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SPACE PLASMA

New Mechanism for the Formation of Discrete Stripes in the Solar Radio Spectrum

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Abstract—Dispersion relations are derived for the eigenfrequency spectrum of a spatially periodic nonlinear plasma resonators created in the solar atmosphere due to the development of thermal instability. The eigenfrequency spectra of such resonators are calculated, and it is shown that they are capable of generating tens of discrete stripes (a so-called zebra structure) the number of which is independent of the ratio of the plasma frequency to the gyrofrequency in the source. This may help to overcome all difficulties in explaining the large number of stripes in the zebra structure, as well as the small magnitude of the magnetic field. The spatially periodic plasma resonators under consideration act as a filter with numerous transparency windows separated from one another by opaque regions. The number of stripes and their frequencies in the zebra structure depend on the spatial period of plasma nonuniformity, which is equal to meters or decameters for conditions typical of the solar atmosphere. The high brightness temperature of radio emission in the zebra structure is attributed to coherent emission from a large number of identical small-scale plasma sources. Some regular properties of the observed zebra structure are explained.

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1. INTRODUCTION

The zebra structure (ZS), or zebra pattern, in the solar radio spectrum is produced by the emission of radio waves excited simultaneously at many (up to several tens) of close, approximately equidistant, discrete frequencies. Several models for the formation of the ZS have been proposed in the literature, but each of them encounters a number of difficulties in interpreting the data from new observations. Hence, it is still relevant to find the true mechanism responsible for producing ZSs. The regular ZS gradually came to be understood as being caused by a mechanism based on the double plasma resonance, when the upper hybrid frequency at the discrete levels in the solar corona becomes a multiple of the electron gyrofrequency [1, 2]. In order to explain the dynamics of the stripes in the ZS, this mechanism, in particular, suggests that there are fast variations in the magnetic field in the source, but this is in conflict with the fact that the magnetic field determined from the frequency separation between the stripes is too weak.

In [3–5], a unified model was proposed in which the formation of ZS stripes in the emission and absorption spectra was attributed to the oblique propagation of whistlers and the formation of fibers in the spectra was attributed to the channeled propagation of whistlers along a magnetic trap. This model explains the occasionally observed continuous conversions of ZS stripes into fibers and vice versa but it encounters serious difficulties in explaining the time and frequency stability of ZS stripes over tens of seconds.

In searching for ways to overcome such difficulties, a new ZS theory was recently proposed [6] in which the underlying mechanism is the emission of the so-called auroral choruses (magnetospheric bursts) via the escape of a Z mode captured into regular plasma density variations. In this theory, however, the high intensity of the emitted radiation cannot be explained due to incoherent emission from separate individual sources. In addition, the theory implies some stringent conditions, such as the generation of a high-power ion acoustic wave. The theory developed in the present paper is free of these drawbacks.

In the solar atmosphere, thermal instability can give rise to nonlinear thermal structures in which the plasma parameters, as well as the magnetic and electric fields, vary periodically in space [7, 8]. In a direction perpendicular to the magnetic field, the spatial period L on which the plasma parameters in such thermal structures vary is inversely proportional to the magnetic induction B (hereafter, it is assumed that the electron collision frequency ν_e in the solar atmosphere is much lower than the electron gyrofrequency, $B_e = eB/(m_e c)$). For typical parameters of the solar atmosphere, we have L = 1–30 m. The period L also depends on the plasma temperature T and density n, as well as on the difference between the emission function and the plasma heating function in the region under consideration. This is why the period can be much longer, $L \gg 30$ m, but only under some very special conditions.

It is well known that the spectrum of natural oscillations of any finite-size body is discrete, which is a consequence of the boundary conditions at the body surface. Depending on particular circumstances, the spectrum of oscillations of an inhomogeneous plasma can be either continuous or discrete [9]. As will be shown below, the wave spectrum of an infinite plasma with spatially periodic density variations exhibits both continuous and discrete properties: it consists of discrete finite-width stripes, within each of which the frequency depends continuously on the parameters of the wave and of the plasma itself. It is therefore natural to attribute the ZSs observed in the solar radio spectra to a simple effect of the propagation of electromagnetic waves through a plasma layer having a periodic structure: in essence, such a layer acts as a filter with numerous transparency windows. The spectrum of the broadband electromagnetic radiation that was generated in the solar atmosphere by any of the known mechanisms and then passed through such a filter contains only those frequencies that have been transmitted by the filter. This mechanism results in the ZS in the spectrum.

The goal of the present work is to prove this possibility and to construct a model that explains the observed regular properties of the ZS.

2. SPECTRUM OF EIGEN WAVES IN A SPATIALLY PERIODIC PLASMA

We consider a one-dimensional case in which the plasma and field parameters vary only along the x coordinate with the period $L_x = L$. We assume that the magnetic field is directed along the z axis, $\mathbf{B} = (0, 0, B)$, and is thus perpendicular to the direction in which the parameters in question vary. Let us calculate the eigen waves in such a spatially periodic plasma. From Maxwell's equations for the perturbed electric field vector $\mathbf{E}^*$, we obtain

$$\nabla \times \nabla \times \mathbf{E}^* + \frac{1}{c^2}\frac{\partial^2 \mathbf{E}^*}{\partial t^2} = -\frac{4\pi}{c^2}\frac{\partial \mathbf{j}}{\partial t}, \quad \mathbf{j} = en(\mathbf{V}_i - \mathbf{V}_e), \tag{1}$$

where $n = n(x)$ is a known periodic function of x with the period $L_x = L$. The perturbed electron and ion velocities, V_e and V_i, can be calculated from the hydrodynamic equations in the immobile, cold, collisionless ($\nu_e = 0$) plasma approximation:

$$\frac{\partial \mathbf{V}_{ei}}{\partial t} = \frac{Z_{ei}e}{m_{ei}}\mathbf{E}^* + Z_{ei}[\mathbf{V}_{ei} \times \mathbf{B}_{ei}], \quad \mathbf{B}_{ei} \equiv \frac{e\mathbf{B}}{m_{ei}c}, \tag{2}$$
$$Z_e = -1, \quad Z_i = 1.$$

The solution to set of Eqs. (1) and (2) for the quantities $X = \mathbf{E}$, $\mathbf{V}_e$, and $\mathbf{V}_i$ can be sought for in the form

$$X = \mathrm{Re}\, X_a(x, \omega, k)\exp(i(kx - \omega t)). \tag{3}$$

In other words, we are considering waves propagating in the direction along which the parameters of the unperturbed plasma vary. In investigating the wave propagation in periodic media, the parameter k is commonly referred to as the Bloch wave vector [10]. We represent the electric field as

$$E \equiv E_a(x, \omega, k)\exp(ikx). \tag{4}$$

With relationships (2)–(4), we readily reduce Eq. (1) to

$$\nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2}\mathbf{E}$$
$$= \frac{\omega_e^2}{c^2(B_e^2 - \omega^2)}\{\omega^2\mathbf{E} - i\omega\mathbf{E} \times \mathbf{B}_e - \mathbf{B}_e(\mathbf{E} \cdot \mathbf{B}_e)\}$$
$$+ \frac{\omega_i^2}{c^2(B_i^2 - \omega^2)}\{\omega^2 E + i\omega E \times B_i - B_i(E \cdot B_i)\}, \tag{5}$$
$$\omega_{ei}^2 \equiv \frac{4\pi e^2 n}{m_{ei}},$$

where $n = n(x)$ and $B = B(x)$ are known periodic functions with the period L and ω_e and ω_i are the electron and ion plasma frequencies, respectively.

In the case under consideration, namely, $\mathbf{B} = (0, 0, B)$ vector equation (5) has two independent solutions, describing ordinary and extraordinary waves [1]:

$$\mathbf{E} = (0, 0, E), \tag{6}$$

$$\mathbf{E} = (E_x, E_y, 0). \tag{7}$$

For solution (6), which corresponds to ordinary waves and in which the perturbed electric field has the only nonzero component, parallel to the unperturbed magnetic field, Eq. (5) can be greatly simplified to become

$$\frac{d^2E}{dx^2} + \frac{\omega^2 - \omega_p^2}{c^2}E = 0, \quad \omega_p^2 \equiv \omega_e^2 + \omega_i^2. \tag{8}$$

Since the frequency ω_p is a periodic function of the coordinates, Eq. (8) is the familiar Hill equation [11], whose solutions satisfy the equality

$$E(x + L) = E(x)\exp(\alpha L), \quad \alpha = ik, \tag{9}$$

where α is a complex number called the characteristic index of the solution. In this case, the function (cf. expression (4))

$$E_a(x) \equiv E(x)\exp(-\alpha x), \quad E_a(x + L) = E_a(x) \tag{10}$$

is periodic with the period L [11]. In the literature on the propagation of electromagnetic waves in periodic media, relationship (10) is known as the Bloch theorem [10, 12].

Let us find an analytic solution to Eq. (8) in a particular case in which the nonuniform plasma density and magnetic field, $n(x)$ and $B(x)$, are approximated by step functions:

$$n(x) = n_1, B(x) = B_1 \quad \text{for} \quad 0 < x < x_1 < L,$$
$$n(x) = n_2, \quad B(x) = B_2 \quad \text{for} \quad x_1 < x < L = x_2, \qquad (11)$$
$$n(x+L) = n(x), \quad B(x+L) = B(x) \quad \text{for } x,$$

where n_1, n_2, B_1, and B_2 are constants.

In the frequency range $\omega_{p1}^2 \le \omega^2 \le \omega_{p2}^2$, Eq. (8) has a solution of the form

$$E = E_c\cos(k_1 x) + E_s\sin(k_1 x),$$
$$k_1 \equiv \sqrt{(\omega^2 - \omega_{p1}^2)}/c, \quad 0 \le x \le x_1 < L, \qquad (12)$$

$$E = E_1\sinh(q_2(x - x_1)) + E_2\cosh(q_2(x - x_1)),$$
$$q_2 \equiv \sqrt{(\omega_{p2}^2 - \omega^2)}/c, \quad x_1 \le x \le x_2 = L. \qquad (13)$$

Using the condition that the functions $E(x)$ and dE/dx are continuous at the point $x = x_1$ and taking into account equality (9), we obtain a solution at the point $x = 0$:

$$E_2 = E_c\cos(k_1 x_1) + E_s\sin(k_1 x_1),$$
$$E_1 = \frac{k_1}{q_2}\{E_s\cos(k_1 x_1) - E_c\sin(k_1 x_1)\}, \qquad (14)$$

$$E_c\xi = E_1\sinh(f) + E_2\cosh(f), \quad \xi \equiv \exp(ikL),$$
$$E_s\xi = \frac{q_2}{k_1}\{E_1\cosh(f) + E_2\sinh(f)\}, \qquad (15)$$
$$f \equiv q_2(x_2 - x_1).$$

Four linear homogeneous equations (14) and (15) for the unknown constants E_1, E_2, E_s, and E_c can have a nontrivial solution only under the condition

$$\xi^2 - 2p\xi + 1 = 0, \longrightarrow \xi = p \pm \sqrt{p^2 - 1},$$
$$p \equiv \cosh(f)\cos(k_1 x_1) + \sinh(f)\sin(k_1 x_1)\frac{q_2^2 - k_1^2}{2q_2 k_1}, \qquad (16)$$
$$\cos(kL) = p, \quad \mathrm{mod}(p) \le 1,$$
$$\alpha = ik = \frac{1}{L}\ln\{p \pm \sqrt{(p^2 - 1)}\}, \quad \mathrm{mod}(p) > 1.$$

This is the sought-for dispersion relation for calculating the frequency spectrum of wave perturbations (3) propagating through a periodic medium in a periodic magnetic field that are described by formulas (11). We can see that waves with the real Bloch wave vector k can propagate only at frequencies for which $\mathrm{mod}(p) \le 1$. The eigenfrequency spectrum depends implicitly on the magnetic field only through the spatial period L, which is inversely proportional to the magnetic field amplitude when thermomagnetic structures are spatially periodic.

Note that, to within the notation, Eq. (8) coincides with the one-electron Schrödinger equation for a one-dimensional crystal [12]. It is therefore not surprising that, to within the notation, dispersion relation (16) coincides with that obtained in [12] for the Ψ function of an electron in a crystal with a model, stepwise constant, periodic potential.

In writing dispersion relation (16), we assumed that the Bloch wave vector k is real, which corresponds to an initial-value problem [9]. In solving the boundary-value problem (in which the wave frequency is a given real quantity) for $\mathrm{mod}(p) \le 1$, the formula $\cos(kL) = p$ in dispersion relation (16) is satisfied. For $\mathrm{mod}(p) > 1$, we obtain from dispersion relation (16) the penetration depth of the field into the medium: $L_p = 1/\alpha = L/\ln(\mathrm{mod}(p) + (p^2 - 1)^{1/2})$.

For solution (7), which corresponds to extraordinary waves, we obtain from vector equation (5) the equation

$$\frac{d^2E_y}{dx^2} + QE_y = 0, \quad Q \equiv a + \frac{\omega^2}{c^2} - \frac{b^2c^2}{ac^2 + \omega^2},$$
$$a \equiv \frac{\omega^2}{c^2}\left(\frac{\omega_e^2}{B_e^2 - \omega^2} + \frac{\omega_i^2}{B_i^2 - \omega^2}\right), \qquad (17)$$
$$b \equiv \frac{\omega}{c^2}\left(\frac{B_i\omega_i^2}{B_i^2 - \omega^2} - \frac{B_e\omega_e^2}{B_e^2 - \omega^2}\right).$$

Note that, at the branch points $\omega = \pm B_{e,i}$, the quantity Q has a removable singularity of the type $\infty - \infty \ne \infty$; as a result, Q is finite at these points. But if $\omega^2 + ac^2 = 0$, then we have $Q = \infty$.

For the case

$$Q(0 < x < x_1) = Q_1 > 0, \quad Q(x_1 < x < x_2) = Q_2 < 0,$$
$$k_1 \equiv Q_1^{1/2}, \quad q_2 \equiv (-Q_2)^{1/2}, \quad N = 1 \qquad (18)$$

(which will be denoted as the $N = 1$ case), we can see that the solution to dispersion relation (17) coincides with solution (8) and the dispersion relation for the extraordinary waves in question coincides completely with dispersion relation (16): $\cos(kL) = p \equiv p_1$; moreover, the quantities k_1 and q_2 are defined by the third and fourth of formulas (18).

For $Q_1 < 0$ and $Q_2 > 0$ ($N = 2$), Eq. (17) can be solved in a similar way. In this case, instead of dispersion relation (16), we arrive at

$$\cos(kL) = p_2 \equiv \cosh(q_1 x_1)\cos(f_2)$$
$$+ \sinh(q_1 x_1)\sin(f_2)\frac{q_1^2 - k_2^2}{2q_1 k_2}, \qquad (19)$$
$$k_2 \equiv (Q_2)^{1/2}, \quad q_1 \equiv (-Q_1)^{1/2},$$
$$f_2 \equiv k_2(x_2 - x_1), \quad N = 2.$$

For $Q_1 > 0$ and $Q_2 > 0$ ($N = 3$), solving Eq. (17) yields the dispersion relation

$$\cos(kL) = p_3 \equiv \cos(k_1x_1)\cos(f_3) - \sin(k_1x_1)\sin(f_3)\frac{k_1^2 + k_2^2}{2k_1k_2}, \quad (20)$$

$$k_1 \equiv (Q_1)^{1/2}, \quad k_2 \equiv (Q_2)^{1/2}, \quad f_3 \equiv k_2(x_2 - x_1), \quad N = 3.$$

In the limit of an infinitely small discontinuity such that $k_1 = k_2$, dispersion relation (20) gives

$$\cos(kL) = \cos(k_1L) \longrightarrow k = \pm(\omega^2 - \omega_p^2)^{1/2}/c.$$

We can see that, in this limiting case, the wave spectrum coincides with that in the case of a homogeneous plasma.

Finally, for $Q_1 < 0$ and $Q_2 < 0$ ($N = 4$), the dispersion relation can be written as

$$\cos(kL) = p_4 \equiv \cosh(qx_1)\cosh(f_4) + \sinh(qx_1)\sinh(f_4)\frac{q_1^2 + q_2^2}{2q_1q_2}, \quad (21)$$

$$q_1 \equiv (-Q_1)^{1/2}, \quad q_2 \equiv (-Q_2)^{1/2}, \quad f_4 \equiv q_2(x_2 - x_1), \quad N = 4.$$

3. ANALYSIS OF THE PROPERTIES OF SOLUTIONS TO THE DISPERSION RELATIONS

Note that the dispersion relations for ordinary waves (6) can be derived from dispersion relations (16), (19), (20), and (21) for extraordinary waves (7) by formally setting $B_{e,i} = 0$. In this case, the quantities k and q defined by formulas (12) and (13) coincide with those defined by formula (18).

It is convenient to express the frequencies ω, ω_{p2}, B_e, and B_i in units of ω_{p1}, the quantities k and q in units of ω_{p1}/c, and the lengths x_1 and $x_2 = L$ in units of c/ω_{p1} in order to write dispersion relations (16), (19), (20), and (21) in dimensionless units, none of which are explicitly dependent on ω_{p1}. This indicates that, if the solutions to these equations are known for some values of the plasma and field parameters, then, when the densities n_1 and n_2 increase q^2 times, when the magnetic field increases q times, and when the spatial period L decreases q times, all the wave frequencies (the solutions to the equations) increase q times.

We first consider ordinary waves (6) because the dispersion relation for them is simpler than that for the extraordinary waves (see dispersion relations (16) and (20) with $B_{e,i} = 0$).

Figure 1 shows how the wave frequency ω, i.e., the solution to dispersion relation (16), depends on the parameter $\cos(kL)$ (where k is the Bloch wave vector) for $n_2 = 10^{11}$ cm^{-3}, $n_1 = n_2/9$, $L = 3$ m, and $x_1 = 0.9L$. Note that (see also [12]) this dependence is non-single-valued: to one value of k there correspond many frequencies. We can see that, in the frequency range $\omega_{p1} \leq \omega \leq \omega_{p2}$, the spectrum consists of five very narrow transparency stripes separated from one another by broad opaque regions (forbidden zones). In the frequency range $\omega > \omega_{p2}$, the spectrum consists of numerous transparency stripes, separated by comparatively narrow opaque regions, in which the curve $\omega(\cos(kL))$ is discontinuous. In the limit $\omega \longrightarrow \infty$, the width of the opaque regions approaches zero. The value $L = 3$ m was chosen in order to obtain the observed frequency difference between the neighboring narrow opaque regions. If the spatial period L is set to be m times longer, then the number of stripes in the frequency range $\omega_{p1} \leq \omega \leq \omega_{p2}$ is m times larger, so the frequency difference is then m times smaller.

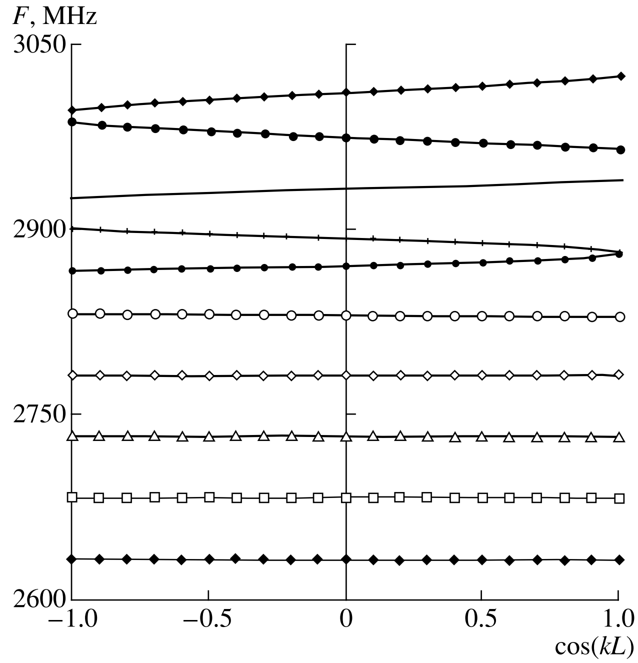

Fig. 1. Frequency of ordinary waves (6) vs. parameter $\cos(kL)$ for $n_2 = 10^{11}$ cm^{-3}, $n_1 = n_2/9$, $x_1 = 0.9L$, and $L = 3$ m. The large symbols correspond to the frequencies $\omega < \omega_2$ ($N = 1$), and the small symbols correspond to the frequencies $\omega > \omega_2$ ($N = 3$). The width of the five transparency windows, ΔF, at the frequencies $\omega < \omega_2$ ($N = 1$) increases with frequency: $\Delta F_1 = 0.06$, $\Delta F_2 = 0.12$, $\Delta F_3 = 0.27$, $\Delta F_4 = 0.73$, and $\Delta F_5 = 2.56$ MHz.

From Fig. 2 we can see that the difference between the neighboring frequencies decreases with increasing spatial period L and that, at a fixed L value, it increases with frequency. These results agree with the observational data [13].

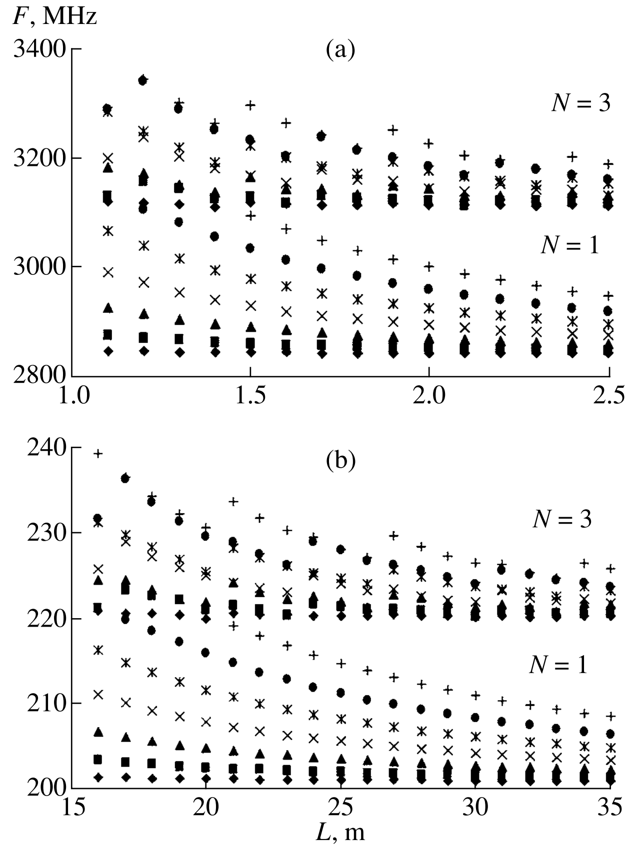

Fig. 2. The first seven eigenfrequencies of waves described by Eq. (5) with $B = 0$ and $\cos(kL) = 1$ vs. spatial period: (a) L = 1–2.5 m for $n_1 = 1.0 \times 10^{11}$ cm^{-3} and $n_2 = 1.2 \times 10^{11}$ cm^{-3} and (b) L = 15–35 m for $n_1 = 5 \times 10^8$ cm^{-3} and $n_2 = 6 \times 10^8$ cm^{-3}.

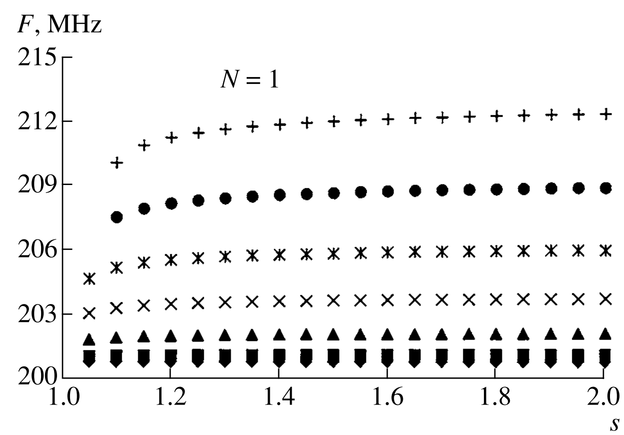

Fig. 3. The first seven eigenfrequencies F of waves (6) vs. ratio $s \equiv n_2/n_1$ in the case $N = 1$ for $L = 30$ m, $n_1 = 5 \times 10^8$ cm^{-3}, and $\cos(kL) = 1$.

If the frequency scale F in Fig. 2 is increased, say, by a factor of $r = 10$ and the spatial period is shortened by the same factor, $r = 10$, then the resulting figure will describe the spectrum of eigen waves in a plasma with densities n_1 and n_2 higher than those in the original figure by a factor of $r^2 = 100$.

For waves (6), there exist solutions with $N = 1$ and $N = 3$. For waves (7), solutions with $N = 1$, 2, and 3 are possible. At $N = 4$, there are no solutions because the left-hand side of dispersion relation (21) is less in absolute value than unity, while the right-hand side always exceeds unity.

From Fig. 3 we can readily see that, at $N = 1$, the frequency F depends weakly on the parameter $s = n_2/n_1$. For $N = 3$, the first seven eigenfrequencies increase approximately linearly with this parameter, from 206–212 MHz at $s = 1.05$ to 284–293 MHz at $s = 2$. Within the interval s = 1.05–2, the difference between the neighboring frequencies changes only slightly. The larger the ratio n_2/n_1 at a fixed value of L, the greater the number of transparency windows in the frequency range $\omega_{p1} \le \omega \le \omega_{p2}$.

Figure 4 shows how the first seven eigenfrequencies F depend on the magnetic induction in the range B = 0–70 G for $N = 1$, 2, and 3, the parameter values being L = 30 m, $n_1 = 5 \times 10^8$ cm^{-3}, $n_2 = 6 \times 10^8$ cm^{-3}, and $\cos(kL) = 1$. We can see that, as the magnetic induction B increases, the frequency difference F_7–F_1 increases at $N = 1$ and 3 and decreases at $N = 2$, while, on the contrary, the frequencies themselves decrease at $N = 1$ and 3 and increase at $N = 2$.

The high brightness temperature of the radio emission in a ZS—a factor required for reliable detection of such structures—is ensured by coherent emission from a large number of identical, spatially periodic plasma layers.

In the linear approximation at hand, the wave amplitudes cannot be determined. It is known from observations that the wave amplitudes at the neighboring frequencies of the ZS are comparable in magnitude. This can be readily explained by taking into account the fact that the radio source in the solar atmosphere is broadband (i.e., the intensity of the source varies insignificantly over a wide frequency band) and that the periodic plasma structure, in essence, acts as a filter with numerous narrowband frequency windows, which transmit the waves. The natural result is the formation of a ZS. Let us address this point in more detail.

Consider the propagation of a broadband radio-frequency wave in a plasma along the x axis. Let the plasma be homogeneous in the regions $x < 0$ and $x > NL$, and let there be N identical inhomogeneous plasma layers, each having the thickness L, in the region $0 < x < NL$. In this case, in the limit $N \gg 1$, the region $0 < x < NL$ can be regarded as an "infinite" periodic medium to which the above results can be applied. In essence, such a region operates as a filter with numerous frequency windows separated from one another by opaque zones (see Fig. 1). Of all the frequencies of an incident broadband radio-frequency wave, such a filter will transmit only those that correspond to its transparency windows. The wave amplitudes at the frequencies corresponding

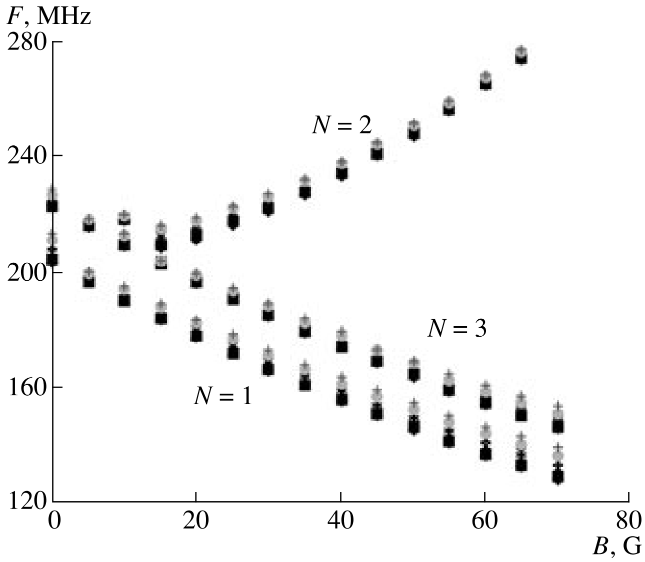

Fig. 4. The first seven eigenfrequencies of all three wave branches vs. magnetic induction B for $L = 30$ m, $n_1 = 5 \times 10^8$ cm^{-3}, $n_2 = 6 \times 10^8$ cm^{-3}, and $\cos(kL) = 1$.

to opaque zones are attenuated within the filter to become nearly zero at its exit ($x = NL$). It is such a filter that produces what is commonly called a ZS from the originally broadband solar radio spectrum. This is the essence of the physical mechanism proposed here to explain the formation of ZSs in the radio emission spectra from the solar plasma. In the mechanism proposed, the originally broadband solar radio waves can be generated by any of the known mechanisms [14], which are not, however, the subject of the present study.

4. CONCLUSIONS

The results obtained can be briefly summarized as follows.

(i) Numerous ZS stripes observed in the solar radio spectra can naturally be explained as resulting from the propagation of electromagnetic waves through a periodically inhomogeneous plasma, which functions as a frequency filter having many narrowband transparency windows. Such a spatially periodic plasma (with a spatial period equal to meters or decameters) is naturally produced in the solar atmosphere due to the development of thermal instability.

(ii) The narrow dark stripes observed in the solar radio spectra are merely a consequence of the existence of narrow opaque zones in a periodic medium (see Fig. 1).

(iii) Since the conditions for the onset of thermal instability in the solar atmosphere are more favorable in the temperature range $T \geq 10^5$ K, which corresponds to low plasma densities and low eigenfrequencies of the radio waves, ZSs in the solar radio spectra should be more often observed at meter wavelengths than in the decimeter and centimeter wavelength ranges. This conclusion agrees with the observational data.

(iv) The higher the frequency, the larger the frequency difference between the neighboring stripes in the observed ZSs. This result corresponds to the propagation of ordinary waves (6), with the electric field vector parallel to the unperturbed magnetic field, through a spatially periodic plasma.

(v) The number of discrete stripes is independent of the ratio of the plasma frequency to the electron gyrofrequency in the source. This result may help to overcome all difficulties in explaining the large number of stripes in the ZS, as well as the small value of the magnetic field, which is determined from the frequency separation between the stripes in, e.g., a model based on the double plasma resonance.

(vi) Observations of ZSs in the solar radio spectra give indirect experimental evidence for the existence of small-scale periodic structures with spatial periods equal to meters or decameters in the solar atmosphere and provide the possibility for their experimental study. Theoretically, there is no doubt that such structures do exist.

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