of non-equilibrium electrons. The spectral details are explainable if before the ZP appearance the source consists of the background plasma and two non-equilibrium components, namely, energetic electrons with loss-cone distribution, which are responsible for the existence of the continuum, and much more energetic electrons with ring distribution, which, in principle, can excite ZP. But if the loss-cone electron number density is much larger than that of the ring electrons, then the ZP may be suppressed and only the continuum is present. But if an electron beam gets into such a source, then the loss-cone may be filled in by such a beam and the combined distribution function of these two components becomes one of equilibrium. This means that the loss-cone instability responsible for the continuum is quenched and, if the ring electrons were absent, we would have seen the type III burst in absorption. Such bursts are sometimes observed in dynamic spectra (Zaitsev and Stepanov, 1975). But when the loss-cone instability stops and does not suppress the ring-electron instability, the ZP becomes visible against the type III absorption burst. Thus, the analysis of such complicated ZP leads to the conclusion that several ensembles of non-equilibrium electrons are present in the coronal source.

4. Conclusions

A specific solar radio burst with a fine structure such as a zebra pattern is shown to be a source of information regarding the physical conditions in coronal magnetic loops, parameters of electrons accelerated during a flare and the kind of instability causing the occurrence of quasi-equidistant parallel drifting bands of enhanced radiation against the type IV continuum. As follows from the DPR theory, the observed ZP originates in a weakly anisotropic plasma with magnetic field decreasing with height faster than the electron number density. The values found for the parameters of the background coronal plasma do not contradict those known from optical measurements and other radio data. Enhanced radiation is generated in the spaced DPR regions due to a kinetic instability at the longitudinal plasma waves propagating perpendicularly to the magnetic field. The electrons responsible for the DPR instability, causing the appearance of a striped spectrum, must be trapped by the magnetic field and have a distribution with a shortage of small velocities perpendicular to the magnetic field. The velocity of the non-equilibrium electrons must exceed the thermal velocity of electrons in the background plasma by no less than an order of magnitude. Also, a small number of non-equilibrium electrons is enough to excite the kinetic instability of longitudinal cyclotron waves in the DPR regions.

To conclude, it should be mentioned that the solar corona is not the only place where the waves with ZP spectrum can be generated. The striped spectrum was recorded in the kilometric radiation from Saturn (Tao *et al.*, 2010), in the auroral Very Low Frequency (VLF) hiss (Titova *et al.*, 2007), and, finally, in the most exotic object – the intermediate pulse in the Crab pulsar (Hankins and Eilek, 2007). It is interesting and very important that in all cases the stripes of enhanced radiation are not strictly equidistant and the frequency spacing grows with the frequency, just as in the solar ZP. This fact is easily understood in the framework of the DPR theory and is hardly explained by other theories. So, it is not excluded that the nature of all these events is the same, and the DPR effect is occurring in the sources under quite different conditions.

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