Original research article

Effect of dust particle on dusty plasma's dispersion characteristic

Yu Renjiao[a,c], Chen Yun-yun[a,b,c,*], Zhao De-lin[a,c]

[a] *Jiangsu Key Laboratory for Optoelectronic Detection of Atmosphere and Ocean, Nanjing University of Information Science & Technology, Nanjing, 210044, China*
[b] *Jiangsu Collaborative Innovation Center on Atmospheric Environment and Equipment Technology (CICAEET), Nanjing University of Information Science and Technology, Nanjing, 210044, China*
[c] *School of Physics and Optoelectronic Engineering, Nanjing University of Information Science and Technology, Nanjing, 210044, China*

A B S T R A C T

In this paper, the effect of dust particle on dusty plasma's dispersion characteristic is studied under two possible conditions. Firstly, based on the known complex refractive index formula, the dispersion ability of the real and imaginary parts are determined. Then, the dispersion ability of the dusty plasma under two different conditions is discussed, according to the neutral conditions between particles in dusty plasma. The research results show that: (1) The magnitude of dispersion ability decreases significantly with the incident electromagnetic wave's angular frequency increases; (2) The value of the dispersion ability under condition 1 is much smaller than the dispersion ability under condition 2. Finally, it is pointed that the dispersion ability difference between dusty and common plasma can be mainly attributed to the dust particle, and the effect of dust particle radius and number density on the dispersion ability of dusty plasma is similar.

1. Introduction

About ninety years ago, Tonks and Langmuir firstly proposed the term "plasma" to describe the luminescent ionized gas generated in a tube by discharge. "Plasma" stands for macroscopically neutral gas containing many interacting charged particles (electrons and ions) and neutral particles [1]. Dust particle is a ubiquitous component of the cosmic plasma environment, and plasma represents the bulk of the solid matter in the universe. It is usually between a few microns and a few hundred microns in size, and is not neutral but negatively or positively charged depending on the plasma environment. Therefore, the ionized gas and dust particle form "dusty plasma" [2–4]. It is commonly found in plasma assisted manufacturing in space environments (such as the solar nebula, planetary rings, molecular clouds, iris, and the middle earth layer), radio frequency discharges, and microelectronic devices (semiconductor processing industry) [5].

People began to study charged dust particle in the universe, which greatly promoted the development of space dusty plasma physics [6,7]. In the late 1980s, dusty plasma physics has made great progress, mainly due to the need for plasma surface treatment, in which the formation of dust particle plays a major and harmful role. However, at the same time, the addition of dust particle in plasma processing has created new materials with many beneficial properties. In recent years, people have conducted detailed studies on the electromagnetic properties of dusty plasma. Li Fang et al. studied the imaginary dispersion effect of dust particle on electromagnetic waves, and pointed out that dust particle have an important influence on imaginary dispersion and scattering effects [8]. Shi Yanxiang discussed the dispersion ability of the weak ionized dusty plasma under the action of a weak electromagnetic field, and

* Corresponding author at: Jiangsu Key Laboratory for Optoelectronic Detection of Atmosphere and Ocean, Nanjing University of Information Science & Technology, Nanjing, 210044, China.
E-mail address: yunqq321@sina.cn (Y.-y. Chen).

also considered the collision and electron charging and discharging on dust particle. The influence of the radius and number density of dust particle on the electrical conductivity of the dusty plasma is considered in consideration of the charge and discharge of dust particle [9]. In further, the influence of the potential difference between the dust particle and the background plasma on the conductivity is studied [10,11].

Considering the electrically neutral condition of the dusty plasma $N_e + Z_d N_d = N_i$, when the density of dust particles is large, it will affect the electron number density, and further affect the dispersion ability. Therefore, in the following sections, the dispersion ability will be studied under two conditions ($Z_d N_d \approx N_e$ and $Z_d N_d \ll N_e$).

2. Basic parameters and theory

2.1. Basic parameters

The parameters of dust particle include number density N_d, radius r_d and charge number Z_d. When there is no external interference, dusty plasma usually satisfies the electrical neutrality, as [12,13]:

$$q_i N_i = e N_e - q_d N_d, \tag{1}$$

where N_i and N_e represent number density of ions and electrons respectively, q_i is ion charge and e is the charge constant, $q_d = Z_d e$ is charge quantity for dust particle which is usually negative.

The simplification of Eq. (1) is as follows:

$$N_i = N_e + Z_d N_d. \tag{2}$$

According to Ref. [14], the size of dust particle is mainly distributed between $1\mu m$ and $10\mu m$, and the density of dust particle is mainly between $10^{10}/m^3$ and $10^{15}/m^3$. In many laboratory and space plasma conditions, most electrons may adhere to the surface of the dust particle during the charging process, which may result in a significant consumption of the electron number density in the ambient dusty plasma. When $Z_d N_d \ll N_e$, the existence of dust particle does not affect the overall distribution of electrons in plasma, but only considering additional collisions between electrons and dust particles. Therefore, the dispersion ability of the dusty plasma will be studied under the following two conditions ($Z_d N_d \approx N_e$ and $Z_d N_d \ll N_e$).

2.2. Dispersion ability

According to Ref.15, $\frac{dn}{d\omega}$ and $\frac{d\kappa}{d\omega}$ are respectively defined as the dispersion ability of the real and imaginary parts for further discussion, they are written as:

$$\frac{dn}{d\omega} = \frac{1}{2\sqrt{2}} \frac{\frac{x'}{\varepsilon_0}[1 + \frac{x}{\varepsilon_0} + \sqrt{\left(1 + \frac{x}{\varepsilon_0}\right)^2 + y^2}] + yy'}{\sqrt{\left(1 + \frac{x}{\varepsilon_0}\right)^2 + y^2} \sqrt{\left(1 + \frac{x}{\varepsilon_0}\right) + \sqrt{\left(1 + \frac{x}{\varepsilon_0}\right)^2 + y^2}}}, \tag{3}$$

$$\frac{d\kappa}{d\omega} = \frac{1}{2\sqrt{2}} \frac{\frac{x'}{\varepsilon_0}[1 + \frac{x}{\varepsilon_0} - \sqrt{\left(1 + \frac{x}{\varepsilon_0}\right)^2 + y^2}] + yy'}{\sqrt{\left(1 + \frac{x}{\varepsilon_0}\right)^2 + y^2} \sqrt{-\left(1 + \frac{x}{\varepsilon_0}\right) + \sqrt{\left(1 + \frac{x}{\varepsilon_0}\right)^2 + y^2}}}, \tag{4}$$

Where

$$x = \frac{(\eta_{ed} + \eta_{\phi_d})(\upsilon_{eff} + \upsilon_{ch})c}{(\omega^2 + \upsilon_{eff}^2)(\omega^2 + \upsilon_{ch}^2)} - \frac{\varepsilon_0 \omega_p^2}{\omega^2 + \upsilon_{eff}^2},$$

$$y = \frac{\omega_p^2 \upsilon_{eff}}{\omega(\omega^2 + \upsilon_{eff}^2)} + \frac{(\eta_{ed} + \eta_{\phi_d})(\omega^2 - \upsilon_{eff}\upsilon_{ch})c}{\varepsilon_0 \omega(\omega^2 + \upsilon_{eff}^2)(\omega^2 + \upsilon_{ch}^2)},$$

$$x' = -\frac{(\eta_{ed} + \eta_{\phi_d})(\upsilon_{eff} + \upsilon_{ch})c[4\omega^3 + 2\omega(\upsilon_{ch}^2 + \upsilon_{eff}^2)]}{(\omega^2 + \upsilon_{eff}^2)^2(\omega^2 + \upsilon_{ch}^2)^2} + \frac{2\omega\varepsilon_0\omega_p^2}{(\omega^2 + \upsilon_{eff}^2)^2},$$

$$y' = -\frac{\omega_p^2 \upsilon_{eff}(3\omega^2 + \upsilon_{eff}^2)}{\omega^2\left(\omega^2 + \upsilon_{eff}^2\right)^2} + \frac{(\eta_{ed} + \eta_{\phi_d})c\left[2\omega^2\left(\omega^2 + \upsilon_{eff}^2\right)(\omega^2 + \upsilon_{ch}^2)\right]}{\varepsilon_0\omega^2\left(\omega^2 + \upsilon_{eff}^2\right)^2(\omega^2 + \upsilon_{ch}^2)^2}$$
$$- \frac{(\eta_{ed} + \eta_{\phi_d})c\left[(\omega^2 - \upsilon_{eff}\upsilon_{ch})\left(5\omega^4 + 3\upsilon_{eff}^2\omega^2 + 3\upsilon_{ch}^2\omega^2 + \upsilon_{eff}^2\upsilon_{ch}^2\right)\right]}{\varepsilon_0\omega^2\left(\omega^2 + \upsilon_{eff}^2\right)^2(\omega^2 + \upsilon_{ch}^2)^2},$$