Solar Phys
DOI 10.1007/s11207-013-0327-3

On Polarization of the Zebra Pattern in Solar Radio Emission

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Received: 21 December 2012 / Accepted: 9 May 2013

Abstract The problem of strong polarization of the zebra-type fine structure in solar radio emission is discussed. In the framework of the plasma mechanism of radiation at the levels of the double plasma resonance, the polarization of the observed radio emission may be due to a difference in rates of plasma wave conversion into ordinary and extraordinary waves or different conditions of escaping of these waves from the source. In a weakly anisotropic plasma which is a source of the zebra-pattern with rather large harmonic numbers, the degree of polarization of the radio emission at twice the plasma frequency originating from the coalescence of two plasma waves is proportional to the ratio of the electron gyrofrequency to the plasma frequency, which is a small number and is negligible. Noticeable polarization can therefore arise only if the observed radio emission is a result of plasma wave scattering by ions (including induced scattering) or their coalescence with low-frequency waves. In this case, the ordinary mode freely leaves the source, but the extraordinary mode gets into the decay zone and does not exit from the source. As a result, the outgoing radio emission can be strongly polarized as the ordinary mode. Possible reasons for the polarization of the zebra pattern in the microwave region are discussed.

Keywords Plasma physics · Radio bursts, theory · Sun: corona · Sun: radio emission

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Published online: 29 May 2013

1. Introduction

Polarization of radiation is a very important part of the theory of any solar radio emission. This paper is devoted to interpretation of the polarized fine structure in the dynamic spectra of solar radio emission, namely, polarization of the so-called zebra pattern (ZP). It is usually recorded against the background of type IV continuum as quasi-harmonic stripes of enhanced and lowered radiation drifting synchronously in time. The stripes are almost equidistant (the frequency spacing slightly increases with frequency), and the number of stripes in different events changes from three to several tens. ZP is seen in the whole frequency range of the observed solar radio emission – from microwaves to meter wavelengths.

Measurements of polarized radio emission in the zebra stripes have experienced significant problems. Note that we will deal with circular polarization only: even if a linearly polarized component is contained in the radiation escaping from the source, it is impossible to detect it in the radiation passing through the solar atmosphere and arriving at the Earth because of the strong Faraday effect on the propagation path in the solar corona.

At present the data on the ZP polarization are rather poor. This is due to the fact that, first, not all spectrographs recording dynamic spectra are equipped with polarimeters. The second reason is that in order to detect the polarized radiation in zebra stripes, measurements with high frequency resolution are necessary. Indeed, if the frequency band of the receiver is rather wide, both enhanced radiation in zebra stripes and the background can be recorded together, but their polarization is possibly different. From this point of view, the single frequency measurements appear to be rather useful if they are combined with dynamic spectra which make understandable the temporal change of the polarization associated, for example, with the transition from one zebra stripe to another. Further, in order to obtain reliable information about polarization inside zebra stripes, measurements with high spatial resolution are desirable. Otherwise, the antenna pattern contains not only the ZP source, but also the surrounding corona that can influence the polarization of recorded radio emission. Finally, to determine the sense of polarization, that is, to identify the normal mode, it is necessary to know the direction of the magnetic field in the source (for example, in the north polarity of the magnetic field, the right-hand polarization corresponds to the extraordinary mode). This means that the polarization study requires combination of radio and optical measurements. It is clear that there is a significant problem in finding the location of the ZP source in active regions with a complicated structure at the photosphere.

Thus, obtaining reliable information about the polarization of enhanced radiation in zebra stripes is a really difficult problem, and only few observers managed to get some data about the degree and sense of ZP polarization.

The results of measurements at metric and decimetric wavelengths are described mainly by Chernov, Korolev, and Markeev (1975), Chernov and Zlobec (1995), and Chernov (2006). In the bulk of described events (90 %) the radiation in zebra stripes is strongly polarized: the degree of polarization is, as a rule, very high up to 100 %. The sense of rotation is the same for the ZP and the background (as well as for other kinds of fine structure observed in the frequency band coinciding with that of ZP). According to the opinion of the above authors the sense of rotation corresponds to the ordinary mode. The results are obtained mainly by records at a frequency of 237 MHz in Trieste combined with the spectrographic data. A few events were simultaneously recorded by the Nançay Radioheliograph, which gave an idea about the source location. But in most cases the mode type was related to the polarity of the leading sunspot in the corresponding active region, under the assumption that the ZP source is located just above the leading sunspot. From a statistical analysis, the authors also conclude that the ZP emission is polarized as the ordinary mode.

This conclusion was confirmed by the first interferometric observation of a ZP radio burst with simultaneous high spectral and high time resolution performed by the Frequency-Agile Solar Radiotelescope Subsystem Testbed and the Owens Valley Solar Array (Chen *et al.*, 2011). These observations clearly demonstrated that the property of ZP is quite consistent with the model of the double plasma resonance (DPR) and is strongly polarized in the sense of the ordinary mode.

ZP at microwaves is observed not so often as at meter and decimeter wavelengths and demonstrates a large diversity of spectral and polarizational features. The data on microwave ZP are obtained mainly by a spectrograph of China Academy of Science (Huairou) in the frequency band of 5.2 – 7.6 GHz. The observations with high spatial resolution at a frequency of 5.7 GHz are performed by Siberian Solar Radio Telescope (Irkutsk). Results of such observations are given, for example, Huang *et al.* (2003), Huang (2004), Altyntsev *et al.* (2005, 2011), Chernov (2006, 2010), Ning *et al.* (2007), and Tan *et al.* (2012). In the recorded events the ZP consists of both small and large numbers of stripes, being weakly or strongly polarized in the sense of both ordinary and extraordinary modes, and its frequency spacing is constant or grows weakly with the frequency. In some cases, even the inversion of polarization over the frequency band was observed (Huang and Lin, 2006; Huang, Song, and Li, 2013). The possibility is not excluded that some of the recorded events originate from the DPR effect similar to ZP at longer wavelengths (see, for example, Kuznetsov, 2007). But evidently, all this variety of the ZP spectral-polarizational properties at microwaves cannot be explained in the framework of a single source model and with one generation mechanism. In order to develop the theory of the microwave ZP it is necessary to select some general regularities and formulate the most important properties of this structure. Also, the analysis of individual events is worth studying. Therefore, in Section 3, devoted to the theory of the polarized ZP, we consider only one carefully studied event which permits clear interpretation.

2. ZP Polarization at Meter and Decimeter Wavelengths

Prior to the interpretation of polarized zebra structure we recall the main points of the theory of ZP. At present, the main ZP features are explained best of all in the framework of the so-called plasma mechanism of radiation containing a kinetic instability of plasma waves due to the presence of non-equilibrium electrons and transformation of these plasma waves into electromagnetic emission.

It is well known that the non-equilibrium electrons with velocities exceeding the thermal velocity in a plasma are easiest to excite plasma waves at the frequency $f \approx f_\mathrm{p}$ (or $f \approx f_\mathrm{UH}$ in the magnetoactive plasma), which are longitudinal electrostatic modes. Here $f_\mathrm{p} = (e^2 N/\pi m_\mathrm{e})^{1/2}$ is the plasma frequency, $f_\mathrm{UB} = (f_\mathrm{p}^2 + f_B^2)^{1/2}$ is the frequency of the upper hybrid resonance for the waves propagating perpendicularly to the magnetic field B, $f_B = eB/2\pi m_\mathrm{e} c$ is the electron gyrofrequency, e and m_e are the electron charge and mass, respectively, c is the velocity of light, and N is the electron number density. The longitudinal plasma waves are distinguished by the fact that their refractive index is greater than unity, *i.e.*, the phase velocity is less than the velocity of light, so that the electrons with velocity equal to or greater than the phase velocity can give part of their energy to the wave in a resonant manner. For the electromagnetic waves with phase velocity exceeding the velocity of light, such a resonant interaction is impossible, and it is the reason why plasma waves are excited more effectively. It is important that this is true for any kind of non-equilibrium distribution of electrons whether it represents electron beams or trapped particles.

ZP events last for a rather long time and cannot be associated with transient particles. Therefore for its interpretation it is necessary to invoke electrons which are non-equilibrium over velocities perpendicular to the magnetic field, namely, the electrons trapped by the magnetic field. The best explanation for the whole observational ZP properties is provided by a theory based on the double plasma resonance effect. About comparative analysis of different theories for the origin of ZP, see Zlotnik (2009). This effect can be realized in a magnetic trap filled with weakly anisotropic equilibrium plasma where the following inequality is valid:

$$p \equiv f_B/f_{\mathrm{p}} \ll 1, \tag{1}$$

and a group of trapped electrons which are non-equilibrium over velocities transverse to the magnetic field. The effect of double plasma resonance is that the growth rate of instability stimulated by such electrons greatly increases in the regions where the upper hybrid frequency $f_{\mathrm{UH}} = \sqrt{f_{\mathrm{p}}^2 + f_B^2}$ (or plasma frequency f_{p} in weakly anisotropic coronal plasma under condition given by Equation (1)) coincides with the harmonics of electron gyrofrequency:

$$f_{\mathrm{p}} = s f_B, \tag{2}$$

where s is a harmonic number. It is these levels that are the sources of resolved ZP stripes. In this case the longitudinal plasma waves are excited in the directions nearly perpendicular to the magnetic field. The calculation showed (Zheleznyakov and Zlotnik, 1975a, 1975b; Winglee and Dulk, 1986; Kuznetsov and Tsap, 2007) that under typical conditions in coronal traps the frequency distance Δf_{s} between zebra stripes is

$$\Delta f_{\mathrm{s}} \approx f_B(L_B/L_N), \tag{3}$$

where L_B and L_N are the characteristic scales of the variation in magnetic field and electron number density in a non-homogeneous source. Under typical coronal conditions, the inequality $L_B \ll L_N$ is usually valid, which implies that the frequency spacing Δf_{s} is much less than the gyrofrequency f_B. The calculations performed in the above works showed that the frequency interval δf where the plasma waves are excited due to the DPR effect is less than both of the two intervals given above: $\delta f < \Delta f_{\mathrm{s}} \ll f_B$. It is exactly this condition that provides the appearance of resolved stripes in the dynamic spectrum.

An excess of the growth rate $\gamma \approx (N_{\mathrm{e}}/N_0) f_B$ over the effective electron-ion collision frequency $\nu_{\mathrm{ei}} \approx (5.5 N_0 T^{-3/2}) \ln(10^4 T^{2/3} N_0^{-1/3})$ determines the lower boundary of the non-equilibrium electron number density necessary for the excitation and weak damping of plasma waves (Zheleznyakov and Zlotnik, 1975a, 1975b): $N_{\mathrm{e}}/N_0 > 3 \times 10^{-6}$ for typical values representing the ZP source; $T = 10^6$ K, $f_{\mathrm{p}} = 1.5 \times 10^8\ \mathrm{s}^{-1}$, $s = 10-20$, and $v_{\mathrm{e}}/v_{\mathrm{T}} = 20$ (v_{e} and v_{T} are the mean velocities of the non-equilibrium and thermal coronal electrons, respectively). It is clear that for appropriate plasma parameters, the considered DPR instability is easily excited even at a very low number density of the non-equilibrium electrons.

The excited longitudinal plasma waves cannot escape the plasma source because they are strongly absorbed in the rarefied layers due to Landau damping. Therefore, outside the plasma source such radiation can be detected only if it is transformed (in a linear or non-linear manner) into electromagnetic emission which freely escapes the plasma source. In the theory of solar radio emission this problem is thoroughly studied, and for some types of bursts, such conversion mechanisms are elaborated and confirmed by observations (Zheleznyakov, 1970, 2000). As the analysis showed, it is the non-linear coalescence of plasma waves which is the most effective process in the solar corona, as well as scattering of plasma waves by plasma particles or non-linear interaction with low frequency waves:

$$l + l \rightarrow t, \qquad f_{\mathrm{p}} + f_{\mathrm{p}} \approx 2 f_{\mathrm{p}}, \tag{4}$$

$$l + i \rightarrow t, \qquad f_{\mathrm{p}} + f_{\mathrm{lf}} \approx f_{\mathrm{p}}. \tag{5}$$

The process given by Equation (5) results in the appearance of electromagnetic radiation at a frequency which only slightly differs from the frequency of the plasma wave. It is the so-called fundamental emission. Coalescence [Equation (4)] of two plasma waves leads to the emergence of electromagnetic emission at twice the plasma frequency. This concept was brightly confirmed by observations of type II and III solar radio bursts which often display emission at frequencies with a ratio of 1:2 (Wild, Smerd, and Weiss, 1963; Kundu, 1965; Zheleznyakov, 1970).

Our problem is how radiation emerging in the solar corona as a result of DPR effect can be polarized. In an isotropic plasma, the electromagnetic emission originating from the coalescence of longitudinal plasma waves (by processes represented by Equations (4) and (5)) is non-polarized. In a magnetoactive plasma, transformation into two normal transverse waves, *i.e.* ordinary and extraordinary waves, can proceed with different rates depending on the probability of non-linear coalescence of longitudinal waves (which is a function of the magnetic field), as well as dispersion properties of transverse modes. Hence, the polarization of radio emission received on the Earth is determined by different rates of transformation of plasma waves into transverse waves and different conditions of propagation and escape of ordinary and extraordinary waves from the corona.

2.1. Polarization of Emission at Twice the Plasma Frequency

Spectral intensity of the electromagnetic emission emerging as a result of coalescence [Equation (4)] of two plasma waves with wave numbers $\mathbf{k}_1$ and $\mathbf{k}_2$, frequencies ω_1 and ω_2, and spectral energy densities $W_{\mathbf{k}_1}$ and $W_{\mathbf{k}_2}$, is determined by (Tsytovich, 1970)

$$I_{\omega}^{\mathrm{obs}} = (4\pi)^4 \frac{\omega_{\mathrm{p}}^3}{c^3} \frac{L}{n|\partial(\omega^2 n^2)/\partial\omega|} \int |S|^2 W_{\mathbf{k}_1} W_{\mathbf{k}_2} \delta\Lambda, \tag{6}$$

$$\delta\Lambda = \delta(\omega - \omega_1 - \omega_2)\delta(\mathbf{k} - \mathbf{k}_1 - \mathbf{k}_2)\, \mathrm{d}\mathbf{k}_1\, \mathrm{d}\mathbf{k}_2, \tag{7}$$

where $\omega = 2\pi f$ and L is the source size along the line of sight. The right-hand-side of Equation (6) involves two terms which are different for ordinary and extraordinary waves. The first is $|S|$ which is a contraction of the non-linear conductivity tensor determining the probability of plasma wave coalescence. The second term is in the denominator of Equation (6) and contains the refraction index n which is different for ordinary and extraordinary waves in the magnetoactive plasma.

Obviously, in a weakly anisotropic plasma where the condition given by Equation (1) is valid, all the terms which are included in Equation (6) and depend on the magnetic field can be regarded as the first (linear) term of the expansion with respect to the small parameter p [Equation (1)]. For the plasma waves concentrated both inside and outside the cone aligned along the magnetic field with the opening angle θ_0, and under the condition that their energy density inside the cone does not depend on θ_0, the intensity of emission [Equation (6)] into ordinary and extraordinary modes can be written as

$$I_{\omega} = I_{\omega}^{0}\big[1 \pm pA(\alpha, \theta_0)\big], \tag{8}$$

where I_ω^0 does not depend on the magnetic field, and the parameter A is determined by the width of the angular spectrum of plasma waves θ_0 and the angle α between the magnetic field and the line of sight. The upper and lower signs in Equation (8) refer to extraordinary and ordinary modes, respectively. Equation (8) results in the following degree of polarization of radiation at twice the plasma frequency:

$$\rho = \frac{I_\omega^{(\mathrm{e})} - I_\omega^{(\mathrm{o})}}{I_\omega^{(\mathrm{e})} + I_\omega^{(\mathrm{o})}} = \pm p A(\alpha, \theta_0). \tag{9}$$

The parameter $A(\alpha, \theta_0)$ was calculated by Melrose and Sy (1972), Melrose, Dulk, and Smerd (1978), and Zlotnik (1981). It appears that for the plasma waves localized outside the cone with the opening angle θ_0, *i.e.*, under the conditions appropriate to the ZP source, the value A is always positive (independently of the angles α and θ_0) and does not exceed a few units (Melrose, Dulk, and Gary, 1980). This result differs form the calculations of $A(\theta_0, \alpha)$ for the plasma waves concentrated inside the cone (Melrose, Dulk, and Smerd, 1978, 1980; Zlotnik, 1981). In the latter case, the parameter A can be positive or negative, depending on the angles α and θ_0, but the absolute value does not exceed a few units. At small values of θ_0, the polarization can correspond to the ordinary mode, and it explains the observed polarizational data of type III bursts. For the emission arising from the coalescence of plasma waves whose wave vectors are outside the cone, the polarization always corresponds to the extraordinary mode, and the polarization degree is insignificant in a weakly anisotropic plasma under the condition given by Equation (1), that is,

$$0 < \rho \ll 1. \tag{10}$$

In reference to the ZP polarized as the ordinary mode with $\rho = 50 - 100~\%$, this means that the observed emission cannot be the result of coalescence [Equation (4)] of two plasma waves.

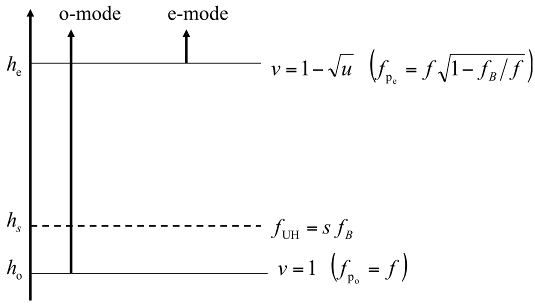
2.2. Polarization of Fundamental Emission

Here we consider possible polarization of electromagnetic emission at the fundamental frequency arising as a result of scattering of plasma waves by plasma ions or their coalescence with low frequency waves [Equation (5)]. From a general point of view it is evident that in a weakly anisotropic plasma when Equation (1) is satisfied, the difference in the conversion rates into ordinary and extraordinary modes, as well as the difference in the dispersion properties of the normal waves, can lead to a small effect of the order of $p = f_B/f_\mathrm{p} \ll 1$, which can hardly explain the observed strong ZP polarization. However, a significant difference in the intensities of the ordinary and extraordinary waves in the emission coming to an observer can be associated with the essentially different conditions of escape of ordinary and extraordinary waves from the corona at a frequency close to the plasma frequency. Indeed, the ordinary and extraordinary waves do not penetrate into the plasma deeper than the levels where the refractive indices become zero: $n^2 = 0$. These points of reflection are located at different levels (see Figure 1) and are determined by the following equations (Ginzburg, 1964; Zheleznyakov, 1970, 2000):

$$v = 1; \quad f_{\mathrm{p_o}} = f \quad \text{(ordinary mode)}; \tag{11}$$

$$v = 1 - \sqrt{u}; \quad f_{\mathrm{p_e}} = f\sqrt{1 - \frac{f_B}{f}} \quad \text{(extraordinary mode)}, \tag{12}$$

Figure 1 The levels of ordinary (o) and extraordinary (e) mode reflection in the solar corona. The dotted line is the DPR level.



and also the location of the reflection points does not depend on the angle α between the magnetic field and the line of sight. In Equations (11) – (12), the standard notations of plasma parameters are used: $v = f_p^2/f^2$ and $u = f_B^2/f^2$. It is important that the level above which undamped ordinary waves can propagate is always located lower in the corona than the corresponding level for extraordinary waves: $f_{p_e} < f_{p_o}$. This means that if the source of radiation at frequency f is located higher in the corona than the level given by Equation (12) of the extraordinary mode reflection, then both waves freely propagate in the coronal plasma. In this case, the outgoing emission is not polarized. If this source is located lower than the level given by Equation (11) of the ordinary mode reflection, then both modes exponentially decay in such a dense plasma. But if the source is located between these two levels, then the only ordinary wave can leave the plasma. In this case, the emission can be completely polarized as the ordinary mode. In a weakly anisotropic plasma, the difference in plasma frequencies at the reflection levels is

$$f_{p_o} - f_{p_e} \approx f_B/2. \tag{13}$$

Thus, the emission is polarized as the ordinary mode if the wave frequency slightly exceeds the local plasma frequency but no more than $f_B/2$.

The idea that a polarized component in solar radio emission emerges due to different condition of escape of the ordinary and extraordinary waves from a source in the corona was put forward fairly long time ago (Fomichev and Chertok, 1968; Zheleznyakov, 1970). It was successfully used for the interpretation of the polarization of type II and III bursts. In this paper, we study possible realization of this effect in the ZP sources in the framework of the DPR model. For this purpose it is necessary to estimate how the frequency of the electromagnetic wave originating, for example, from scattering of plasma waves by ions differs from the frequencies f_{p_o} and f_{p_e} and to find whether the source of electromagnetic emission can be located between the reflection levels given by Equations (11) and (12) of the ordinary and extraordinary waves.

Let us assume that the DPR level corresponding to the harmonic number s is located at a height h_s (Figure 1). First we consider the idealized case where the plasma wave is excited only at a given specified height. In this region the DPR condition

$$f_p(h_s) + \frac{f_B^2(h_s)}{2 f_p(h_s)} = s f_B(h_s) \tag{14}$$

is fulfilled and the frequency of excited plasma waves is

$$f_{pl} \approx f_p(h_s) + \frac{f_B^2(h_s)}{2 f_p(h_s)} + \frac{3}{2} \frac{k_{pl}^2 v_T^2}{(2\pi)^2 f_p(h_s)}. \tag{15}$$

Note that in the framework of the DPR model the frequency f_{pl} slightly differs from the local plasma frequency $f_{\mathrm{p}}(h_s)$, and $f_{\mathrm{pl}} > f_{\mathrm{p}}(h_s)$. This means that if the plasma waves are transformed into electromagnetic waves without changing the frequency, the level of the ordinary mode reflection would have been located in the corona lower than the DPR level, that is, $h_0 < h_s$. If in this case the difference in the plasma wave frequency f_{pl} and the local Langmuir frequency $f_{\mathrm{p}}(h_s)$ is not greater than $f_B/2$, then the DPR level would have been located at a height lower than the level h_{e} of the extraordinary mode reflection.

Let us demonstrate that this condition is fulfilled under conditions typical of the ZP sources. Indeed, the second term on the right-hand side of Equation (15) is about $f_B/2s$, which for typical harmonic numbers of the ZP, $s = 10-20$, is certainly much less than $f_B/2$. When estimating the third term of the sum in Equation (15) we take into account that the magnitude of the wave vector k_{pl} is determined by the non-equilibrium electron velocity v_{e} and is about $k_{\mathrm{pl}} \approx 2\pi f_{\mathrm{p}}/v_{\mathrm{e}}$. In this case, the estimate of the mentioned term leads to the value $1.5(k_{\mathrm{pl}}^2 v_{\mathrm{T}}^2)/(4\pi^2 f_{\mathrm{p}}) \approx 1.5 s f_B (v_{\mathrm{T}}^2/v_{\mathrm{e}}^2) = (0.01-0.04) f_B$ (here, the numerical values are obtained for $s = 10-20$ and $v_{\mathrm{e}}/v_{\mathrm{T}} = 10-20$). Thus, for typical parameters of the ZP, the condition $f_{\mathrm{pl}} - f_{\mathrm{p}}(h_s) \ll f_B/2$ is easily realized. Hence, the source of the zebra stripe is located between the reflection levels of ordinary and extraordinary waves, so that the radiation at the frequency f_{pl}, which coincides with the frequency of the plasma wave excited at the height h_s, escapes from the source being polarized as the ordinary mode.

In the actual case of a non-uniform plasma with plasma waves excited in some frequency range with a possible frequency shift due to transformation into electromagnetic emission, the situation described above will not change, if the mentioned frequency shifts do not remove the DPR level from the height interval between h_{o} and h_{e}. Here, the critical point is that the DPR level is close to the ordinary wave reflection point because this DPR level is quite far from the extraordinary reflection level. This follows from the fact that even the frequency spacing between zebra stripes described by Equation (3) under typical conditions does not exceed $f_B/2$, since in real solar sources the magnetic field changes along the height much faster than the electron number density, *i.e.*, $L_B/L_N \ll 1$. This means that even the neighboring DPR level with the harmonic number $(s+1)$ is located lower than the height h_{e} of the extraordinary mode reflection, and the existence itself of the resolved zebra stripes proves that their bandwidth δf_{s} is much smaller than the frequency spacing between the stripes: $\delta f_{\mathrm{s}} \ll \Delta f_{\mathrm{s}} \approx f_B(l_B/L_N)$.

Further, we estimate the influence of the non-zero frequency interval in which plasma waves are excited on the location of the ZP source relative to the levels h_{o} and h_{e}. It follows from the analysis of plasma wave instability in a homogeneous plasma with different ratios of f_{p} and f_B (Zheleznyakov and Zlotnik, 1975a, 1975b) that the DPR effect is realized in a narrow frequency range neighboring the harmonic frequency $s f_B$ from above. Such a "detuning" $\Delta f_{\mathrm{UH}} = f_{\mathrm{UH}} - s f_B$ does not exceed $(0.01-0.1) f_B$. This is exactly the condition that determines the frequency range of plasma waves excited due to the DPR effect in an inhomogeneous source. Outside this range, the double resonance vanishes, and the growth rate of the plasma waves becomes much less. But for any bandwidth of the plasma wave spectrum, its broadening leads to an increase in f_{pl} compared to the plasma frequency $f_{\mathrm{p}}(h_s)$ at a given height h_s. This means that corrections due to the plasma inhomogeneity and the non-zero bandwidth of the plasma wave spectrum do not move the DPR level away from the source of the polarized radiation between the reflection levels of the ordinary and extraordinary waves.

We now consider a possible frequency change due to transformation of plasma waves into electromagnetic waves. According to Tsytovich (1975), such a process reduces the frequency:

$$f^{\mathrm{obs}} = f_{\mathrm{pl}} - \Delta f_{\mathrm{i}}, \tag{16}$$

where Δf_{i} can be estimated in order of magnitude as

$$\Delta f_{\mathrm{i}} \approx (k_{\mathrm{pl}}/2\pi) v_{\mathrm{T_i}} \tag{17}$$

($v_{\mathrm{T_i}} = \sqrt{(m_{\mathrm{e}}/m_{\mathrm{i}})} v_{\mathrm{T}}$ is the mean velocity of thermal ions in the plasma). A decrease in the electromagnetic wave frequency compared to f_{pl} results in that the reflection level h_{o} of the ordinary mode shifts to the lower electron number density. If such an effect was compared with $f_{\mathrm{pl}} - f_{\mathrm{p}}(h_s)$ or Δf_{UH}, then the reflection level h_{o} of the ordinary mode could have been located higher in the corona than the DPR level at the height h_s. In this case, the electromagnetic emission could not leave the source, that is, the occurrence itself of the observed ZP proves that such frequency change does not happen. Such a conclusion is confirmed by numerical estimations. Taking $(k_{\mathrm{pl}}/2\pi) \approx f_{\mathrm{p}}/v_{\mathrm{e}}$ in Equation (17), we obtain $\Delta f_{\mathrm{i}} \approx s f_B \sqrt{(m/m_{\mathrm{i}})} (v_{\mathrm{T}}/v_{\mathrm{e}})$, which reduces to $\Delta f_{\mathrm{i}} \approx (0.01-0.04) f_B$ at $s = 10-20$, $v_{\mathrm{e}}/v_{\mathrm{T}} = 10-20$. This interval is substantially less than the values $f_{\mathrm{pl}} - f_{\mathrm{p}}(h_s)$ and Δf_{UH} which increase the frequency f_{pl} in Equation (16) compared to $f_{\mathrm{p}}(h_s)$. Thus, the most part of the ZP source is located in the region from which the electromagnetic emission polarized as an ordinary mode escapes.

2.3. Test of Induced Scattering Predominance

Thus, the ZP cannot be highly polarized if it is due to the coalescence [Equation (4)] of plasma waves into electromagnetic emission at twice the plasma frequency. Conversely, the observed polarization is quite explainable if the detected ZP emission is the fundamental emission.

The scattering by ions into the fundamental emission can be spontaneous or induced depending on the energy density of excited plasma waves. If the energy density is rather small, then the scattering proceeds in a spontaneous way, and in this case the emission at twice the plasma frequency prevails. This is due to the fact that only the plasma waves with almost oppositely directed wave vectors can participate in the process of coalescence resulting in the emission at twice the Langmuir frequency. Under the DPR conditions, the plasma waves are excited almost perpendicularly to the magnetic field, that is, the wave vectors are concentrated in a disk, perpendicular to the magnetic field (more exactly, in a narrow angle interval around this disk). In this case, each wave vector can choose the oppositely directed partner, so that the combinational scattering occurs at the waves of the overthermal level. This means that the emission intensity is greater than that from spontaneous scattering of plasma waves by thermal ions. However, if the energy density of the excited plasma waves is large enough and the scattering by ions becomes induced, then the intensity at the fundamental frequency can appear to be greater than the emission intensity at twice the plasma frequency.

We now estimate if the energy density of plasma waves in typical ZP sources is large enough to ensure the induced character of the scattering by ions. The scattering becomes induced if the optical depth of the source relative to the process of induced conversion is greater than unity (Zaitsev, 1975):

$$\tau_{\mathrm{ind}} = \int \mu_{\mathrm{ind}} \, \mathrm{d}l > 1 \tag{18}$$

(here, μ_{ind} is the corresponding absorption coefficient, and integration is performed for the scattering layer along the line of sight). In principle, when estimating the possible part of induced scattering, it is necessary to compare the value τ_{ind} with the optical depth τ_{coll} relative to collisional wave damping. However, estimations show that in the source of ZP $\tau_{\mathrm{coll}} < 1$ is satisfied, so that it is enough to take into account the only condition given by Equation (18).

The coefficient of absorption (amplification) of electromagnetic waves due to induced conversion is determined by the following relation (Tsytovich, 1975; Zaitsev, 1975):

$$\mu_{\mathrm{ind}} \approx \sqrt{\frac{\pi}{8}}\frac{4\pi^2 f_{\mathrm{p}}^2}{m_{\mathrm{i}} v_{\mathrm{gr}} N v_{\mathrm{T_i}}^2}\int \frac{\sin^2\vartheta}{|\mathbf{k}-\mathbf{k}_{\mathrm{pl}}|}\frac{f-f_{\mathrm{pl}}}{f_{\mathrm{pl}}} \cdot \exp\left\{-\frac{2\pi^2 (f-f_{\mathrm{pl}})^2}{|\mathbf{k}-\mathbf{k}_{\mathrm{pl}}|^2 v_{\mathrm{T_i}}^2}\right\} W_{\mathbf{k}_{\mathrm{pl}}}\,\mathrm{d}\mathbf{k}_{\mathrm{pl}}, \tag{19}$$

where v_{gr} is the group velocity of electromagnetic waves, ϑ is the angle between the wave vectors $\mathbf{k}$ and $\mathbf{k}_{\mathrm{pl}}$ of the electromagnetic and plasma waves, and $W_{k_{\mathrm{pl}}}$ is the spectral energy density of the excited plasma waves. If we take into account that in the DPR model the plasma waves are excited in a narrow angle interval across the magnetic field, then for approximate estimations we can put $W_{\mathbf{k}_{\mathrm{pl}}}\,\mathrm{d}\mathbf{k}_{\mathrm{pl}} \approx W(k_{\mathrm{pl}})k_{\mathrm{pl}}^2\,\mathrm{d}k_{\mathrm{pl}}\delta(\theta-\pi/2)\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi/2\pi$ (here θ and φ are the angles in a spherical system of coordinates $(k_{\mathrm{pl}},\varphi,\theta)$ defining the variable vector $\mathbf{k}_{\mathrm{pl}}$ in the space of wave vectors), and put $\cos\vartheta = \cos\varphi\sin\alpha$. Besides, we take into consideration that the width of the plasma wave spectrum exceeds the width of the kernel in Equation (19), so that the condition of differential scattering

$$\frac{3}{2}\left(\frac{v_{\mathrm{T}}}{2\pi f_{\mathrm{pl}}}\right)\left(k_{\mathrm{pl_{max}}}^2 - k_{\mathrm{pl_{min}}}^2\right) > k_{\mathrm{pl}}\sqrt{\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}} \tag{20}$$

is satisfied.

The total energy density of plasma waves is $W_{\mathrm{pl}} = \int W(k_{\mathrm{pl}})k_{\mathrm{pl}}^2\,\mathrm{d}k_{\mathrm{pl}} = \int W_{k_{\mathrm{pl}}}\,\mathrm{d}k_{\mathrm{pl}}$, where the designation $W_{k_{\mathrm{pl}}} = W(k_{\mathrm{pl}})k_{\mathrm{pl}}^2$ is introduced. Then Equation (19) is reduced to the following relation (Zlotnik, 1977):

$$\mu_{\mathrm{ind}} \approx \frac{\pi}{144}\cdot\frac{(2\pi f_{\mathrm{p}})^3(1+\cos^2\alpha)}{v_{\mathrm{gr}} m_{\mathrm{i}} N k_{\mathrm{pl}} v_{\mathrm{T}}^4}\cdot\frac{\mathrm{d}}{\mathrm{d}k_{\mathrm{pl}}}(k_{\mathrm{pl}} W_{k_{\mathrm{pl}}}). \tag{21}$$

In order to perform integration in Equation (18) we passed from integration over the coordinate l to integration over the absolute values of the wave vector k_{pl} taking into account the non-uniformity of the source along the line of sight. Such substitution is determined by the dispersion relation of plasma waves $f_{\mathrm{pl}} = (f_{\mathrm{p}}^2 + f_B^2 + 3k_{\mathrm{pl}}^2 v_{\mathrm{T}}^2/4\pi^2)^{1/2}$ at $f_{\mathrm{pl}} = \mathrm{const}$ and has the form:

$$\mathrm{d}l \approx -\frac{3k_{\mathrm{pl}} v_{\mathrm{T}}^2}{(2\pi^2 f_{\mathrm{p}}^2/L_N) + (4\pi^2 f_B^2/L_B)}\,\mathrm{d}k_{\mathrm{pl}}. \tag{22}$$

Comparison of the two terms in the denominator of Equation (22) shows that for the parameters typical of ZP (for example, $s \approx 10$, $L_N/L_B = 5-10$), the second term rewritten as $(4\pi^2 f_{\mathrm{p}}^2/L_N)(f_B^2/f_{\mathrm{p}}^2)(L_N/L_B) \approx (4\pi^2 f_{\mathrm{p}}^2/L_N)(2L_N/s^2 L_B)$ is much smaller than the first one, so we can use the expression coinciding with that for the isotropic plasma:

$$\mathrm{d}l \approx -\frac{3k_{\mathrm{pl}} v_{\mathrm{T}}^2 L_N}{2\pi^2 f_{\mathrm{p}}^2}\,\mathrm{d}k_{\mathrm{pl}}. \tag{23}$$

Substituting it into Equation (18) and using an approximate expression for the group velocity $v_{\mathrm{gr}} \approx c\sqrt{4\pi^2 f_B^2 + 3k_{\mathrm{pl}}^2 v_{\mathrm{T}}^2}/(2\pi f_{\mathrm{p}})$, we reduce Equation (18) to the following form:

$$\tau_{\mathrm{ind}} = \frac{\pi^3}{2}\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}\frac{f_{\mathrm{p}}^2(1+\cos^2\alpha)L_N v_{\mathrm{T}}^2}{cN\kappa T}\int \frac{k_{\mathrm{pl}}^2}{\sqrt{4\pi^2 f_B^2 + 3k_{\mathrm{pl}}^2 v_{\mathrm{T}}^2}}\frac{\mathrm{d}}{\mathrm{d}k_{\mathrm{pl}}}(k_{\mathrm{pl}} W_{k_{\mathrm{pl}}})\,\mathrm{d}k_{\mathrm{pl}}. \tag{24}$$

Performing integration by parts and taking into account that the width of the wave number spectrum is $\Delta k_{\mathrm{pl}} \approx k_{\mathrm{pl}}$ (when the dispersion of the hot electron velocities is of the order of the mean velocity, that is, $\Delta v_{\mathrm{e}} \approx v_{\mathrm{e}}$ (see Zheleznyakov and Zlotnik, 1975a, 1975b for details), we transform Equation (24) in the following way:

$$\tau_{\mathrm{ind}} \approx \frac{\pi^3}{2}\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}\frac{f_{\mathrm{p}}^2(1+\cos^2\alpha)L_N}{c}\frac{v_{\mathrm{T}}^2}{v_{\mathrm{e}}^2}\frac{1}{[(f_B^2/f_{\mathrm{p}}^2)+(3v_{\mathrm{T}}^2/v_{\mathrm{e}}^2)]^{3/2}}\frac{W_{\mathrm{pl}}}{N\kappa T}. \tag{25}$$

For approximate estimations we put $k_{\mathrm{pl}} \approx 2\pi f_{\mathrm{pl}}/v_{\mathrm{e}}$ and took it out of the integral when passing from Equation (24) to Equation (25). If $f_B \to 0$, then the above relation within the accuracy of the numerical multiplier coincides with the formula for τ_{ind} for the isotropic plasma (Zaitsev, 1975; Zaitsev and Stepanov, 1983):

$$\tau_{\mathrm{ind}} = \frac{\pi^3}{6\sqrt{3}}\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}\frac{f_{\mathrm{p}}^2(1+\cos^2\alpha)L_N}{c}\frac{v_{\mathrm{e}}}{v_{\mathrm{T}}}\frac{W_{\mathrm{pl}}}{N\kappa T}. \tag{26}$$

For parameters typical of the ZP sources, both terms in the denominator of Equation (25) are of the same order of magnitude, but the second one is slightly larger: $f_{\mathrm{p}}^2/f_B^2 \approx s^2 = 100-400$ and $3v_{\mathrm{e}}^2/v_{\mathrm{T}}^2 = 300-1200$ at $s \approx v_{\mathrm{e}}/v_{\mathrm{T}} = 10-20$. Thus, for approximate estimations it is acceptable to use Equation (26) for the isotropic plasma.

In order to estimate the energy density W_{pl} of plasma waves which ensures the implementation of criteria given by Equation (18), we put parameters $f_{\mathrm{p}} = 1.3 \times 10^9$ Hz ($N = 2 \times 10^{10}\ \mathrm{cm}^{-3}$) and $L_N \approx 1.4 \times 10^{10}$ cm found by Chen *et al.* (2011) for the ZP event on 14 December 2006 into Equation (26), and choose the ratio $v_{\mathrm{e}}/v_{\mathrm{T}} = 10-20$ which is optimal for ZP generation. Then we get the following inequality criteria for the induced character of the non-linear scattering process:

$$\frac{W_{\mathrm{pl}}}{N\kappa T} > (2-4)\times 10^{-7} \tag{27}$$

or at the temperature $T = 10^6$ K

$$W_{\mathrm{pl}} > (0.5-1.0)\times 10^{-6}\ \mathrm{erg\,cm^{-3}}. \tag{28}$$

For understanding how large or small is the estimated value of the plasma wave energy density [Equation (28)] it is reasonable to compare it with the total kinetic energy of the electrons responsible for the excitation of plasma waves. If we take a lower boundary of the electron number density of trapped hot electrons, $N_{\mathrm{e}} \approx 3 \times 10^2\ \mathrm{cm}^{-3}$ (it is the value necessary for the instability growth to exceed the collisional damping), and the velocity of hot electrons $v_{\mathrm{e}}/v_{\mathrm{T}} = 20$, which are the optimal values for the DPR mechanism, then we obtain the kinetic energy

$$N_{\mathrm{e}}\frac{m_{\mathrm{e}}v_{\mathrm{e}}^2}{2} \approx 10^{-1}\ \mathrm{erg\,cm^{-3}}, \tag{29}$$

which is in several orders of magnitude higher than the required energy density of plasma waves. This means that in the course of plasma wave excitation hot electrons have to give only a small part of their energy to plasma waves. Thus, the value given by Equation (28) looks quite reasonable.

Assuming that such an energy is reachable, that is, the criterion given by Equation (18) is valid, and the scattering becomes the induced one, the brightness temperature of the resulting electromagnetic radiation is (Zaitsev, 1975)

$$T_{\mathrm{b}} \approx 3\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}}T \approx 5.5\times 10^{9}\ \mathrm{K} \tag{30}$$

and appears to be very close to the brightness temperature $T_{\mathrm{b}} \approx 1.6\times 10^{9}$ K measured for the event observed by Chen *et al.* (2011).

Hence, the observed ZP polarization is quite explainable by the induced scattering of plasma waves by ions for reasonable parameters of the coronal plasma and the electrons trapped by the magnetic field. Once again this confirms that the DPR mechanism can be responsible for the origin of the ZP features.

2.4. Possible Reasons for Depolarization of Radiation at the Fundamental Frequency

Thus, the observed highly polarized ZP can be explained by the difference in conditions of escape of the ordinary and extraordinary modes from the source at a frequency close to the local plasma frequency. According to the concept given in Section 2.2, the escaping radiation is polarized in the sense of the ordinary mode, and the degree of polarization must be about 100 %, since the extraordinary emission does not go away from the DPR region, but the ordinary waves freely propagate and escape from the source. Observations show (see Section 1) that in most recorded events the sense of polarization really corresponded to the ordinary mode, but the measured degree of polarization was often less than 100 %, although its value was usually rather high.

One of the reasons for such a depolarization was considered by Chernov and Zlobec (1995) who discussed the effect of linear coupling of eigenmodes in the region of transverse (relative to the magnetic field) propagation where the WKB approximation is not applicable. This effect is well known in the theory of solar microwave emission (Cohen, 1960; Zheleznyakov and Zlotnik, 1964). Indeed, the totally polarized emission can be depolarized when passing through such a layer: if a wave with 100 % circular polarization of a given sense falls on the layer of transverse propagation and partly transforms into another mode (of the opposite sense), then at the output the circular polarization degree is less than 100 %. However, it can be shown that this effect cannot be effective for the waves of meter and decimeter waveband and cannot ensure the observed depolarization of the ZP.

As a matter of fact, according to Cohen (1960) and Zheleznyakov and Zlotnik (1964), if the 100 % circularly polarized radiation falls on the region where the magnetic field is perpendicular to the line of sight, then the polarization degree at the output of the layer is

$$\rho = 1 - 2\mathrm{e}^{-2\delta_0}, \tag{31}$$

where the coupling parameter $2\delta_0$ depends on parameters of the background plasma (magnetic field $B_\perp$) and the wave (frequency f and the gradient of the angle α between the magnetic field and the line of sight) in the following way:

$$2\delta_0 = \frac{e^5}{32\pi^2 m^4 c^4}\cdot\frac{N B_\perp}{(\mathrm{d}\alpha/\mathrm{d}z)\, f^4}. \tag{32}$$

It is evident that at frequencies $f \ll f_{\mathrm{t}}$ where the transitional frequency f_{t} is found from Equations (31) – (32) under the condition $\rho = 0$ (or $2\delta_0 = \ln 2 \approx 0.7$), the parameter $2\delta_0$ is large enough, which corresponds to weak coupling. In this case, the WKB approximation is valid, and the wave propagates following the change of the medium parameters. This means that when crossing the region of transverse magnetic field, the type of the wave does not change, but due to the sign reversal of the magnetic field projected on the line of sight the sense of polarization also reverses. Thus, if, for example, the left-hand radiation with the frequency $f \ll f_{\mathrm{t}}$ falls on the region of transverse propagation, then the right-hand polarization will be detected at the output of the layer, and *vise versa*.

At comparatively high frequencies $f \gg f_{\mathrm{t}}$ the parameter $2\delta_0$ is rather small, that is, strong coupling happens, and one wave is fully transformed into another. In this case, the sense of the rotation of the electric field is preserved when crossing the transverse magnetic field. Obviously, at the frequency $f \approx f_{\mathrm{t}}$ one mode is partly transformed into another, and in the case where the totally polarized radiation falls on the layer, the escaping emission can be partly polarized. Of course, the total degree of polarization will be 100 % as at the input of the layer, but here the linearly polarized component will be a part of the output radiation (at $f = f_{\mathrm{t}}$ the radiation is fully linearly polarized), but this component is not detectable in the solar radio emission because of the strong Faraday effect along the propagation path in the corona (Zheleznyakov, 1970).

However, the observed ZP depolarization is hardly explained by the linear coupling effect. The reasons are the following. First, for reasonable parameters of the corona, the value f_{t} gets into the microwave band. For the frequency f_{t} to be in the meter waveband it is necessary that the magnetic field $B_\perp$ does not exceed a fraction of a gauss which is unrealistic under the coronal conditions. It is this fact that finds difficulty in explaining the existence of bipolar sources of noise storms in the meter solar radio emission by the effect of linear coupling in the transverse magnetic field (Gopalswamy, White, and Kundu, 1991; White, Thejappa, and Kundu, 1992). Second, the interaction parameter $2\delta_0$ is so sharply dependent on the frequency ($\propto f^{-4}$) that the depolarization can be detected only in a very narrow frequency range, but on both sides of this range the radiation is completely polarized with the opposite senses of rotation. In particular, when the frequency differs from f_{t} as little as 10 %, the degree of polarization changes by 60 %. This means that even if the frequency f_{t} gets into the observed ZP frequency range, the depolarization may be detected only in one or two stripes, but on both sides of these stripes the radiation would be completely polarized with the opposite senses of rotation. Such features have never been observed in ZP at meter and decimeter wavelengths.

Another reason for the possible depolarization seems an accumulation of radiation from zebra stripes and the background between stripes (on-stripe and off-stripe, following the terms introduced by Chen *et al.* (2011)) in the frequency band of the receiving equipment. Indeed, if the off-stripe radiation was unpolarized, the total polarization of both components would have been lowered. However, the off-stripe radiation also owes its origin to the plasma mechanism, so that if the on- and off-stripe sources are closely located, then the off-stripe emission should also be strongly polarized with the same sense of rotation. According to a few observations described by Chernov (2006), the sense and degree of polarization are the same for the on- and off-stripe emission. However, the selection of on- and off-stripe polarization is a very difficult problem which can be solved only by high frequency resolution measurements. Thus, the similarity of the on- and off-stripe polarization cannot be considered as a well-established fact.

At the same time, the observations by Chen *et al.* (2011) clearly indicate the spatial separation of the sources of the ZP and the background sources. In this context, it is not improbable that the observed depolarization may be associated with the input of the layer $f_{\mathrm{p'}} = f_{\mathrm{p}}/2$

into radiation at the frequency $f = f_{\mathrm{p}}$. As was shown in Section 2.3, the induced scattering into the wave at the fundamental frequency prevails over the combinational scattering into radiation at twice the plasma frequency under the condition of a sufficiently high intensity of plasma waves arising as a result of instability. It is quite probable that in the DPR regions (the sources of on-stripe emission) such a high level of energy density of plasma waves can be achieved, but the energy level of the plasma waves excited outside the DPR region (the sources of off-stripe emission) is not sufficient for the induced scattering; thus, the escaping off-stripe emission at the frequency $f = f_{\mathrm{p}}$ is a result of combinational scattering of the plasma waves. This means that the radiation originating from the region between two neighboring DPR regions at a frequency close to f_{p} is observed at the frequency $f \approx 2f_{\mathrm{p}}$, and the off-stripe radiation at the frequency close to f_{p} is excited in the layer $f_{\mathrm{p}'} = f_{\mathrm{p}}/2$ located higher in the corona. In this case, the total radiation can be partly polarized. The mentioned difference in the spatial location of the on- and off-stripe sources, which was observed by Chen *et al.* (2011), can be an argument in favor of this point of view.

2.5. ZP Polarization in Microwave Band

As was pointed out in Section 1, in the microwave region there was observed one exclusive event with the sense of rotation corresponding to the extraordinary mode. This case cannot be understood as the difference in output conditions for the ordinary and extraordinary waves, and is therefore worth special study.

The event on 5 January 2003 described in detail by Altyntsev *et al.* (2005) was also distinguished by some other features. It contained a small amount of stripes (no more than four), in which the time variations occurred simultaneously. The analysis of many ZP events in which the changes seemed to be simultaneous revealed a time delay (a peculiar kind of frequency drift) of such changes from one stripe to another, and it confirms the possibility of separated sources of different stripes in the DPR model of ZP. However, a more thorough analysis of the 5 January 2003 event showed that the changes in frequency were quite simultaneous, which proves that the total ZP was generated in the same source. This fact (together with a small quantity of stripes) permits the authors Altyntsev *et al.* (2005) and Kuznetsov (2005) to conclude that this event is understood as the generation of Bernstein modes in a compact source with a uniform magnetic field and their subsequent transformation into electromagnetic radiation by coalescence with the plasma waves at the upper-hybrid frequency or coalescence of Bernstein modes with different harmonic numbers (Zheleznyakov and Zlotnik, 1975a, 1975b). The frequency of the observed radio emission is determined by the sum of the frequencies:

$$f = f_{\mathrm{UH}} + s f_B \quad \text{or} \quad f = s_1 f_B + s_2 f_B. \tag{33}$$

The excitation of Bernstein modes and their possible role in the ZP were investigated by Zheleznyakov and Zlotnik (1975a, 1975b), Altyntsev *et al.* (2005), and Kuznetsov (2005). It is important that the growth rate of Bernstein modes is an order of magnitude lower than that of the DPR effect, but the constraints for the velocity of the non-equilibrium electrons is weaker. In particular, the resolved zebra stripes arising due to the Berstein mode instability can exist for the velocities $v_{\mathrm{e}} = (4-6)v_{\mathrm{T}}$, which conforms with the electron energy of 30 – 50 keV observed at the temperature of flaring plasma $T \approx 10$ MK.

Calculations of the intensity of electromagnetic radiation arising from the coalescence of Bernstein modes with the upper hybrid plasma wave give the following value (Zlotnik, 1976, 1977; Kuznetsov, 2005):

$$I_{\mathrm{f}} \approx I_{\mathrm{f}}^0 (1 \mp \cos\alpha)^2, \tag{34}$$

where α is the angle between the magnetic field and the line of sight, the upper and lower signs correspond to the extraordinary and ordinary modes, and the multiplier I_{f}^{0} is the same for both waves. It is clear from Equation (34) that the ratio between the ordinary and extraordinary mode intensities depends essentially on the angle under which the radio emission is observed. The degree of circular polarization is

$$\rho \approx \frac{2\cos\alpha}{1+\cos^2\alpha}, \tag{35}$$

and depending on the angle α can adopt a value from -1 up to $+1$. In a wide angle interval $\alpha \leq 60^\circ$ the degree of circular polarization acquires high values (more than 80 %). The sense of rotation can correspond to both ordinary ($\rho > 0$ at $0 < \alpha < \pi$) and extraordinary ($\rho < 0$ at $\pi < \alpha < 0$) modes. Thus, the polarization of the ZP corresponding to the extraordinary mode, which was observed in the 5 January 2003 event, is quite understandable in the model of generation of Bernstein modes in the compact sources and their coalescence with plasma waves.

We emphasize once more that when identifying the type of the wave using the observed sense of rotation and the polarity of the magnetic field at the photosphere it is necessary to take into account the possible reversal of rotation in the magnetoactive plasma in the solar corona (Cohen, 1960; Zheleznyakov and Zlotnik, 1964; Zheleznyakov, 1970). Assume, for instance, that in the source of the north polarity we have left-handed rotation, that is, the ordinary mode. Further, the wave can get into the region where the magnetic field is perpendicular to the line of sight. In the absence of linear coupling, that is, when the WKB approximation is valid, the wave remains the ordinary one, but the projection of the magnetic field on the line of sight reverses, so that the rotation becomes the right-handed one. From the point of view of an observer at infinity, the right-handed rotation in the north polarity corresponds to the extraordinary mode. Thus, such configurations can sometimes lead to an incorrect identification of the type of the wave prevailing in the observed radio emission. However, in the microwave region the condition of strong linear coupling is usually realized for the reasonable coronal parameters. In this case, the wave propagates through the region of transverse magnetic field "ignoring" the reversal of the projection of the magnetic field on the line of sight (the type of the wave changes and the sense of rotation holds). Therefore, in the considered event the polarization, most probably, corresponds to the extraordinary mode.

It should be noted also that together with the effect of linear coupling in the transverse magnetic field, the polarization of microwave emission may be changed due to greater absorption of the extraordinary wave compared to that of the ordinary wave, along the propagation path in the corona (Meshalkina *et al.*, 2004). This effect is probably not important for radio emission at meter and centimeter wavelengths, but in the microwave band it can increase predominance of the ordinary mode.

3. Conclusions

The consideration above permits us to make the following conclusions.

i) The radiation with ZP spectrum is as a rule strongly polarized, and the sense of rotation corresponds to the ordinary mode (except for one exclusive event at microwaves).
ii) In the framework of the plasma mechanism of ZP radiation the prevalence of the ordinary mode is possible only in the case where the conversion of longitudinal plasma

waves into transverse electromagnetic ones is more effective at the fundamental than at twice the Langmuir frequency. Strong polarization is explained by the hindered escape of the extraordinary mode and free escape of the ordinary mode from the source of plasma radiation at a frequency close to the upper hybrid one.

iii) Depolarization of the radio emission propagating in the corona cannot be associated with the effect of linear coupling of electromagnetic waves in the region of transverse magnetic field. One of the possible reasons for depolarization is the contribution of the weakly polarized component escaping from the level $f_{\mathrm{p}}/2$.

iv) Strong ZP polarization at microwaves corresponding to the extraordinary mode cannot be explained in the framework of the DPR model. The most probable origin of this kind of spectrum is the excitation of Bernstein modes in a compact uniform source and their coalescence with the plasma waves. It does not imply, however, that the suggested mechanism is the prevailing one for the microwave ZP. A large variety of the ZP spectral and polarizational properties does not allow a single interpretation and requires further investigation.

It should be emphasized once more that measurements of the ZP polarization are the reliable way to learn whether the observed ZP frequency is the fundamental or the second harmonic of the plasma frequency. In the case of strong polarization with the sense of the ordinary mode, the observed ZP frequency certainly corresponds to the fundamental. The ZP observations are actually the only way to get information about the structure and magnitude of the magnetic field immediately in the sources of electron acceleration. New radio telescopes which permit to localize the radio sources relative to the photospheric magnetic structure and, therefore, to determine the mode type at several frequencies simultaneously and for both right-hand and left-hand modes (Chen *et al.*, 2011; Altyntsev *et al.*, 2011) can be very helpful for this purpose.

Acknowledgements This work was partly supported by the Russian Foundation for Basic Research (Project Nos. 13-02-00157-a, 11-02-00103-a, 12-02-91161-GFEN-a, and 12-02-00173-a).

References

Altyntsev, A.T., Kuznetsov, A.A., Meshalkina, N.S., Rudenko, G.V., Yan, Y.: 2005, *Astron. Astrophys.* **431**, 1037.
Altyntsev, A.T., Lesovoi, S.V., Meshalkina, N.S., Sych, R.A., Yan, Y.: 2011, *Solar Phys.* **273**, 163.
Chen, B., Bastian, T.S., Gary, D.E., Jing, J.: 2011, *Astrophys. J.* **736**, 64.
Chernov, G.P.: 2006, *Space Sci. Rev.* **127**, 195.
Chernov, G.P.: 2010, *Res. Astron. Astrophys.* **10**, 821.
Chernov, G.P., Zlobec, P.: 1995, *Solar Phys.* **160**, 79.
Chernov, G.P., Korolev, O.S., Markeev, A.K.: 1975, *Solar Phys.* **44**, 435.
Cohen, M.H.: 1960, *Astrophys. J.* **131**, 664.
Fomichev, V.V., Chertok, I.M.: 1968, *Sov. Astron.* **12**, 21.
Ginzburg, V.L.: 1964, *The Propagation of Electromagnetic Waves in Plasmas*, Pergamon, Oxford, 142.
Gopalswamy, N., White, S.M., Kundu, M.R.: 1991, *Astrophys. J.* **379**, 366.
Huang, G.: 2004, *J. Geophys. Res.* **109**, 02105.
Huang, G., Lin, J.: 2006, *Astrophys. J. Lett.* **639**, L99.
Huang, G., Song, Q., Li, J.: 2013, arXiv:1301.2817.
Huang, G.L., Wu, H.A., Grechnev, V.V., Sych, R.A., Altyntsev, A.T.: 2003, *Solar Phys.* **213**, 341.
Kundu, M.R.: 1965, *Solar Radio Astronomy*, Interscience, New York, 98.
Kuznetsov, A.A.: 2005, *Astron. Astrophys.* **438**, 341.
Kuznetsov, A.A.: 2007, *Astron. Lett.* **33**, 319.
Kuznetsov, A.A., Tsap, Yu.T.: 2007, *Solar Phys.* **241**, 127.
Melrose, D.B., Sy, W.N.: 1972, *Aust. J. Phys.* **25**, 387.

Melrose, D.B., Dulk, G.B., Gary, D.E.: 1980, *Proc. Astron. Soc. Aust.* **4**, 50.
Melrose, D.B., Dulk, G.B., Smerd, S.F.: 1978, *Astron. Astrophys.* **57**, 279.
Meshalkina, N.S., Altyntsev, A.T., Sych, R.A., Chernov, G.P., Yan, Y.: 2004, *Solar Phys.* **221**, 85.
Ning, Z., Wu, H., Xu, F., Meng, X.: 2007, *Solar Phys.* **242**, 101.
Tan, B., Yan, Y., Tan, C., Sych, R., Gao, G.: 2012, *Astrophys. J.* **744**, 166.
Tsytovich, V.N.: 1970, *Nonlinear Effects in Plasma*, Plenum, New York, 39, 70.
Tsytovich, V.N.: 1975, *Theory of Turbulent Plasma*, Consultant Bureau, New York, 181.
White, S.M., Thejappa, G., Kundu, M.R.: 1992, *Solar Phys.* **138**, 163.
Wild, J.P., Smerd, S.F., Weiss, A.A.: 1963, *Annu. Rev. Astron. Astrophys.* **1**, 291.
Winglee, R.M., Dulk, G.A.: 1986, *Astrophys. J.* **307**, 808.
Zaitsev, V.V.: 1975, *Sov. Astron. Lett.* **1**, 206.
Zaitsev, V.V., Stepanov: 1983, *Solar Phys.* **88**, 297.
Zheleznyakov, V.V.: 1970, *Radio Emission from the Sun and Planets*, Pergamon Press, New York, 89, 318.
Zheleznyakov, V.V.: 2000, *Radiation in Astrophysical Plasmas*, Kluwer Academic, Dordrecht, 95,337.
Zheleznyakov, V.V., Zlotnik, E.Ya.: 1964, *Sov. Astron.* **7**, 485.
Zheleznyakov, V.V., Zlotnik, E.Ya.: 1975a, *Solar Phys.* **43**, 431.
Zheleznyakov, V.V., Zlotnik, E.Ya.: 1975b, *Solar Phys.* **44**, 461.
Zlotnik, E.Ya.: 1976, *Radiophys. Quantum Electron.* **19**, 337.
Zlotnik, E.Ya.: 1977, *Sov. Astron.* **21**, 744.
Zlotnik, E.Ya.: 1981, *Astron. Astrophys.* **101**, 250.
Zlotnik, E.Ya.: 2009, *Cent. Eur. Astrophys. Bull.* **33**, 281.