PECULIARITIES OF LOW-FREQUENCY WAVES IN DUSTY PLASMA WITH FERROMAGNETIC GRAINS

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We have obtained the dispersion equation for the spectrum of weakly damped electromagnetic waves in the magnetoactive dusty plasma with ferromagnetic grains with a constant magnetic moment. This equation takes into account the dispersion of the magnetic permeability tensor associated with small rotational vibrations of the dipole moments of grains in a strong external magnetic field. In this system, the additional resonance appears in the vicinity of the frequency of rotational vibrations as compared with the case of a conventional magnetoactive electron-ion plasma. This resonance results in the appearance of a narrow nontransparent band for the Alfven and the fast magnetosonic wave. A possibility of realization of properties of the left-hand media by the magnetoactive dusty plasma with ferromagnetic grains is discussed.

1. Introduction

The tensor of magnetic permeability of the conventional electron-ion plasma is usually to be set independent of the frequency and equal to unity. The situation changes in the dusty plasma with grains possessing a constant magnetic dipole moment d_m in a strong constant uniform magnetic field H_0, when the energy of a dipole in the field is much greater than the thermal energy corresponding to the temperature T of the grain component $d_mH_0/T \gg 1$. In such a field, the dipole moments of grains are oriented along the force lines of the magnetic field. We may say that this corresponds to the model of "cold dipoles".

Under the action of a varying magnetic field $\vec{H}(x,y,z,t)$, the magnetic moments of grains execute small rotational vibrations around the force lines of the magnetic field with a frequency $\omega_0 = \sqrt{d_mH_0/J}$ (J is the moment of inertia of a grain) [1]. These small vibrations are analogous to the "trembling" of a magnet arrow in the Earth's magnetic field. We assume that the magnetic field is strong enough for the inequality $\omega_0 \gg \omega_T$ to hold ($\omega_T = \sqrt{T/J}$ is the frequency of thermal rotation of magnetic dipoles). In this model, we neglect the translation motion of dipoles because the center-of-mass of a grain moving with the thermal velocity $v_T \approx \sqrt{T/M}$(M is the mass of the grain) for the period of thermal rotation passes the distance of the order of its size $v_T/\omega_T = \sqrt{J/M} \sim a$.

The computation of the varying magnetization of the subsystem of magnetic dipoles connected with small rotational motion of the magnetic dipoles allows one to obtain the tensor of magnetic permeability. It is of the Drude type and resonantly depends on the frequency of the varying magnetic field ω and the frequency ω_0 [1]. In typical dusty plasmas, the dispersion of the permeability tensor is essential in a very narrow frequency band $\omega \approx \omega_0$ due to the weak magnetic dipole-dipole interaction between grains that is a result of a relatively small number density of grains in typical dusty plasmas. Outside of this domain, the magnetic permeability of a dusty plasma with ferromagnetic grains is practically equal to unity.

It is worth noting that the frequency of the ferromagnetic resonance related to the precession of the magnetization vector around a constant magnetic field does not depend on the moment of inertia of a grain and, at the same magnetic fields H_0, is much higher than ω_0. In the present paper, we consider only the influence of small mechanical rotational vibrations of the magnetic moments of ferromagnetic grains on the propagation of weakly damping low-frequency waves in a cold magnetoactive dusty plasma.

2. Dispersion Equation of Dusty Magnetoactive Plasma with Ferromagnetic Grains

To find the dispersion relations or the dependence of the frequency of electromagnetic waves $\omega(\vec{k})$ on the wave vector $\vec{k}$ in the magnetoactive dusty plasma, we use the material Maxwell's equations for the Fourier transforms of the field components

$$c\vec{k} \times \vec{E}(\vec{k},\omega) = \omega\mu(\vec{k},\omega)\vec{H}(\vec{k},\omega),$$

$$c\vec{k} \times \vec{H}(\vec{k},\omega) = \omega\varepsilon(\vec{k},\omega)\vec{E}(\vec{k},\omega). \quad (1)$$

Here, $\hat{\mu}(\vec{k},\omega)$ and $\hat{\varepsilon}(\vec{k},\omega)$ are the Fourier transforms of the magnetic permeability and dielectric permittivity tensors, respectively, that are chosen according to the models of "cold dipoles" [1] and cold magnetoactive plasma [2]. It is necessary to note that $\vec{E}(\vec{k},\,\omega)$ and $\vec{H}(\vec{k},\,\omega)$ are the Fourier transforms of the plasma self-consistent field.

The system of equations (1) written in the vector form presents a system of six linear homogeneous algebraic equations for six Fourier components of the electromagnetic field.

The nonzero solution of this system exists if the determinant of this system is equal to zero. To obtain this determinant, we have to use the explicit form of the tensors μ and ε. In the cylindrical system of coordinates with the z axis parallel to the external magnetic field H_0, these tensors may be written, in accordance with [1] and [2], as

$$\mu_{xx}=\mu_{yy}=\mu(\omega)=1+\frac{\Omega_m^2}{\omega_0^2-\omega^2},\quad \mu_{zz}=1, \tag{2}$$

$$\varepsilon_{xx}(\omega)=\varepsilon_{yy}(\omega)\equiv\varepsilon_1=1-\sum_\alpha\frac{\Omega_\alpha^2}{\omega^2-\omega_{B\alpha}^2},$$

$$\varepsilon_{xy}(\omega)=\varepsilon_{yx}^*(\omega)\equiv-i\varepsilon_2,\ \ \varepsilon_2=\sum\frac{\omega_{B\alpha}}{\omega}\frac{\Omega_\alpha^2}{\omega^2-\omega_{B\alpha}^2},$$

$$\varepsilon_{zz}(\omega)\equiv\varepsilon_3=1-\sum_\alpha\frac{\Omega_\alpha^2}{\omega^2}. \tag{3}$$

The rest components of the tensors $\hat{\mu}$ and $\hat{\varepsilon}$ are equal to zero. Summation in (3) is carried out over all kinds of charged particles α (electrons and ions). Typical frequencies of grains are in the range of very low frequencies in comparison with ω_0 and are not taken into account here. In these formulas, we have introduced the notations

$$\Omega_m=\sqrt{N_d d_m^2/J}, \tag{4}$$

where N_d is the number density of grains;

$$\Omega_\alpha=\sqrt{4\pi\,e_\alpha^2 N_\alpha/m_\alpha},\quad \omega_{H\alpha}=e_\alpha H_0/m_\alpha c, \tag{5}$$

are the cyclotron and Langmuir frequencies of charged particles of the α kind, respectively.

In accordance with the cylindrical symmetry of the problem, we choose the wave vector $\vec{k}$ in the xz plane with nonzero components $k_x = k\sin\theta$ and $k_z = k\cos\theta$, ($k_y = 0$). Excluding the components of the magnetic field out of the system of equations (1), we obtain the system of three linear homogeneous equations for the Fourier components of the electric field

$$\left(\mu\varepsilon_1^2-n^2\cos^2\theta\right)E_x-i\mu\varepsilon_2E_y-n^2\sin\theta\cos\theta\,E_z=0,$$

$$i\mu\,\varepsilon_2E_x+[\mu\varepsilon_1-n^2(\cos^2\theta+\mu\sin^2\theta)]E_y=0,$$

$$n^2\sin\theta\cos\theta\,E_x+\left(\mu\varepsilon_3-n^2\sin^2\theta\right)E_z=0, \tag{6}$$

where $n=\frac{kc}{\omega}$ is the refraction index.

Nontrivial solutions of (6) can be obtained from the condition of vanishing the determinant of this system of equations that gives the following biquadratic equation for the refraction index n:

$$An^4+Bn^2+C=0. \tag{7}$$

The coefficients of this equation are given by the expressions

$$A=\ \ \mu(\cos^2\theta+\mu\sin^2\theta)\,(\varepsilon_1\sin^2\theta+\varepsilon_3\cos^2\theta),$$

$$B=-\mu^2\Big[(\varepsilon_1^2-\varepsilon_2^2)\,\sin^2\theta+$$

$$+\varepsilon_1\varepsilon_3(1+\cos^2\theta+(\mu-1)\sin^2\theta\Big],$$

$$C=\ \ \mu^3\,\varepsilon_3\,(\varepsilon_1^2-\varepsilon_2^2). \tag{8}$$

For the cold magnetoactive dusty plasma, they depend only on the frequency of an electromagnetic wave and the direction of its propagation. At $\mu(\omega)=1$, the dispersion equation (7) coincides with the dispersion equation for the conventional electron-ion magnetoactive plasma [2].

As in the case of the electron-ion magnetoactive plasma, the dispersion equation (7) has two solutions

$$n_\pm^2(\omega,\,\theta)=\frac{-B\pm\sqrt{B^2-4AC}}{2A} \tag{9}$$

that describe the refraction indices of the so-called ordinary (+) and extraordinary (–) waves. Therefore, two waves of the same frequency but corresponding to the different refraction indices may propagate in the magnetoactive dusty plasma in the same direction. As usual, while analyzing the dependences of the refraction indices on the frequency, it is important to determine the domains of transparency $n^2(\omega,\theta) > 0$ and domains of non-transparency $n^2(\omega,\theta) < 0$.

In comparison with the conventional magnetoactive electron-ion plasma, the presence of grains with magnetic moments results in some peculiarities in the propagation of low-frequency electromagnetic waves (at frequencies close to ω_0). The simplest way to see this is to consider the waves propagating along the magnetic field $H_0(\theta = 0)$. In this case, (9) can be rewritten as

$$n_{\pm}^2(\omega,\,0) = \mu(\omega)\frac{-B_0 \pm \sqrt{B_0^2 - 4A_0C_0}}{2A_0}, \tag{10}$$

where the coefficients A_0, B_0, and C_0 are obtained from (8) at $\theta = 0$, do not depend on $\mu(\omega)$, and coincide with the corresponding coefficients for the conventional electron-ion magnetoactive plasma. It is convenient to rewrite (10) in the form

$$n_{\pm}^2 = \mu(\omega)\varepsilon(\omega), \tag{11}$$

where

$$\varepsilon(\omega) = \frac{-B_0 \pm \sqrt{B_0^2 - 4A_0C_0}}{2A_0} \tag{11a}$$

is the dielectric permittivity for the electromagnetic wave propagating along the magnetic field.

It is clear that, in the transparency domains $n^2 > 0$, the following inequalities hold true:

$$\mu(\omega) > 0,\;\; \varepsilon(\omega) > 0, \tag{12}$$

$$\mu(\omega) < 0,\;\; \varepsilon(\omega) < 0. \tag{13}$$

The media with $\mu(\omega) > 0$ is transparent for the electromagnetic waves provided that $\varepsilon(\omega > 0$ and they are not transparent at $\varepsilon(\omega < 0$. According to the modern terminology, such media are referred to the normal or right-handed media. Inequality (13) shows that the electromagnetic waves can propagate in the media with simultaneously negative magnetic permeability and dielectric permittivity, at least, in some range of frequencies. They are called the left-handed media. The first mention about such media and the description of their some properties were given firstly in [3].

The explicit form of components of the tensors of magnetic permeability and dielectric permittivity (2) and (3) and the numerical evaluation of their parameters show that the magnetoactive dusty plasma with ferromagnetic grains in some frequency domain can behaves itself like the left-handed media [1].

In the next section, we consider the peculiarities of the propagation of electromagnetic waves in the medium under consideration.

3. Influence of Magnetized Grains on the Propagation of Electromagnetic Waves in Cold Magnetoactive Plasma

The analysis of the propagation of electromagnetic waves in the magnitoactive dusty plasma is carrying out according to the general scheme [2,4]. First of all, we have to specify the plasma or hybrid resonant frequencies that are determined by the condition

$$A(\omega,\theta) \to \infty,\;\; n^2 \to \infty. \tag{14}$$

We recall that, in the case of the conventional electron-ion magnetoactive plasma, there are three resonances at the frequencies $\omega_{\infty}^{(1)}(\theta)$, $\omega_{\infty}^{(2)}(\theta)$, and $\omega_{\infty}^{(3)}(\theta)$ (the first two are related to the high-frequency range where the ion's motion is unimportant and the third frequency depends considerably on the ion's motion) [2]. In the magnetoactive dusty plasma with magnetized grains, the additional resonances appear. They can be determined, according to (14) and (8), from the equation

$$\mu(\omega)(\cos^2\theta + \mu(\omega)\sin^2\theta) = 0 \tag{15}$$

which splits into two equations

$$\mu(\omega) = 0 \tag{15a}$$

and

$$\cos^2\theta + \mu(\omega)\sin^2\theta = 0. \tag{15b}$$

The second equation makes sense at $\theta \neq 0$. At $\theta = \pi/2$, it reduces to the first one. These resonances originate from the magnetic subsystem associated with grains.

In the dusty plasma under consideration due to the strong inequality $\Omega_m \ll \omega_0$, the transversal components (with respect to the field H_0) of the permeability tensor differ from unity only in a very narrow frequency range $\Delta\omega \approx \Omega_m$ [1]. They tend to $+\infty$ as $\omega \to \omega_0$ from the left ($\omega < \omega_0$) and tend to $-\infty$ as $\omega \to \omega_0$ from the right ($\omega < \omega_0$). It is worth noting that the frequency $\omega_0 = \sqrt{d_m H_0/J}$ lies in a comparatively wide radio-frequency range (see the numerical evaluations below). This means that the ferromagnetic dusty component produces the resonance quite close to $\omega = \omega_0$ and may affect the low-frequency electromagnetic waves. To understand the character of influence of the dusty component on the propagation of electromagnetic waves, we draw a

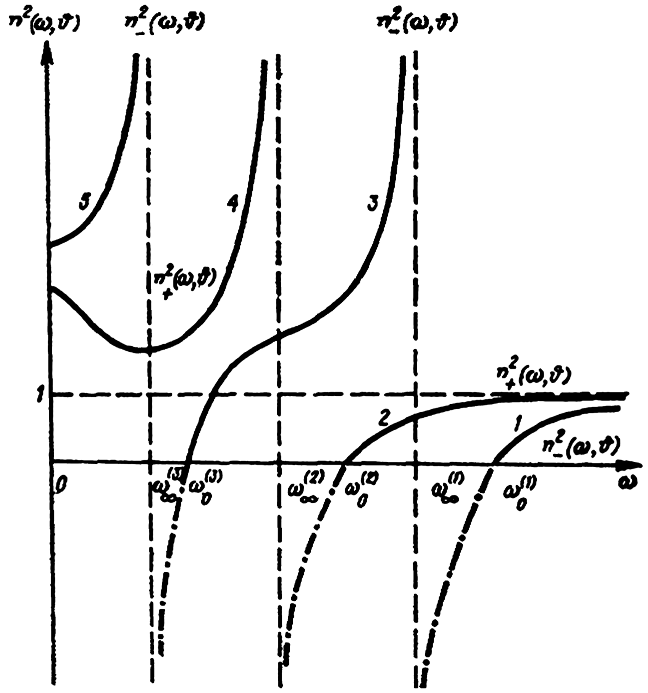

Fig. 1. Square of the refraction index $n^2(\omega,\,\theta)$ as a function of the frequency ω at $0 < \theta < \pi/2$ in the conventional electron-ion plasma according to the general theory [2]. *1*, fast extraordinary; *2*, ordinary; *3*, slow extraordinary wave; *4*, fast magnetosonic wave; *5*, Alfven wave. The vertical dashed lines correspond to the plasma resonances $\omega_\infty^{(1,2,3)}$, $\omega_0^{(1,2,3)}$ are the location of zeroes of $n^2(\omega,\theta) = 0$. The domain $n^2(\omega,\,\theta) < 0$ is nontransparent at any frequencies

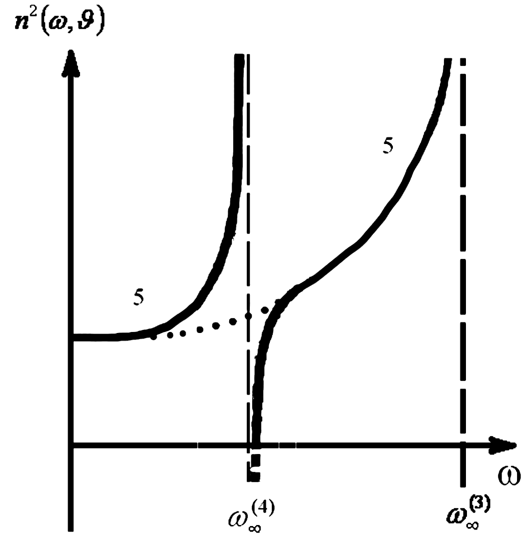

Fig. 2. Schematically $n^2(\omega)$ versus ω for the Alfven wave (5) in the dusty plasma with ferromagnetic grains provided that $\omega_\infty^{(4)} \approx \omega_0 < \omega_\infty^{(3)}$. The dotted line shows $n^2(\omega)$ in the electron magnetoactive electron-ion plasma near $\omega_0 \pm \Delta$. The Alfven wave cannot propagate in a narrow frequency region $\omega_0 + \Delta$, where $n^2(\omega) < 0$, and, at $\omega_0 - \Delta$, the Alfven wave velocity sharply decreases

vertical line at the point $\omega = \omega_0$ on the graph $n_\pm^2(\omega,\,\theta)$ versus frequency ω taken from the general theory of waves in the electron-ion plasma [2] (Fig. 1.).

Figure 2 corresponds to the situation, which arises in the magnetoactive dusty plasma with ferromagnetic grains, when the frequency of the additional resonance $\omega_\infty^{(4)} \approx \omega_0$ is less than the ion cyclotron frequency ω_{Bi}. The straight line ω_0 is an asymptote to curves *4* and *5*. It is clear that, in a very narrow region of frequencies $\omega < \omega_0$, $n^2 \to +\infty$, and, at $\omega > \omega_0$, $n^2 \to -\infty$. This means that the magnetosonic and Alfven waves of the frequency ω_0 cannot propagate in this dusty plasma.

Now we consider the dispersion law of Alfven waves propagating along the external magnetic field H_0 when their dispersion law coincides with that of fast magnetosonic waves. With the help of (8) and (10), it is easy to get

$$n_\pm^2 = \mu(\omega)c^2/V_A^2, \tag{16}$$

where $V_A = \frac{H_0}{\sqrt{4\pi N_i m_i}}$ is the Alfven wave velocity, N_i and m_i are the number density of ions and the ion mass, respectively. It is obvious from (16) that the Alfven wave can propagate provided that $\mu(\omega) > 0$. The simplest way to obtain the dispersion law of this wave is to solve (16) with respect to the wave vector. Using the explicit form of the magnetic permeability $\mu(\omega)$ according to (2), we obtain, in view of (16),

$$k = \frac{\omega}{V_A\sqrt{1 + \Omega_m^2/(\omega_0^2 - \omega^2)}}. \tag{17}$$

At $\Omega_m^2/(\omega^2 - \omega_0^2) > 1$, the wave vector k is imaginary, and the medium turns out to be non-transparent for the Alfven and fast magnetosonic waves directed along the magnetic field. As was mentioned above, the inequality $\Omega_m \ll \omega_0$ results in a relative narrowness of the non-transparency region $\Delta\omega$. According to evaluations in [1] for the typical parameters, $\Delta\omega$ is of the order of 10 Hz. If the frequency of the Alfven wave approaches the resonance, $\omega_\infty^{(4)} \approx \omega_{Hi}$, the Alfven wave is usually called the ion cyclotron wave. The refractive index of this wave is given, in accordance with (10) and [2], by the expression

$$n_-^2(\omega,\,\theta = 0) = \mu(\omega)\varepsilon(\omega),$$

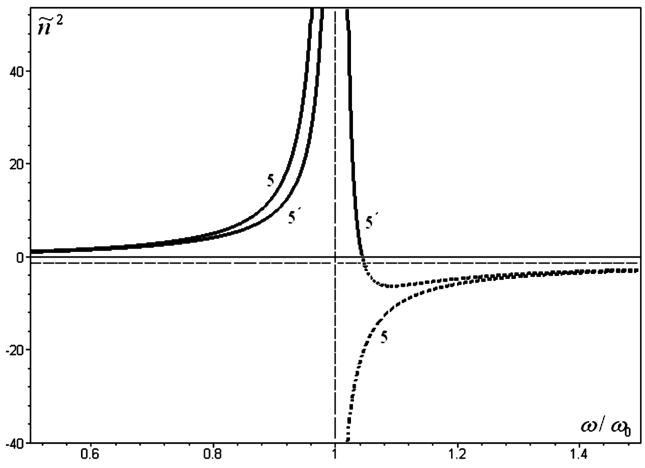

Fig. 3. Dependence $\tilde{n}^2 = n_-^2(\omega, 0) \cdot V_A^2/c^2$ on ω at $\omega_\infty^{(3)} = \omega_{Hi} = \omega_0$ according to (18). In a narrow frequency region, the dusty plasma with ferromagnetic grains behaves itself like a left-handed medium and transmits electromagnetic waves ($\mu(\omega) < 0$, $\varepsilon(\omega) < 0$). Outside of this frequency band, $\tilde{n}^2 = \omega/(\omega_0 - \omega)$. The dotted line corresponds to the case of the conventional electron-ion magnetoactive plasma where the electromagnetic waves of a frequency $\omega > \omega_{Hi}$ cannot propagate

$$\mu(\omega) = 1 + \frac{\Omega_m^2}{\omega_0^2 - \omega^2}, \quad \varepsilon(\omega) = \frac{c^2}{V_A^2}\frac{\omega}{\omega_{Hi} - \omega}. \tag{18}$$

We seek for a solution of (18) in the form $\omega = \omega_{Hi} - \Delta\omega$. For $\omega_0 \gg \omega_{Hi}$ it can be written as

$$\omega(k) = \mu(\omega_0)\left(1 - \frac{\Omega_i^2}{k^2c^2}\right)\omega_{Hi}, \tag{19}$$

where Ω_i is the Langmuir frequency of ions. This expression practically coincides with the standard result for the magnetoactive electron-ion plasma [2]. In this case, $\mu(\omega) = 1 + \frac{\Omega_m^2}{\omega_0^2 - \omega^2}$ is positive and very close to unity due to $\Omega_m \ll \omega_0$ and $\varepsilon(\omega) > 0$ as well. Therefore, the system behaves itself like a conventional right-handed medium.

The situation changes if $\omega_0 \to \omega_{Hi}$. In this case, we again seek for a solution of (18) in the form $\omega = \omega_{Hi} - \Delta\omega$, but now $\omega_0 = \omega_{Hi}$. The result reads

$$\omega = \omega_0\left(1 \pm \frac{\Omega_m}{kV_A\sqrt{2}}\right), \;\; \Omega_m \ll kV_A. \tag{20}$$

The sign "–" corresponds to the right-handed medium, and the sign "+" corresponds to the left-handed one because, in this case, $\mu < 0$ and $\varepsilon < 0$ simultaneously. Schematically, this case is depicted in Fig. 3. We would like to note that, at these frequencies, the conventional electron-ion plasma is nontransparent for the electromagnetic wave in the case where $n^2(\omega) = \varepsilon(\omega) < 0, \;\; \mu(\omega) = 1$.

The fact that the magnetoactive dusty plasma with ferromagnetic grains can manifest the properties of the left-handed medium is of interest, because it is the system completely different from those reported in the literature. It is interesting to evaluate magnitudes of the magnetic field that provide the equality $\omega_0 = \omega_{Hi}$. In the explicit form, it reads $\sqrt{d_m H_0/J} = \frac{eH_0}{m_i c^2}$ and gives the expression

$$H_0 = \frac{m_i^2 c^2 d_m}{Je^2}. \tag{21}$$

Here, m_i is the mass of a single-charged ion, $J = \frac{8\pi}{15}\rho\, a^5$ is the momentum of inertia of a spherical ferromagnetic grain, ρ and a are, respectively, the radius and number density of grains, and and d_m is the built-in point-like dipole moment of a grain. For the sake of simplicity, we consider one-domain particles with $a \leq 10^{-4}$ cm [5]. In this case, the magnetic dipole moment may be evaluated by the formula $d_m = 3 \times 10^{23}\mu_{\rm B}\frac{4\pi}{3\rho}a^3$, where the factor 3×10^{23} is the average number of electrons per one gram of the majority of substances [6], $\mu_{\rm B} = 9.27 \times 10^{-21}$ erg/Gs is the Borh magneton. Considering iron grains with $\rho = 7.8$ g/cm^3, we get

$$d_m = 1.5 \times 10^{-15}\, a^3 \;\; [\text{erg/Gs}],$$

$$J = 1.3 \times 10^{-19}\, a^5 \;\; [\text{g} \cdot \text{cm}^2] \tag{22}$$

with the grain radius a measured in μm. The typical frequencies of small rotational vibrations of the magnetic dipoles

$$\omega_0 = \sqrt{d_m H_0/J} = \frac{114}{a}\sqrt{H_0}. \tag{23}$$

Here, H_0 and a are measured in Gs and μm, respectively. For example, at $H_0 = 10^3$ Gs, we obtain $\omega_0 = 3.6 \times 10^3$ Hz, at $a = 1\mu$m and $\omega_0 = 3.6 \times 10^6$ Hz, at $a = 10^{-3}$ μm (nanoparticles). Therefore, for the realistic magnetic fields, ω_0 corresponds to the radio-frequency range.

Evaluations of the typical magnetic field H_0 and the typical size of ferromagnetic grains that satisfy the condition $\omega_0 = \omega_{Hi}$ can be done with the help of the formula

$$H_0 = 4.5 \times 10^{43}\frac{m_i^2}{a^2}, \tag{24}$$

where the ion mass is measured in grams. Particularly, for the helium plasma with iron grains, $a = 5 \times 10^{-2} \mu$m, $H_0 \cong 530$ Gs, and $\omega_0 = 5.2 \times 10^4$. The corresponding wavelength in vacuum is $\lambda = 3.6 \times 10^6$ cm. In the frequency range where the dusty plasma behaves itself like a left-handed medium, the refraction index $n \gg 1$, and the wavelength $\lambda_L = \lambda/n \ll \lambda$.

4. Discussion of Results and Their Possible Application

In this paper, we have shown that, in the magnetoactive dusty plasma with ferromagnetic grains carrying constant magnetic dipole moments, the dispersion of the magnetic permeability $\mu(\omega)$ must be taken into account. The dispersion is related to small rotational vibrations of magnetic dipoles in the strong external magnetic field. As a result, in such a plasma in comparison with the conventional electron-ion plasma, one more typical frequency $\omega_0 = \sqrt{d_m H_0/J}$ appears. The components of the permeability tensor (2) turn out to be of the Drude type and have a pole at $\omega = \omega_0$. The ferromagnetic dusty component in the magnetoactive electron-ion plasma results in some peculiarities in the propagation of electromagnetic waves through this medium.

The evaluations carried above for the typical parameters of the dusty plasma show that, for micron-size iron grains in the magnetic fields $H_0$of the order of 10^3 Gs, $\omega_0 = 3 \times 10^3$ rad/s. Decreasing the grain size, one can obtain ω_0 of the order of a few MHz. The dispersion of $\mu(\omega)$ in the dusty plasma is important in a very narrow frequency interval where $\Delta\omega = \Omega_m^2/2\omega_0 \ll \omega_0$.The latter is a result of the weak magnetic dipole-dipole interaction between grains in the dusty plasma.

According to the transparency condition (12), (13), the electromagnetic waves can propagate in the dusty plasma in the case of $\varepsilon(\omega) < 0$ and $\mu(\omega) < 0$ simultaneously. We would like to stress that this condition holds true in the so-called left-handed media. The transparency condition for the conventional electron-ion plasma reduces to $\varepsilon(\omega) > 0$, $\mu(\omega) = 1$.

The realization of the condition $\mu(\omega) < 0$ results in the appearance of transparency windows in the frequency range where the electron-ion magnetoactive plasma is non-transparent and vice versa. In this paper, we illustrated this situation for the magnetosonic and Alfven waves.

In conclusion, we would like to draw attention to a possible realization of the transparency windows in the low frequency (radio) range under natural conditions in the atmosphere of some stars. At present, one of the main objects of the observation astronomy is the atmospheres of far stars in the optical range. However, the data on the chemical composition, the formation of dusty particles, and their influence on the light absorption give new possibilities for the utilization of the novel results in the physics of dusty plasma for the modeling, for example, of the properties of the atmospheres of brown dwarfs (BDs). Here, we present some data typical of BDs.

– The red dwarf mass M_{BD} is 10–80 Jupiter masses;

– The temperature of the atmosphere (in the photosphere domain) is about 0.3–1 eV;

– The magnetic field H_0 is up to 1kGs;

The observations of 100 young BDs in the Orion nebula in 2001 reliably proved that the disks of a dust and gases surround them. The main distinction of these stars from the real ones is that the mass of a BD is not enough to burn the hydrogen fusion reaction. They probably had only a comparatively short period of deuterium burning before the beginning of cooling.

The researchers of the BD atmosphere regularly use the so-called “dusty models” [5]. These models assume that the BD photospheres contain condensates of iron, aluminum, and magnesium and their compounds with silicon and oxides. In the cloud models that are a development of the dusty models, the formation of metal clouds and their sedimentation in the form of rains are assumed [6]. As a rule, the grains of condensates are supposed to be of the same size, but it is understandable that some distribution over this parameter is possible as well. One may claim that, due to the considerable gravity force, the grains with a typical size $a > 50$ μm are not present in these atmospheres. Probably, the typical size of grains in the clouds is in the range 0.1–1 μm.

In this paper, we have shown that the dusty plasma with ferromagnetic grains in the strong magnetic field manifests some peculiarities of the propagation of the low-frequency electromagnetic field. Choosing such a plasma as a base model for some layers of the atmospheres of BDs, it is possible to obtain new physical results that may present some interest for observers.

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ОСОБЛИВОСТІ НИЗЬКОЧАСТОТНИХ ХВИЛЬ У ЗАПОРОШЕНІЙ ПЛАЗМІ З ФЕРОМАГНІТНИМИ ГРАНУЛАМИ

В.М. Мальнев, Є.В. Мартиш, В.В. Паньків

Р е з ю м е

Отримано дисперсійне рівняння для спектра слабкозагасаючих електромагнітних хвиль у магнітоактивній запорошеній плазмі з феромагнітними гранулами, які мають сталий магнітний момент. Це рівняння враховує дисперсію тензора магнітної проникності, зумовлену малими ротаційними коливаннями гранул в сильному магнітному полі. У порівнянні з електрон-іонною плазмою в дисперсійному рівнянні досліджуваної запорошеної плазми з'являється додатковий резонанс в околі частоти ротаційних коливань. Це може спричиняти появу вузької смуги непрозорості для альфвенівської та швидкої звукової хвиль. Обговорюється можливість реалізації властивостей лівосторонніх середовищ у магнітоактивній запорошеній плазмі.