Optik 127 (2016) 2476–2480

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

The study of dusty plasma's conductivity with dual-temperature model

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ARTICLE INFO

Article history:
Received 24 March 2015
Accepted 3 November 2015

Keywords:
Plasma
Interactive factor
Dust particle
Conductivity

ABSTRACT

The concept of two interactive factors is proposed to describe and deduce the dusty plasma's complex conductivity on considering the ions' contribution. In the specific analysis and calculation, the actual fact that the temperature of electrons and ions in plasma may not be equal is taken into account. The theoretical deduction indicates that the ion-dust and electronic-dust interactive factors have a close relate to the corresponding particle number density, mass, and temperature, as well as the radius and number density of the particles. In further, it is found that the two interactive factors are both composed by the charging response factor and the electric potential impact factor. The most critical result is the condition which can be used to judge whether the contribution of ions to the conductivity can be ignored is proposed.

1. Introduction

The dust particles, which become a form of the solid matter of the universe, widely exist in the universe. Meanwhile, it is well known that the gas in the universe is often in a state of ionized or partially ionized, which is usually called plasma (common plasma). Therefore, plasma and the submerged dust particles form a complex system – dusty plasma (complex plasma), which widely exists in the space [1,2], such as interstellar space, the ionosphere of earth, and the comet and planet ring and so on, as well as in fusion reactors [3,4] and the device of plasma processing industry [5]. The dusty plasma has been researched since 1990s [6], and Tsytovich [7] definitely proposed three indispensible factors to distinguish it from the common plasma. The definite elaboration about the universal existence and the difference from the common plasma makes the research on the dusty plasma gradually increase [8–11]. Recently, there are researchers corrected the kinetic and the structural characteristics of the two dimension dusty plasma under the screened coulomb potential [12]. However, the dusty plasma's absorption characteristic is seldom reported until recent years [13–15]. It is found that, the complex dielectric constant should be obtained on the basis of correcting and deriving the complex conductivity. In fact, the above deductive process usually starts from the charging current of electrons and ions on the dust particles. And, it is noted that almost all the involved researches ignored the charging effect of ions on the dust particles. However, there are no any definite reports proving that the effect can be ignored directly so far. Consequently, this paper focuses on deriving, analyzing and discussing the complex conductivity of dusty plasma, on condition of considering the effect of ions' charging on the dust particles. As a result, a condition which can be used to judge whether the contribution of ion can be ignored will be proposed. The relevant results will be benefit to improve the research on the dusty plasma's absorption characteristics.

2. Theory and derivation

Currently, most of the studies on the conductivity of dusty plasma or absorption characteristics aim at the problem of communication, therefore, the microwave or the millimeter wave are generally considered. Under the action of electromagnetic with high frequency, the charging current of ion can be ignored directly, that is the reason why the response of ion can be ignored under the action of high frequency electromagnetic. Yet, if the dusty plasma is under the action of electromagnetic with low frequency, its action

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http://dx.doi.org/10.1016/j.ijleo.2015.11.082
0030-4026/

can't be ignored. This paper is developed on the premise of the effect cannot be ignored.

2.1. Basic theory

Supposing that the minimum speed of electron impacting the dust particle is equal to zero, that is $v_e^m = 0$, and the charging current of electron and ion on dust particles respectively as follows [16]:

$$I_\text{e} = -\frac{3\pi e^2 r_\text{d}^2 N_\text{e} \vec{E}}{m_\text{e}(i\omega + \upsilon_\text{eff})}\left(1 + \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B} T_\text{e}}\right), \tag{1}$$

$$I_\text{i} = \frac{3\pi e^2 r_\text{d}^2 N_\text{i} \vec{E}}{m_\text{i}(i\omega + \upsilon_\text{eff})}\left(1 - \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B} T_\text{i}}\right), \tag{2}$$

where e denotes the charge constant, r_d indicates the dust particle radius, $\vec{E}$ is the incident electromagnetic wave field, N_e and T_e represent the number density and the temperature of electrons respectively, N_i and T_i are the number density and the temperature of ions, m_i and m_e delegate the mass of ion and electron, ω is the incident electromagnetic wave angular frequency, υ_eff is the effective collision frequency, ϕ_d is the dust particle potential, and κ_B is the Boltzmann constant.

The relation between the complex conductivity (σ_cd) and the charging current of electrons and ions on the dust particles is [16]:

$$\frac{\sigma_\text{cd}}{N_\text{d}} ik\vec{E} + \upsilon_\text{ch}\frac{k\sigma_\text{cd}}{\omega N_\text{d}}\vec{E} = I_\text{e} + I_\text{i}, \tag{3}$$

where N_d indicates the number density of dust particles, k is the incident electromagnetic wave number, υ_ch is the charging frequency.

The complex conductivity σ_cd can be presented as:

$$\sigma_\text{cd} = \frac{\omega N_\text{d}}{k\vec{E}(i\omega + \upsilon_\text{ch})}(I_\text{e} + I_\text{i}) \tag{4}$$

Distinctly, Eq. (4) expresses the complex conductivity which is derived from the charging effect of electrons and ions on the dust particles.

2.2. The complex conductivity

Substituting the charging current into Eq. (4), we can have:

$$\begin{aligned}
\sigma_\text{cd} &= \frac{\omega N_\text{d}}{k\vec{E}(i\omega + \upsilon_\text{ch})}\left(-\frac{3\pi e^2 r_\text{d}^2 N_\text{e}\vec{E}}{m_\text{e}(i\omega + \upsilon_\text{eff})}\left(1 + \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B} T_\text{e}}\right)\right.\\
&\quad \left. + \frac{3\pi e^2 r_\text{d}^2 N_\text{i}\vec{E}}{m_\text{i}(i\omega + \upsilon_\text{eff})}\left(1 - \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B} T_\text{i}}\right)\right)\\
&= \frac{\omega N_\text{d}}{k\vec{E}(i\omega + \upsilon_\text{ch})}\left[\frac{3\pi e^2 r_\text{d}^2 \vec{E}}{(i\omega + \upsilon_\text{eff})}\left(\frac{N_\text{i}}{m_\text{i}} - \frac{N_\text{e}}{m_\text{e}}\right)\right.\\
&\quad \left. - \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B}}\frac{3\pi e^2 r_\text{d}^2\vec{E}}{(i\omega + \upsilon_\text{eff})}\left(\frac{N_\text{e}}{m_\text{e}T_\text{e}} + \frac{N_\text{i}}{m_\text{i}T_\text{i}}\right)\right]\\
&= \frac{\omega N_\text{d}}{k\vec{E}(i\omega + \upsilon_\text{ch})}\frac{3\pi e^2 r_\text{d}^2\vec{E}}{(i\omega + \upsilon_\text{eff})}\\
&\quad \times\left[\left(\frac{N_\text{i}}{m_\text{i}} - \frac{N_\text{e}}{m_\text{e}}\right) - \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B}}\left(\frac{N_\text{i}}{m_\text{i}T_\text{i}} + \frac{N_\text{e}}{m_\text{e}T_\text{e}}\right)\right]\\
&= \frac{3\pi e^2 r_\text{d}^2 \omega N_\text{d}}{k(i\omega + \upsilon_\text{ch})(i\omega + \upsilon_\text{eff})}\left[\left(\frac{N_\text{i}}{m_\text{i}} - \frac{N_\text{e}}{m_\text{e}}\right)\right.\\
&\quad \left. - \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B}}\left(\frac{N_\text{i}}{m_\text{i}T_\text{i}} + \frac{N_\text{e}}{m_\text{e}T_\text{e}}\right)\right]
\end{aligned} \tag{5}$$

In further, Eq. (5) can be described as:

$$\sigma_\text{cd} = \frac{\left[3\pi e^2 r_\text{d}^2 N_\text{d}\frac{N_\text{i}}{m_\text{i}}\left(1 - \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B}}\frac{1}{T_\text{i}}\right) - 3\pi e^2 r_\text{d}^2 N_\text{d}\frac{N_\text{e}}{m_\text{e}}\left(1 + \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B}}\frac{1}{T_\text{e}}\right)\right]}{\times(\omega^2 + \upsilon_\text{ch}^2)(\omega^2 + \upsilon_\text{eff}^2)\frac{\omega}{k}[(-\omega^2 + \upsilon_\text{ch}\upsilon_\text{eff}) - i\omega(\upsilon_\text{ch} + \upsilon_\text{eff})]} \tag{6}$$

Defining

$$\mu_\text{id} = 3\pi e^2 r_\text{d}^2 N_\text{d}\frac{N_\text{i}}{m_\text{i}}\left(1 - \frac{2}{3}\frac{e\phi_\text{d}}{\kappa_\text{B}}\frac{1}{T_\text{i}}\right), \tag{7}$$

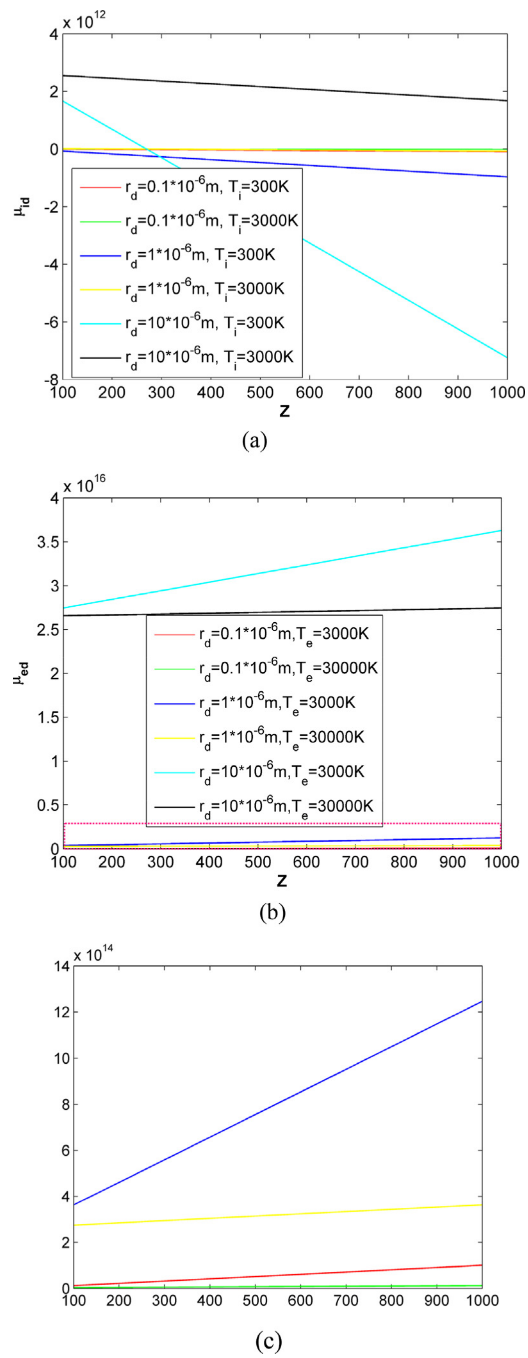

Fig. 1. The dependence of the two interactive factors on the charge number. (a) μ_id, (b) μ_ed, and (c) the marked region in (b).