FEATURES OF STOCHASTIC DECAY IN THE MAGNETOACTIVE PLASMA

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The regular and stochastic decay processes of transverse electromagnetic waves in the magnetoactive plasma investigated. The essential attention noted to decay into oscillations with dynamics that takes into account ion plasma component. The threshold of transition into dynamics chaos defined. It was shown that transition may take place at abnormally small amplitudes of decaying wave. Dynamics of fields in the dynamics chaos regime investigated.

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INTRODUCTION

Wave interaction is one of the fundamental processes in the plasma physics and plasma electronics. The linear processes of such interaction well investigated. The weakly nonlinear interactions are enough well investigated essentially three wave interaction in isotropic plasma are investigate in detail (see [1 - 3]). In particular, in the work [1], in general the algorithm that allows to obtain equations describing not only wave interaction in isotropic matter but in gyrotropic one too was formulated. But, it is needed to note that dynamics in gyrotropic matters practically was not studied. It is conditioned, first of all that this studying has large technical difficulties. These difficulties is conditioned first of all by abundant dispersion properties of gyrotropic matters (magnetoactive plasma). In connection with these difficulties the issue about three wave interaction in gyrotropic plasma was only slightly affected in [4]. It needed to note also one feature of work where three wave processes in plasma consider. This connected with that practically in all works the dynamics of electron component of plasma only considered

In presented work the process of three wave interaction magnetoactive plasma is considering. In this case as ordinary decay as modified one will considered. The modified decay is such process where linear stage is characterized by increment that is large than frequency of low frequency wave taking part in the process of three wave interaction. Below in the section 2 the equations describing three wave interaction with taking into account low frequency oscillations properties of that in particular defined by ion component of plasma. In this section, the analytical expression for criterion of transition of regular dynamics into stochastic decay regime obtained. In the third section the process of stochastic dynamic of interacting wave considered. In conclusion the main results formulated.

1. FORMULATION OF PROBLEM AND BASIC EQUATIONS

Nonlinear wave interaction in plasma well studied area of plasma physics. Usually studying of processes of such wave interaction is limited by weakly nonlinear approximation. In this approach, it is supposed that in the interaction the natural waves of electrodynamics system take part. Amplitudes of these waves slowly vary in time and space under influence of nonlinear process. The simplest case when three waves take part in interaction studied most in detail. The basic approaches and results in this area presented, for example, in works [1 - 3]. In the work [5, 6] it was shown that three wave decay processes may be chaotic. The criterion of transfer to chaos has been found in this work. Some aspects of the dynamic of chaotic decays considered in [7 - 12]. The results of numerical investigation presented in these work, the spectrum and correlation functions presented too. It was shown if transition of decay into chaotic regime takes place, spectrum of interacting waves is expanding. Width of correlation function is finite. The results of analytical and numerical investigations have been confirmed by experiment.

In this work the process of three wave decay in unlimited gyrotropic matter (magnetoactive plasma) will be investigated. It is supposed that external uniform magnetic field is directed along z axis and interacting waves may propagate under arbitrary angle relatively magnetic field direction. The space and temporal dependence of electromagnetic field may be presented as sum eigen waves and has next form

$$\vec{E}(\vec{r},t)=\sum_m \vec{E}_m(\vec{r},t)\exp(i\omega_m t - i\vec{k}_m\vec{r}), \qquad (1)$$

where $\vec{E}_m(\vec{r},t)$ – complex slowly varying amplitude of wave, ω_m and $\vec{k}_m$ – are frequency and wave vector correspondingly. Algorithm for obtaining equations for slowly varying amplitudes of waves taking part in decay process in the infinitely extended uniform plasma presented in works [1 - 3] in detail. In [1] it generalized for magnetoactive plasma. Nonlinear dispersion equation for one of the interacting wave has the following form:

$$\left[k_m^2-\left|\vec{e}_m\vec{k}_m\right|^2-\frac{\omega_m^2}{c^2}\left(e_\alpha^*\varepsilon_{\alpha\beta}e_\beta\right)\right]E_m = i\frac{4\pi\omega}{c^2}\vec{e}_m^*\left(\vec{j}_{nl}\right)_m, \qquad (2)$$

where E_m – module of complex of amplitude of wave taking part in decay process, $\vec{e}_m=\vec{E}_m/E_m$ – unit wave vector of polarization, $\varepsilon_{\alpha\beta}$ – permittivity tensor of magnetoactive plasma, c – velocity of light, $\left(\vec{j}_{nl}\right)_m$ – nonlinear current. Expressions for components of permittivity tensor for magnetoactive plasma may be find in [13, 14].

In the nonlinear addendums (items, summands) taking into consideration multiplication of perturbation of density and velocity plasma waves taking part in decay process. The multiplication of perturbation of density and velocity of the plasma waves taking part in decay process has been taken into consideration in the nonlinear items. In this case perturbations corresponding linear approximation are used. In order to right part of equation (2) was resonant to the left part the frequencies and wave vectors must satisfy to synchronism conditions

$$\omega_1 = \omega_2 + \omega_3, \quad \vec{k}_1 = \vec{k}_2 + \vec{k}_3, \tag{3}$$

where ω_1, $\vec{k}_1$ – frequency and wave vector of decaying waves, ω_2, ω_3 – frequencies of waves arising in the decay, $\vec{k}_2$, $\vec{k}_3$ – their wave vectors.

Equation (2) for decaying wave may be presented in the form:

$$D(\omega,\vec{k})E_1 = i\frac{4\pi\omega}{c^2}\vec{e}_1^{\,*}\left(\vec{j}_{nl}\right)_1. \tag{4}$$

Here $D(\omega,\vec{k}) = k^2 - \left|\vec{e}\vec{k}\right|^2 - \frac{\omega^2}{c^2}\left(e_\alpha^* \varepsilon_{\alpha\beta} e_\beta\right)$. As a result of nonlinear interaction amplitudes of wave slowly vary. So modes taking part in decay process is not monochromatic. They are wave packets with some spreading on frequencies and wave vectors. So expression for dispersion equation may be decomposed into Taylor series on small variations on frequency and wave vector from values that are dispersion of monochrome linear dispersion equation. Function $D(\omega,\vec{k})$ may be presented in the form

$$D(\omega,\vec{k}) = D(\omega_1,\vec{k}_1) + \frac{\partial D(\omega_1,\vec{k}_1)}{\partial\omega}(\omega-\omega_1) + \frac{\partial D(\omega_1,\vec{k}_1)}{\partial\vec{k}}\left(\vec{k}-\vec{k}_1\right). \tag{5}$$

Wave with parameters $\left(\omega_1,\vec{k}_1\right)$ is eigen modes for considering electrodynamic system, so the next condition is satisfies:

$$D(\omega_1,\vec{k}_1) = 0\,. \tag{6}$$

To transfer to space and temporal variables it is needed to perform. The inverse Fourier transformation is needed to use to the nonlinear dispersion equation for transfer to space and time variables. This procedure described in detail in [1, 3]. As a result taking into account condition (6) differential equation in partial derivatives for slowly varying amplitudes of interacting waves are obtained. Below equation for decaying wave is presented:

$$\frac{\partial E_1}{\partial t} + \vec{v}_{gr}\left(\omega_1,\vec{k}_1\right)\frac{\partial E_1}{\partial\vec{r}} = i\frac{4\pi\omega_1}{c^2}\frac{\vec{e}_1^{\,*}\left(\vec{j}_{nl}\right)_1}{A_1\left(\omega_1,\vec{k}_1\right)}, \tag{7}$$

where $\vec{v}_{gr}\left(\omega_1,\vec{k}_1\right)$ – group velocity of this wave, $A_i\left(\omega_i,\vec{k}_i\right) = \frac{\partial D\left(\omega_i,\vec{k}_i\right)}{\partial\omega}$. Index j points to any interacting waves.

The perturbations of density and velocity of plasma electrons and ions, containing in nonlinear current, can be expressed through slowly varying amplitudes of waves, taking part in nonlinear interaction. These expressions may be obtained from linear approach of hydrodynamics equations. Analogous equations may be obtained for slowly varying amplitudes that waves which be excited in the decay process. As result, analytical expressions for right parts of equations describing nonlinear wave interaction of three waves may be obtained. These expressions are lengthy, so do not present here.

In the compact form equations describing nonlinear interaction in particular wave decay may be presented in next form:

$$\begin{aligned} &\frac{\partial a_1}{\partial t} = V a_2 a_3, \\ &\frac{\partial a_2}{\partial t} = -V a_1 a_3^*, \\ &\frac{\partial^2 a_3}{\partial t^2} + \omega_3^2 a_3 = -V a_1 a_2^*, \end{aligned} \tag{8}$$

where V – matrix elements of interaction. The change of variables describing electromagnetic field presented in [1] and using of conservation laws for energy and momentum allows to transform set (8) to form where matrix elements of interaction containing in different equations are equal. In the equation (8) there was taken into account that third low frequency wave itself may slowly vary. So we conserve it oscillation properties. If amplitude of decaying wave is enough small that increment of decay instability is less than frequency of LF wave the third equation of set (8) may be done shortened. It has form:

$$\frac{\partial a_3}{\partial t} = -V a_1 a_2^*\,. \tag{9}$$

In this case set of equations (8) coincides with one that presented by many others (see, for example [1 - 3]). It is possible to use results obtained in these works. The existing in this set integrals, named Manly-Row correlation, are most impotent for us:

$$\begin{aligned} &\left|a_1\right|^2 + \left|a_2\right|^2 = const, \\ &\left|a_1\right|^2 + \left|a_3\right|^2 = const. \end{aligned} \tag{10}$$

There are also two integrals:

$$\begin{aligned} &\Sigma = \omega_1\left|a_1\right|^2 + \omega_2\left|a_2\right|^2 + \omega_3\left|a_3\right|^2 = const, \\ &\left|a_1\right|\left|a_2\right|\left|a_3\right|\sin\Phi = const, \end{aligned} \quad . \tag{11}$$

where Σ – total energy of interacting waves, $\Phi = \varphi_1 - \varphi_2 - \varphi_3$, φ_1, φ_2, φ_3 – phases of slowly varying complex amplitudes a_1, a_2, a_3 $\left(a_j = \left|a_j\right|\exp\left(i\varphi_j\right)\right)$. Solution of set (8) taking into account equation (9) investigated in [2]. The qualitative analysis presented in [1]. Decay dynamics is periodical exchange by energy between interacting modes.

Coming back to set of equations (8) it is possible to define criterion for onset of regime with dynamics chaos. This regime arises when amplitude of decaying wave will be enough large that increment of decay instability will be larger than frequency of LF wave. Such estimation obtained in work [5, 6]. We may use this estimation:

$$a_{10} > \frac{\min(\omega_2, \omega_3)}{V}, \qquad (12)$$

where a_{10} – initial amplitudes of decaying wave. As it seen from expression (12) this phenomenon have threshold character.

2. ANALYTICAL EXPRESSION CRITERION OF ARISING OF STOCHASTIC INSTABILITY

Expression (12) is general. It does not contain parameters of the waves taking part in interaction. Earlier expression (12) was concretized for case of waves that characteristic was defined by electron component of plasma only. Below we will consider case of interaction of wave property of which defined not only by electron components, but ion one too.

Further we will consider such decay when frequencies of wave nonlinearly interacting satisfy following relations:

$$\omega_1 \approx \omega_2 >> \omega_3, \;\; k_1 \approx k_2 \approx k_3. \qquad (13)$$

As ω_1 and ω_2 in magnetoactive plasma it can be HF electromagnetic waves, which frequencies are very close. In works [7 - 12] the case is considered when lowest frequency was defined by electron component dynamics and its frequency was order Langmuir one. In this work we interest by decay in which dispersion properties of low frequency significantly defined by ion component of the plasma. In particular, it may be Alfven wave. In this case it's frequency is close to ion cyclotron frequency. One can expect that in this case threshold of transfer to stochasticity will be more less than in case Langmuir waves. The waves with low frequency that are excited in such decay may be used for heating of ion plasma. Thus we have physical mechanism, allowing excites LF waves in plasma. These waves can be used for heating plasma ions.

Let's get an analytical expression for the criterion of transition to chaotic dynamics. For this we use equation (7) that after simplification may be presented in such form:

$$\frac{\partial E_1}{\partial t} = -\frac{4\pi\omega_1}{c^2}\frac{\vec{e}_1^{\,*}\vec{j}_{nl1}}{A_1}. \qquad (14)$$

Expression for current density containing in right part of equation (13) may be presented as following:

$$\vec{j}_{nl1}^{(1)} = -e\left(\tilde{n}_{e2}\tilde{v}_{e3}\right) - e\left(\tilde{n}_{e3}\tilde{v}_{e2}\right). \qquad (15)$$

Expression for perturbation of electron density is:

$$\tilde{n}_{e3} = -i\frac{n_0 e k_{z3}}{m_e\omega_3^2}E_{z3}. \qquad (16)$$

From this follows:

$$\tilde{n}_{e3}\tilde{v}_{e2} = -\frac{n_0 e k_{z3}}{m_e\omega_3^2}E_{z3}\frac{e e_{z2}}{m_e\omega_2}E_2 \approx \frac{1}{\omega_3^2}E_2 E_{z3}. \qquad (17)$$

Using these expressions the (14) may be presented in the following form:

$$\frac{\partial E_1}{\partial t} = V E_2 E_3. \qquad (18)$$

From these the expression for matrix element follows:

$$V = \frac{\omega_{pe}^2 e k_3}{m_e c^2 A_1}\frac{1}{\omega_3^2}. \qquad (19)$$

It is needed to note that value of this element is inversely proportional to square of low frequency. This means that width of nonlinear resonance becomes the large the lower is frequency of LF wave. About nonlinear resonance see work [5, 6]. Thus in our case not only distance between nonlinear resonances decreases (this distance decreases proportional to first power of frequency of LF wave) but width of nonlinear resonance increase.(inversely proportional to square frequency of LF wave). As a result value of strength of decaying HF wave that is needed for appearance of regime with dynamics chaos will be proportional to third power the frequency of LF wave:

$$E_{th} = \omega_3^3\frac{m_e c^2 A_1}{\omega_{pe}^2 e k_3}, \qquad (20)$$

where m_e – mass of electron, ω_{pe} – electron plasma frequency. From (20) it follows that strength of HF wave which is needed for appearance of stochastic decay will be abnormally small for decay with participation of waves which properties defined by ions of plasma.

3. DYNAMICS OF WAVES IN THE STOCHASTIC REGIME

In the overwhelming majority of cases wave dynamics in the stochastic regime is fact that main sensitive and easily varying parameters of the interacting waves are their phases. Additional argument for such affirmation is well known fact that amplitudes of interacting waves may be considered in many cases as adiabatic invariants. Besides, if do not concretize reason of appearance of chaotic regime in many cases analysis of chaotic regimes occurses namely with accounting of this fact. In particular, such analysis was used in work [2]. Below we will follow to this analyses algorithm.

The set of equations (8) describes three wave decay in that case when waves participating in nonlinear interaction are regular. In the opposite case nonlinear interaction is becoming stochastic. This process is describing by equations of decay process with random phases. Their obtaining described in detail in [1, 3]. After transition of regular decay process into stochastic regime it dynamics may be described by equations with random phases. We use algorithm described in [1]. First of all we note that set of equations (8) may be presented in next way

$$\frac{\partial |a_1|^2}{\partial t} = V\left(a_1^* a_2 a_3 + a_1 a_2^* a_3^*\right),$$
$$\frac{\partial |a_2|^2}{\partial t} = -V\left(a_1^* a_2 a_3 + a_1 a_2^* a_3^*\right), \qquad (21)$$
$$\frac{\partial |a_3|^2}{\partial t} = -V\left(a_1^* a_2 a_3 + a_1 a_2^* a_3^*\right).$$

After complex transformations set of equations for modules of slowly varying complex wave amplitudes with random phases will have form:

$$\frac{\partial N_1}{\partial t}=W\left(N_2N_3-N_1N_2-N_1N_3\right),$$
$$\frac{\partial N_2}{\partial t}=\frac{\partial N_3}{\partial t}=-\frac{\partial N_1}{\partial t}, \quad (22)$$

where $N_i=|a_i|^2$, $W=V^2\tau$, τ – correlation time between phases.. This set of equations as (8) has integrals (10). Manly-Row correlations allow to transform set of equations (22) to one ordinary differential equation of first order:

$$\frac{\partial N_1}{\partial t}=3W\left[N_1^2-\frac{2}{3}\left(C_{12}+C_{13}\right)N_1+\frac{C_{12}C_{13}}{3}\right], \quad (23)$$

or

$$\frac{\partial N_1}{\partial t}=3W\left(N_1-N_1^{(1)}\right)\left(N_1-N_1^{(2)}\right), \quad (23a)$$

where $C_{12}=N_{10}+N_{20}$, $C_{13}=N_{10}+N_{30}$, N_{10}, N_{20}, N_{30} – initial values of N_1, N_2, N_3 correspondingly, $N_1^{(1,2)}=\frac{1}{3}\left(C_{12}+C_{13}\right)\pm\frac{1}{3}\sqrt{C_{12}^2-C_{12}C_{13}+C_{13}^2}$.

Unlike from (8) equation (23) has stationary points that equal to $N_1^{(1)}$ and $N_1^{(2)}$. Analytical analysis shows that first of them is unstable and second is stable. It may show when time tends to infinity solution tends to stable stationary point independent from initial conditions. Expressions for values of stationary point of N_2, N_3 do not present here because they are enough complex. Stationary values for N_1, N_2, N_3 when conditions $N_{10}>>N_{20}, N_{30}$ are satisfied have the form:

$$N_1^{(2)}=\frac{1}{6}\left(2N_{10}+N_{20}+N_{30}\right),$$
$$N_2^{(2)}=\frac{1}{6}\left(4N_{10}+5N_{20}-N_{30}\right), \quad (24)$$
$$N_3^{(2)}=\frac{1}{6}\left(4N_{10}-N_{20}+5N_{30}\right).$$

As it seen from expressions (24) in the stochastic regime of three wave decay when the amplitude of decaying wave is significantly large than amplitudes of other waves on large temporal interval the square of first wave module will have one third part of it initial value. Squares of modules of waves that generated in decay process essentially increase and will have two third parts from square of initial amplitude value of first wave. But almost all energy will be contained in the first and second waves (because energy of each wave is proportional it frequency $\Sigma_i=\omega_i|a_i|^2$)).

CONCLUSIONS

Note the most important results of presented analysis. First of all note attention that threshold of appearance of regimes with dynamics chaos at three wave interaction abnormally fast decreases when frequency of LF wave participating in interaction decreases. In particular, this means that practically at any strength of transverse wave that propagates in plasma there are regimes with dynamics chaos at participation of LF wave that properties are defined by ion component of plasma. But it is needed to note that such regime may not be immediately detected from characteristics of transverse LF waves. The thing is the smaller amplitude of the HF wave, the smaller diffusion coefficient that characterizes spreading characteristics (first of all of frequency) HF wave. This dynamics (chaotic) may be most significant for ion component of plasma. Plasma ions may enough effectively heat. But note that with increasing amplitudes of decaying wave electron component of plasma may participate in stochastic dynamics. In this case this component (electron) may take main energy stream of decaying wave. In this case the heating of ion component of plasma may decrease.

The stochastic regime of decay analyzed. The stable stationary point is defined. It was shown when square of module of initial amplitude of decaying wave essentially exceeds analogous value of others waves in the stable stationary point the first wave has only third part from initial value. Square of amplitude modules of two others wave are increasing to two third parts of this value of first wave.

Note that above one stage of regular and chaotic three wave decay considered. Such stages may be much. High frequency wave appeared as result of first stage may decay into other more low frequency transverse wave and low frequency one. Such stages may organize cascade of enough number elementary stages. The dynamics of such decays significantly were studied in work [7, 15]. In this case much larger part of energy may be transferred into low frequency region when exist only one stage of decay. It needed to note that above only one low frequency branch of oscillation was take into consideration. In real experiments may participate other branches. The theory of such decays is complex. But it may expect that in these cases namely low frequency region of wave spectrum will be saturated by significant amount of energy. Such mechanism of energy transfer of regular high frequency wave into region of low frequency wave with stochastic dynamics apparently may be effectively used for heating of plasma ion component.

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ОСОБЕННОСТИ СТОХАСТИЧЕСКОГО РАСПАДА В МАГНИТОАКТИВНОЙ ПЛАЗМЕ

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Исследованы регулярный и стохастический процессы распада поперечной электромагнитной волны в магнитоактивной плазме. Особое внимание уделено распаду на низкочастотные колебания с участием динамики ионной компоненты плазмы. Определен порог перехода в режим динамического хаоса. Показано, что он может происходить при аномально малых амплитудах распадающейся волны. Исследована динамика полей в режиме динамического хаоса.

ОСОБЛИВОСТІ СТОХАСТИЧНОГО РОЗПАДУ В МАГНІТОАКТИВНІЙ ПЛАЗМІ

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Досліджені регулярний і стохастичний процеси розпаду поперечної електромагнітної хвилі в магнітоактивній плазмі. Особлива увага приділена розпаду на низькочастотні коливання за участю динаміки іонної компоненти плазми. Визначений поріг переходу в режим динамічного хаосу. Показано, що він може відбуватися при аномально малих амплітудах хвилі, що розпадається. Досліджена динаміка полів у режимі динамічного хаосу.