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Concerning Mechanisms for the Zebra Pattern Formation in the Solar Radio Emission

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Abstract—The nature of the zebra patterns in continuous type-IV solar radio bursts is discussed. The most comprehensively developed models of such patterns involve mechanisms based on the double plasma resonance and plasma wave–whistler interaction. Over the last five years, there have appeared a dozen papers concerning the refinement of the mechanism based on the double plasma resonance, because, in its initial formulation, this mechanism failed to describe many features of the zebra pattern. It is shown that the improved model of this mechanism with a power-law distribution function of hot electrons within the loss cone is inapplicable to the coronal plasma. In recent papers, the formation of the zebra pattern in the course of electromagnetic wave propagation through the solar corona was considered. In the present paper, all these models are estimated comparatively. An analysis of recent theories shows that any types of zebra patterns can form in the course of radio wave propagation in the corona, provided that there are plasma inhomogeneities of different scales on the wave path. The superfine structure of zebra stripes in the form of millisecond spikes with a strict period of ~30 ms can be attributed to the generation of continuous radio emission in the radio source itself, assuming that plasma inhomogeneities are formed by a finite-amplitude wave with the same period.

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1. INTRODUCTION

Studies of the fine structure of solar radio bursts are of great importance for both the refinement of the burst generation mechanisms and the diagnostics of the corona plasma. The most intriguing fine structure is undoubtedly the zebra pattern (ZP) in continuous type-IV radio bursts [1]. The ZP in the solar radio emission is the simultaneous excitation of waves at many (up to a few tens) closely spaced, nearly equidistant frequencies. Figure 1 presents an example of the dynamic ZP in the meter wavelength range [2]. It is seen that there are a wide variety of stripes with different frequency drifts and different frequency separations between stripes. Figure 2 shows a fragment of the ZP in the microwave wavelength range. It is seen that there are a great number of stripes (34 stripes within the 2.6–3.8 GHz frequency range) and a superfine stripe structure in the form of periodic millisecond spikes [3].

The nature of the ZP has been a subject of wide discussion for more than 30 years (see, e.g., [4, 5]). The most comprehensively developed ZP models involve mechanisms based on the double plasma resonance (DPR) and plasma wave–whistler interaction [1]. The DPR-based mechanism, which assumes that the upper hybrid frequency in the solar corona becomes a multiple of the electron-cyclotron frequency, has been discussed in most detail. Over the last five year, there have appeared a dozen papers concerning the refinement of this mechanism, because, it its initial formulation, it failed to describe many features of the ZP [4, 5]. Interpreting the observed ZP parameters and estimating the corona parameters in the framework of this mechanism encounter a number of difficulties. Thus, the modulation depth between the peaks of the growth rate at neighboring electron-cyclotron harmonics is insufficiently large for oscillations could be simultaneously excited at many DPR levels. Moreover, the value of the magnetic field determined from the frequency separation between ZP stripes is too small and corresponds to a large value of the plasma beta, whereas for a coronal magnetic trap, it should be less than unity. Kuznetsov and Tsap [6] assumed that the velocity distribution function of hot electrons within the loss cone can be described by a power law with an exponent of 8–10. In this case, a fairly deep modulation can be achieved, but excitation of waves at multiple DPR levels is still impossible. In order to explain the ZP dynamics in the framework of this mechanism, it is necessary that the magnetic field in the radio source vary sufficiently rapidly, which, however, contradicts the fairly low field values determined from the frequency separation between stripes.

In [1, 7–9], a unified model was proposed in which the formation of ZPs in the emission and absorption spectra was attributed to the oblique propagation of

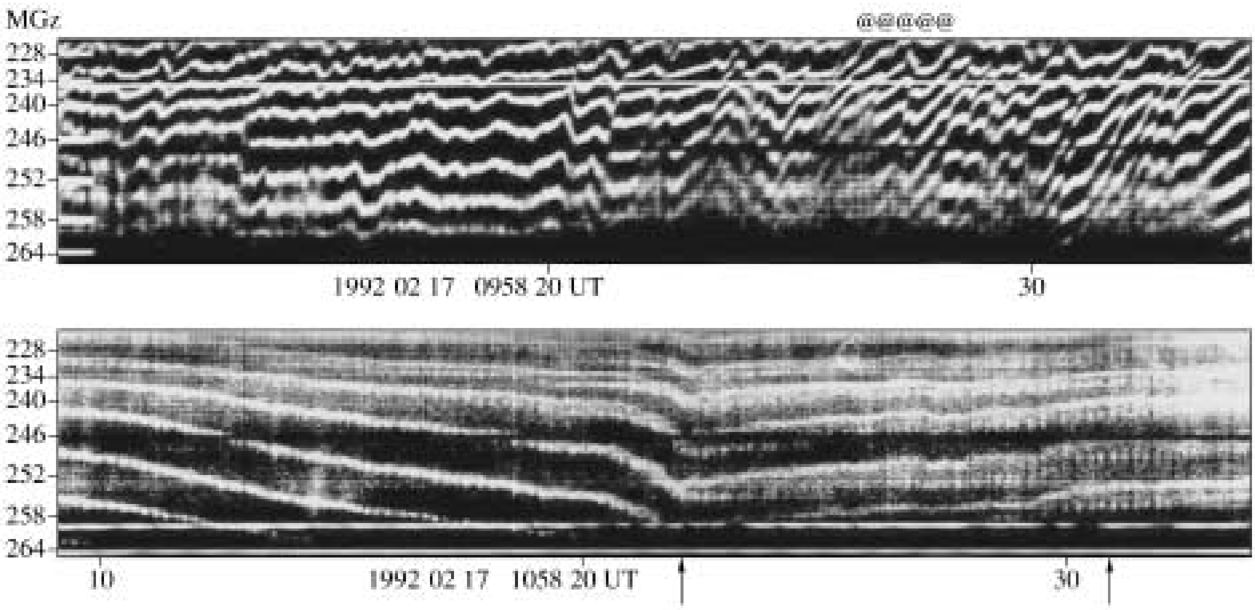

Fig. 1. Dynamic spectrum of the ZP in the meter wavelength range (Fig. 6. in [2]).

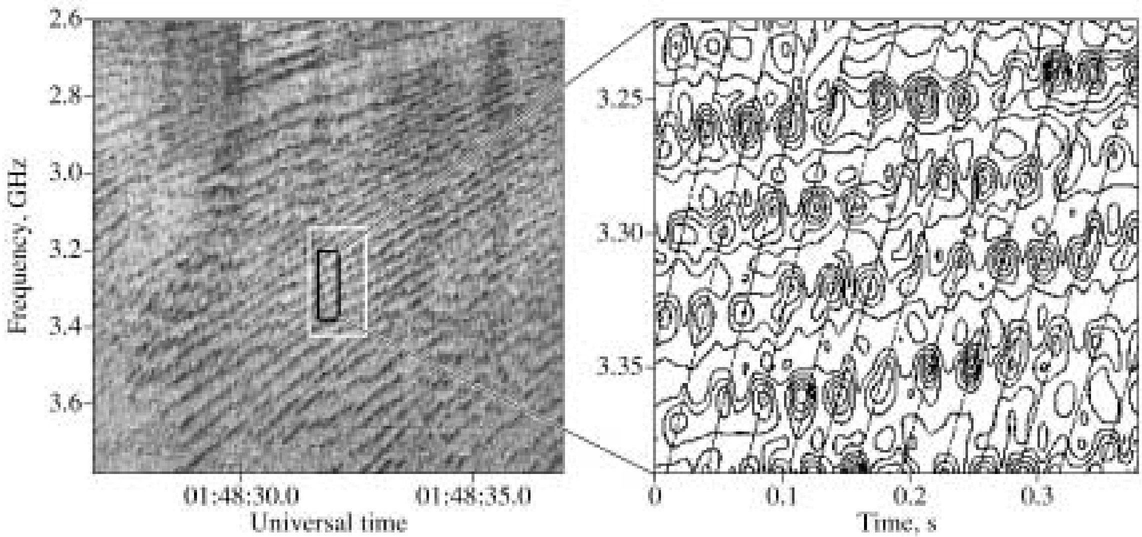

Fig. 2. ZP in the frequency range 2.6–3.8 GHz. The magnified fragment of the spectrum (on the right) demonstrates the superfine structure of stripes in the form of periodic millisecond spikes, which, for better visualization, are shown by contour levels of the intensity (Fig. 1 in [3]).

whistlers, while the formation of stripes with a stable negative frequency drift (the so-called fiber bursts) was explained by the ducted propagation of waves along a magnetic trap. This model explains occasionally observed transformation of the ZP stripes into fibers and vice versa, but fails to describe the existence of ZP stripes with a frequency that is stable over a few tens of seconds.

To overcome difficulties arising in different models, a new ZP theory based on the emission of auroral choruses (magnetospheric bursts) via the escape of the Z mode captured by regular plasma density inhomogeneities was recently proposed [10]. This theory, however, fails to explain the high intensity of radiation emitted by separate incoherent sources. In addition, the theory imposes some stringent conditions, such as the presence a large-amplitude ion-acoustic wave.

It is known [11] that the oscillation spectrum of a nonuniform plasma can be discrete; therefore, the existence of a ZP in the solar radio emission can be attributed to the presence of discrete eigenmodes excited by some mechanism during bursts in the nonuniform solar atmosphere.

Several aspects of this mechanism were considered in [12–14]. In [12], dispersion relations were derived for a discrete spectrum of eigenmodes of a spatially periodic medium in the form of nonlinear structures formed due to the onset of thermal instability. The spectrum of eigenfrequencies of a system of spatially periodic cavities is calculated, and it is shown that such a system is capable of generating a few tens of ZP stripes, the number of which is independent of the ratio of the plasma frequency to the gyrofrequency in the source.

In the present paper, an attempt is made to evaluate which model most adequately describes the observational data and find out where the ZP stripes form (during the excitation of waves in the source or in the course of their further propagation). Calculations show that the DPR-based mechanism fails to describe the generation of a large number of ZP stripes in any coronal plasma model. The mechanism related to the excitation of discrete eigenmodes of a periodically nonuniform plasma [12] can yield the observed number of harmonics. However, in this case, only the possibility of generating harmonics in a one-dimensional stationary problem is considered, i.e., the frequency dynamics of stripes is not analyzed.

2. WHAT IS NEW IN IMPROVED DPR-BASED ZP THEORIES?

The mechanism proposed in [10] can be regarded as an important step in attempts to improve the DPR-based model. The escape of the Z mode is considered at one DPR level (a point radio source), whereas the harmonics are assumed to be eigenmodes that penetrate through regular inhomogeneities, such as an ion-acoustic wave. The number of harmonics is large only if density variations in the ion-acoustic wave reach ~20%. However, as was shown in [15], it is hardly possible that such a strong ion-acoustic wave be generated in the solar corona; in fact, the amplitude of density variations is no more than ~2%. In this case, only a few ZP stripes can be generated by this mechanism, whereas up to a few tens of stripes are usually observed (Fig. 2). In our opinion, a disadvantage of this theory is that it fails to explain the high intensity of radiation emitted by separate incoherent sources.

In the basic papers on the DPR theory [4, 5] the velocity distribution function of fast particles was assumed to be narrow, with an infinitely small spread in velocities; therefore, calculations of the growth rates of upper hybrid waves could hardly provide a realistic picture [1]. This was clearly demonstrated in [6], where the term associated with the velocity spread (to be more exact, the spread over particle momenta $\Delta p/p$) was left in the expression for the anti-Hermitian part of the plasma permittivity. For the actual values of the velocity spread (~0.1) of the loss-cone distribution function, the modulation depth between the peaks of the growth rates turns out to be too small. However, calculations performed with a power-law velocity distribution function with an exponent of 8–10 yielded a modulation depth that was quite sufficient for ZP formation at many harmonics. A steep power-law spectrum of particles can be considered as an analog of a small velocity spread, although such spectra are sometime observed, especially in repeated bursts of hard X-ray emission (data from *RHESSI*).

Kuznetsov and Tsap [6] applied their results to interpret 34 ZP stripes with a superfine structure in the form of millisecond spikes in the 2.6-3.8 GHz frequency range (Fig. 2) under the assumption that the electron beams were generated strictly periodically. However, if we consider the possibility of simultaneous excitation of waves at 34 DPR levels in the corona, assuming that the plasma density depends on the altitude by the conventional barometric formula $f_P = f_{P0}\exp[-(h - h_{B0})/10^4 T]$ and the magnetic field by the formula derived in [16] from the radio data, $B = 0.5(h/R_s)^{-1.5}$, where R_s is the Sun's radius, then we obtain that 34 DPR levels extend in the corona up to altitudes of ~65 000 km, which, according to current knowledge, correspond to the plasma frequency ~250 MHz.

We calculated the DPR levels shown in Fig. 3 by using a barometric formula with the commonly accepted coronal plasma parameters: the electron temperature $T_e = 1.2 \times 10^6$ K and the initial plasma frequency f_{P0} = 3800 MHz at the altitude h_{B0} = 20 000 km. If we use a dipole dependence of the magnetic field for cyclotron harmonics, then the DPR resonances at harmonics with $s \geq 50$ will occur at altitudes of higher than 100 000 km. Thus, simultaneous excitation of waves at 34 levels in the corona is impossible for any realistic profile of the plasma density and magnetic field. For example, if we assume that the magnetic field decreases with altitude more slowly (see, e.g., [17], Fig. 54), then there will be only a few DPR levels at low harmonics. It should be noted that, as a rule, only several first cyclotron harmonics are easy to excite, whereas excitation of harmonics with $s > 50$ is hardly possible.

The superfine stripe structure in the form of millisecond spikes is apparently produced during the generation of the primary continuum radio emission, rather than arising in the course of ZP formation. This is confirmed by detailed analysis of the time evolution of the spectral amplitudes of continuous radiation several seconds before the appearance of the ZP. It is seen from Fig. 4 that, when there are no regular ZP stripes as of yet, the time dependence of the radiation intensity at the frequency 3.19 GHz clearly exhibits regular spikes with a period of ~30 ms. This period is then present in the ZP (see Fig. 2). Thus, the superfine

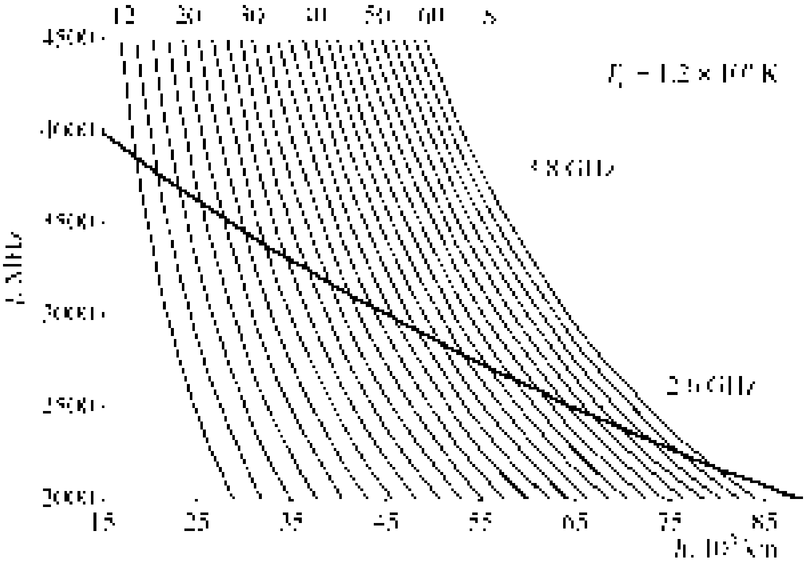

Fig. 3. Altitude dependence of the plasma frequency in accordance with the barometric law (heavy line) and altitude profiles of the electron cyclotron harmonics *s* (light lines) in the solar corona. For the electron temperature $T_e = 1.2 \times 10^6$ K and initial frequency $f_{P0} = 3800$ MHz at an altitude of $h_{B0} = 20\,000$ km, 34 DPR levels form between 2600- to 3800-MHz plasma layers.

structure is not a consequence of wave excitation at DPR levels.

The superfine structure was also observed in the meter wavelength range. It was shown in [2] that such a spiky structure can arise due to periodic acceleration of fast particles, provided that simultaneous splitting of the ZP stripes is caused by the excitation of whistlers under the conditions of the normal and anomalous Doppler effects (new beams).

It should be noted that harmonics can also be generated directly in the source in the form of a nonlinear periodic space charge wave in plasma [18]. In [18], a solution in the form of such a wave propagating in a magnetic field was obtained in the hydrodynamic approach (without taking into account wave dispersion). The spectrum near the breaking point, in the vicinity of which the number of harmonics increases substantially, was calculated. Due to electron bunching, the wave has the form of spatially alternating negatively and positively charged layers with an increased and a decreased electron density. In the presence of a wave electric field, the accelerated particles are subject to additional periodic acceleration and deceleration, due to which an electromagnetic wave is generated.

For a sufficiently large amplitude of density oscillations a, a large number of harmonics with a frequency separation close to the electron-cyclotron frequency can be excited. The number of these harmonics is determined by the parameter $N = \dfrac{3}{2^{3/2}(1-a)^{3/2}}$, characterizing the degree of nonlinearity. Thus, for $a \sim 0.9$, we have $N \approx 34$, which is equal to the number of excited harmonics observed during a radio burst on April 21, 2002 (Fig. 2). Since radio emission can be generated in a relatively small-size source, the key difficulty of the DPR-based model, namely, the excitation of a large number of harmonics in a distributed source, is overcome (Fig. 3).

3. MODELS OF ZP FORMATION DURING RADIO WAVE PROPAGATION IN THE CORONA

Let us consider the capabilities of alternative models. One of the first such models was proposed in [19] and further developed in [12], where a one-dimensional inhomogeneity was considered in which the plasma and field parameters varied periodically in space along one coordinate x with a period $L_x = L$ (e.g., in the presence of nonlinear thermal structures) and the magnetic field $\mathbf{B} = (0, 0, B)$ was perpendicular to the inhomogeneity gradient and directed along the z axis.

The wave equation obtained from Maxwell's equations and hydrodynamic equations for the perturbed velocity of electrons and ions in a cold nonuniform magnetoactive plasma yields a generalized vector equation for the perturbed electric field, which has separate solutions for ordinary and extraordinary waves. The problem is reduced to deriving the corresponding dispersion relations in a spatially inhomogeneous medium in which the profiles of both the plasma density and magnetic field are approximated by stepwise functions. An analysis of the solutions to this problem revealed the existence of transparent regions

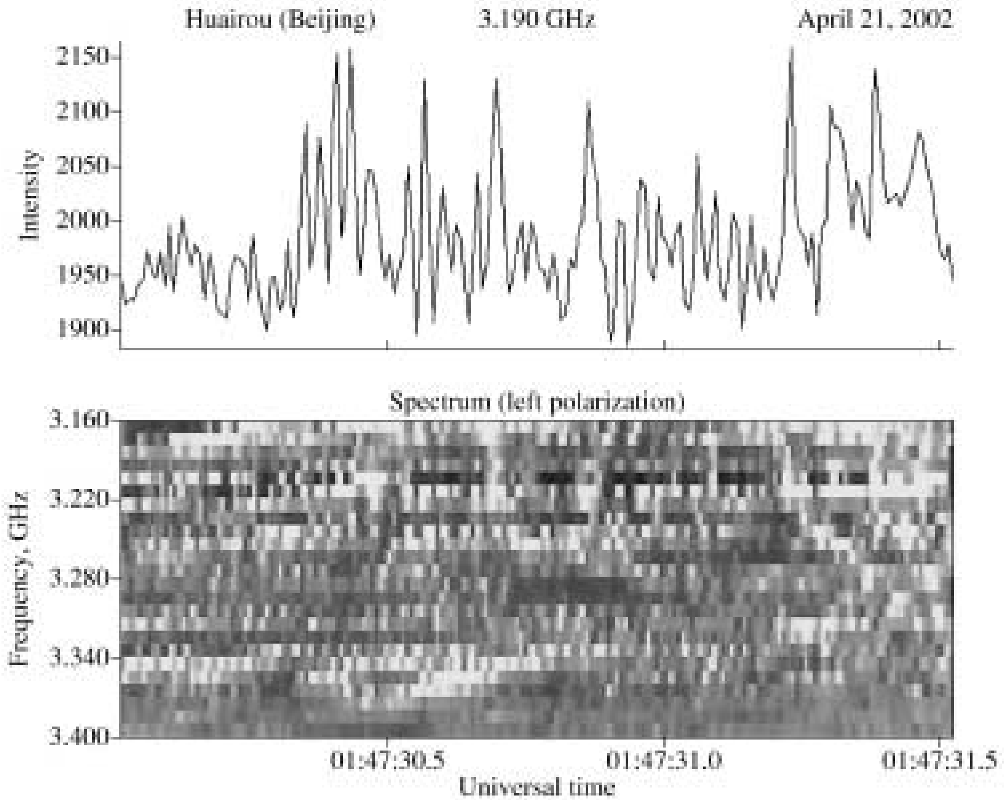

Fig. 4. Superfine structure of the continuum in the form of spikes with a period of ~30 ms.

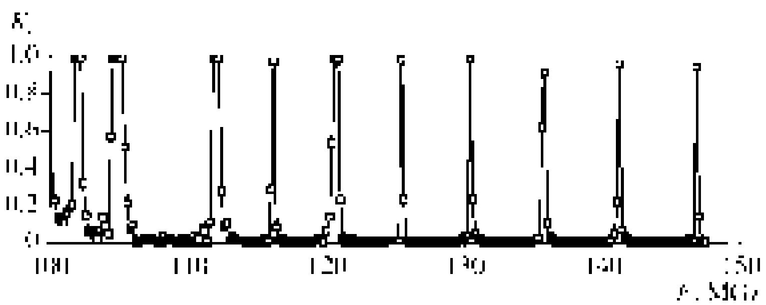

Fig. 5. Reflection coefficient K_r of ordinary waves as a function of the frequency F for $n_1 = n_2 \times 0.84 = n_3$, $n_0 = n_2$, $a = b = 10$ m, $n_2 = 1.2d + 8$, and $N = 50$.

separated by opaque regions of different width depending on the inhomogeneity scale L.

Thus, the dark ZP stripes observed in the radio emission spectrum may form due to the existence of opaque regions in a spatially periodic medium. The frequency separation between transparent regions increases with frequency (in agreement with observations). The number of harmonics grows with increasing amplitude of the inhomogeneity, but is independent of the ratio of the plasma frequency to the gyrofrequency in the source. This may help to overcome all the difficulties in explaining the large number of ZP stripes and small values of the magnetic field determined from the frequency separation of stripes (e.g., in the DPR-based model).

Practically at the same time, Barta and Karlicky [13] analyzed a similar problem in which the formation of harmonics during the propagation of a wave through regular inhomogeneities (such as oscillations behind a shock front) was considered in a simplified approach. The wave equation was written for an unmagnetized plasma, the dispersion relations for

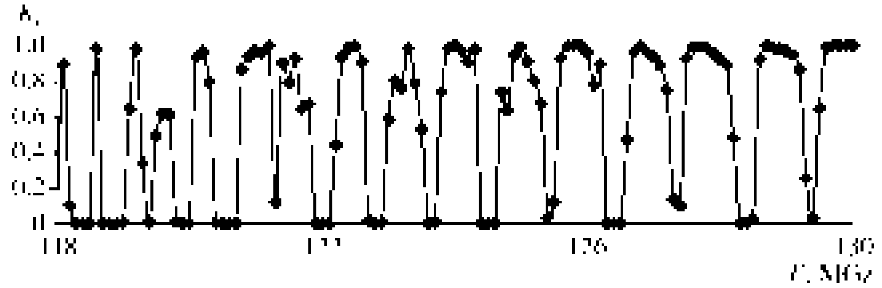

Fig. 6. Transmission coefficient K_t of ordinary waves as a function of the frequency F for $n_0 = n_3 = 1d + 8$, $n_2 = 1.5n_0$, $n_1 = n_2/2$, $a = 45$ m, $b = a$, $N = 10$, and $B = 5$ G.

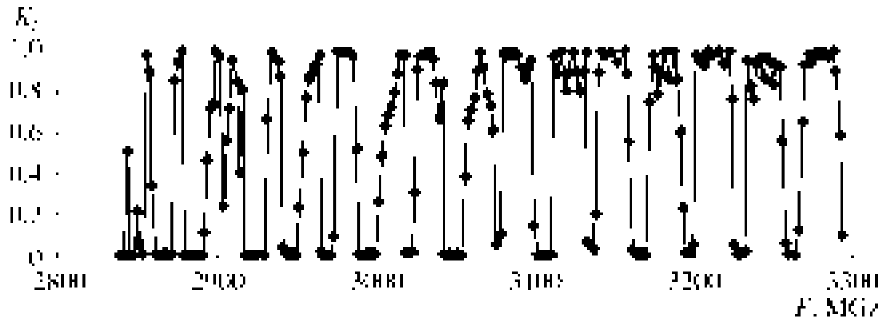

Fig. 7. Transmission coefficient K_t of ordinary waves as a function of the frequency F for $n_1 = n_2/\alpha$, $n_0 = 2n_2/(1 + \alpha) = n_3$, $b = L/(1 + \alpha)$, $a = \alpha b$, $L = 3$ m, $\alpha = 2$, $n_2 = 1.0d + 11$, and $B = 100$ G.

harmonics were not derived, and solutions for the amplitudes of reflected and transmitted waves were sought for. The frequency dependence of the transmission coefficient was found from the conservation laws and boundary conditions admitting the existence of nontrivial solutions. As a result, multiple narrow harmonics (transmission regions called interference stripes) separated by opacity (reflection) regions were obtained. In view of analogy with the results of [12], it is worth comparing the parameters of transmission regions obtained in these two papers.

In [14], a similar problem was considered in an even simpler approach in which the interference pattern produced by the incident rays and those reflected from regular inhomogeneities was analyzed. The problem was solved in the geometrical optics approximation by using the eikonal equation (by analogy with the problem of light propagation through a crystal lattice). The size of the radio emission source was assumed to be infinitely small, and the emission spectrum was considered to be sufficiently broad. It appears that, in the case of radio wave reflection from smooth inhomogeneities, the interference pattern cannot be as contrasting as that produced by light reflected from a solid body. Moreover, the ordinary and extraordinary waves are reflected from layers with different plasma densities. Therefore, the modulation depth of the total interference pattern produced by many small-size sources is relatively small.

4. PROPAGATION OF RADIO WAVES THROUGH *N* IDENTICAL INHOMOGENEOUS LAYERS

In [12], the propagation of electromagnetic waves through a spatially periodic plasma was investigated to explain the ZPs observed in solar radio bursts. The possibility of the existence of one-dimensional spatially periodic structures in the solar atmosphere was demonstrated in [20, 21]. In [12], it was assumed that the waves propagate in a unbounded collisionless plasma along the x axis perpendicular to the magnetic field $\mathbf{B} = (0, 0, B(x))$. Here, we will consider a more realistic model in which a spatially periodic plasma occupies a region of thickness NL containing N identical plasma layers of thickness L. For simplicity, each layer is assumed to consist of two piecewise-homogeneous layers with the thicknesses $a < L$ and $b = L - a$. In the regions $x < 0$ and $x > NL$, the plasma is uniform.

Let us consider the propagation of broadband radio emission in such a plasma. As a matter of fact, the region occupied by the spatially periodic plasma is a frequency filter with multiple transparency windows separated by opaque regions (see Fig. 1 in [12]). If broadband radiation is incident at the filter input ($x = 0$), then, at the output ($x = NL$), the radiation spectrum will contain only the frequencies that correspond to the transparency windows of the filter, while the amplitudes of waves with frequencies corresponding to opaque regions will be practically zero. As a result, after passing through such a filter, a structure similar to the ZP observed in the solar radio spectrum will form. This is the essence of the physical mechanism that we proposed in [12, 19] to explain the ZP formation in solar radio emission. In this case, the mechanism for the generation of primary broadband radio emission can be arbitrary (e.g., beam–plasma or cyclotron loss-cone instability [17]). Analysis of these mechanisms goes beyond the scope of the present study.

Let us first analyze the propagation of an ordinary wave, the field of which is described by the following simple formula (see Eq. (8) in [12]):

$$\frac{d^2E}{dx^2} + k^2E = 0, \quad \omega_p(NL < x < \infty) = \omega_3. \tag{1}$$

The plasma frequency $\omega_p(x)$ and the corresponding constants k_m in different plasma regions are defined by the formulas

$$\begin{gathered} \omega_p(-\infty < x < 0) = \omega_0, \quad \omega_p(NL < x < \infty) = \omega_3, \\ \omega_p((n-1)L < x < a + (n-1)L) = \omega_1, \\ n = 1, 2, \ldots, N, \\ \omega_p(a + (n-1)L < x < nL) = \omega_2, \\ \omega_0 \geq \omega_3 \geq \omega_1, \\ k_m \equiv \sqrt{(\omega^2 - \omega_m^2)}/c, \quad m = 0, 1, 2, 3, \end{gathered} \tag{2}$$

where all of the four frequencies ω_j ($j = 0, 1, 2, 3$) are constant. Let an electromagnetic wave with the frequency $\omega > \omega_0$ propagate along the x axis in the region $x < 0$. Then, taking into account wave reflection from the region $0 < x < NL$, a general solution to Eq. (1) in the region $x < 0$ can be written as

$$E(x < 0) = E_0\exp(ik_0x) + E_r\exp(-ik_0x). \tag{3}$$

where E_0 is the amplitude of the incident wave, which is assumed to be given, and E_r is the amplitude of the reflected wave.

Let us now write the solution to Eq. (1) in the region $0 \leq x \leq NL$. We introduce the notation

$$\begin{gathered} Y_{1n} \equiv E(x = nL), \quad Y_{2n} \equiv \frac{dE(x = nL)}{dx}, \\ n = 0, 1, \ldots, N. \end{gathered} \tag{4}$$

If the constants Y_{10} and Y_{20} are known, then, using Eqs. (12)–(14) from [12], we find

$$Y_{i1} = M_{ij}Y_{j0}, \quad i = 1, 2, \quad j = 1, 2. \tag{5}$$

Hereinafter, we perform summation over repeating indices from $j = 1$ to 2. The components of the matrix M for the case $\omega_1 \leq \omega_0 \leq \omega \leq \omega_2$ are as follows:

$$\begin{aligned} M_{11} &= \cos(g)\cosh(f) - k_1\sin(g)\sinh(f)/q_2, \\ M_{12} &= \sin(g)\cosh(f)/k_1 + \cos(g)\sinh(f)/q_2, \\ M_{21} &= q_2\cos(g)\sinh(f) - k_1\sin(g)\cosh(f), \\ M_{22} &= \cos(g)\cosh(f) + q_2\sin(g)\sinh(f)/k_1, \\ & g \equiv k_1x_1, \quad f \equiv q_2(L - x_1), \\ & q_2 \equiv (\omega_2^2 - \omega^2)^{1/2}/c. \end{aligned} \tag{6}$$

For the case of $\omega_1 \leq \omega_0 \leq \omega_2 \leq \omega$, the components of the matrix M have the form

$$\begin{aligned} M_{11} &= \cos(g)\cos(f) - k_1\sin(g)\sin(f)/k_2, \\ M_{12} &= \sin(g)\cos(f)/k_1 + \cos(g)\sin(f)/k_2, \\ M_{21} &= -k_2\cos(g)\sin(f) - k_1\sin(g)\cos(f), \\ M_{22} &= \cos(g)\cos(f) - k_2\sin(g)\sin(f)/k_1, \\ & f \equiv k_2(L - x_1), \quad k_2 \equiv (\omega^2 - \omega_2^2)^{1/2}/c. \end{aligned} \tag{7}$$

Note that the eigenvalues ξ of the matrix M, which are defined by the equation

$$\begin{gathered} \det(M_{ik} - \xi\delta_{ik}) = \xi^2 - 2p\xi + 1 = 0, \\ 2p = M_{11} + M_{22} \end{gathered} \tag{8}$$

coincide with the parameter ξ in formula (16) from [12] and p is defined by the same formula. In addition, it should be kept in mind that $\det(M_{ik}) = 1$.

Since all N layers are identical, it follows from formula (5) that

$$\begin{gathered} Y_{in} = M_{ij}^nY_{j0}, \quad M_{ij}^1 \equiv M_{ij}, \quad n = 1, 2, \ldots, N, \\ M_{ij}^n = M_{ik}M_{kj}^{n-1}, \quad M_{kj}^0 = \delta_{kj}, \quad i, j, k = 1, 2, \end{gathered} \tag{9}$$

where δ_{kj} is the Kronecker delta.

In the region $x > NL$, there is only the transmitted wave. Therefore, in this region, we have

$$\begin{gathered} E(x \geq NL) = E_t\exp(ik_3(x - NL)), \\ E_t \equiv Y_{1N}, \quad Y_{2N} = ik_3Y_{1N}. \end{gathered} \tag{10}$$

Calculating Y_{2N}/Y_{1N} with allowance for formulas (9) and (10) yields the first equation for the unknown constants Y_{10} and Y_{20}. The second equation for these constants can be obtained from Eqs. (3)–(4) if we take into account that the field $E(x)$ and its derivative dE/dx are continuous at the point $x = 0$. Solving the resulting set of two linear equations, we express Y_{10} and Y_{20} and, thus, all the coefficients Y_{in} (see Eqs. (9))

through E_0 and the parameters of the medium. After simple manipulations, we obtain

$$\frac{E_r}{E_0} = \frac{M_{22}^N - k_3 M_{11}^N/k_0 - i(M_{21}^N/k_0 + k_3 M_{12}^N)}{M_{22}^N + k_3 M_{11}^N/k_0 + i(M_{21}^N/k_0 - k_3 M_{12}^N)},$$

$$\frac{E_t}{E_0} = \frac{2}{M_{22}^N + k_3 M_{11}^N/k_0 + i(M_{21}^N/k_0 - k_3 M_{12}^N)}, \quad (11)$$

$$K_t \equiv \mathrm{mod}\left(\frac{k_3 E_t^2}{k_0 E_0^2}\right), \quad K_r = \mathrm{mod}\left(\frac{E_r^2}{E_0^2}\right) = 1 - K_t,$$

where K_t is the transmission coefficient of the system of plasma layers with the total thickness NL. By definition, this coefficient is equal to the ratio of the intensity $\mathbf{Q} = c[\mathbf{E}, \mathbf{B}]/4\pi$ of the transmitted wave to that of the incident wave. It can easily be shown that the coefficient of reflection from N inhomogeneous plasma layers is $K_r = 1 - K_t$.

Note that the results obtained can also be generalized to the case of extraordinary waves described by Eq. (17) in [12] (cf. Eq. (1)). Below, we will consider some examples of calculating the reflection and transmission coefficients for different parameters of plasma inhomogeneities.

The number of stripes and their shape depend on the parameters (such as the size and number) of inhomogeneities. The profile of the harmonics of the reflection coefficient in the form of narrow peaks separated by a relatively wide frequency intervals (see Fig. 5) can be interpreted as radiation stripes similar to those present in the lower spectrum in Fig. 1. Thus, in this case, the ZP is probably observed in reflected radiation. Note that the harmonics of the reflection coefficient in Fig. 5 agree better with observations than the results of similar calculations presented in Fig. 4 in [13]. In our case, there is an even comb of harmonics in which the frequency separation between neighboring harmonics increases gradually with frequency, whereas in [13], intense harmonics alternate with weak ones. Presumably, inhomogeneities in the form of density dips, which were considered in [13], cannot provide the observed widths of the ZP stripes. Moreover, in our case, the magnetic field is taken into account and harmonics of an ordinary wave agree better with observations.

For a smaller number of larger inhomogeneities with $a = 45$ m, the frequency profile of the transmission coefficient (see Fig. 6) yields nearly symmetric harmonics, which are most frequently observed (see the upper spectrum in Fig. 1).

Figure 7 shows the results of calculations of the transmission coefficient in the microwave range. It is seen that, after passing through inhomogeneities with a thickness of $L = 3$, the spectrum of ordinary waves consists of symmetric harmonics, the frequency separation between which increases gradually with frequency, which agrees with observations. A sufficiently large number of harmonics are produced when the number of inhomogeneities is >10.

5. CONCLUSIONS

An analysis of the difficulties arising in different models shows that the improvement of these models necessitates imposing new stringent conditions on the parameters of plasma and waves in the source. Thus, the efficiency of the quite natural mechanism associated with nonlinear space charge waves depends on whether strong nonlinearity is reached; however, conditions for achieving the nonlinear regime were not considered in [18]. The nonlinearity should rapidly increase and disappear in the course of wavebreaking (at $a = 1$).

The simplest model is related to the propagation of radio waves through regular inhomogeneities, because inhomogeneities are always present in the solar corona [12]. In this case, the dynamics of ZP stripes (variations in the frequency drift, stripe breaks, etc.) may be associated with the propagation of inhomogeneities, their evolution, and their disappearance.

The observed frequency difference between neighboring ZP stripes increases with frequency. This corresponds to the propagation of ordinary waves, the electric field of which is parallel to the unperturbed magnetic field, through a spatially periodic plasma. The number of discrete harmonics does not depend on the ratio of the plasma frequency to the gyrofrequency in the source. The latter circumstance can eliminate all the difficulties that arise in explaining the large number of ZP stripes and the small magnetic field value determined from the frequency separation of stripes (e.g., in the DPR-based model).

The superfine structure observed in the microwave range, when all the continuous emission consists of spikes (Fig. 4), indicates the presence of plasma wave–whistler interaction in the pulsed regime of whistler interaction with ion acoustic waves in the radio emission source generating ordinary waves (this mechanism was considered in [22]). An alternative source of pulsed radio emission may be associated with plasma density pulsations caused by the propagation of a finite-amplitude wave. The generation of electron-cyclotron maser radiation, which is considered a possible cause of the observed spikes [23], is dominated by extraordinary waves.

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