J. Plasma Physics (2014), *vol.* 80, *part* 1, *pp.* 1–7. © Cambridge University Press 2013
doi:10.1017/S0022377813000408

Polarization force for different dusty plasma situations

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(Received 25 December 2012; accepted 19 March 2013; first published online 12 November 2013)

Polarization force (acting on a dust grain) and its modification by polarity of dust, non-isothermal (viz. non-thermal and trapped) ions, adiabaticity of electrons and ions, etc. have been investigated theoretically. It has been found that the polarization force is significantly modified by these effects, i.e. the magnitude of the polarization force is significantly decreased by the presence of non-thermal ions and by the adiabaticity of electrons and ions. On the other hand, it is significantly increased by the presence of trapped ions. It has been also shown that the magnitude of the polarization force is increased (decreased) by electric potential in the case of positively (negatively) charged dust. The relevance of our investigation to some space and astrophysical plasma situations is discussed.

1. Introduction

The interaction between thermal ions (electrons) and highly negatively (positively) charged dust grains is termed as the polarization force. The concept of polarization force (acting on a charged dust grain) and its importance in dusty plasma physics have been explained by Hamaguchi and Farouki (1994a, b). The polarization force ($\mathbf{F}_p$) acting on a dust grain is, mathematically, defined as (Khrapak et al. 1990; Hamaguchi and Farouki 1994a, b)

$$\mathbf{F}_p = -\frac{q_d^2 \nabla \lambda_D}{2\lambda_D^2},$$

where $\lambda_D = \lambda_{Di(e)}/[1 + \lambda_{Di(e)}^2/\lambda_{De(i)}^2]^{1/2} = \lambda_{Di(e)}/[1 + n_{e(i)}T_{i(e)}/n_{i(e)}T_{e(i)}]^{1/2}$, $\lambda_{Di(e)} = [T_{i(e)}/4\pi e^2 n_{i(e)}]^{1/2}$, $T_{i(e)}$ is the ion (electron) temperature in energy unit, $n_{i(e)}$ is the ion (electron) number density, and e is the magnitude of an electron charge. Now, using $T_i n_e \ll T_e n_i$ ($T_e n_i \ll T_i n_e$) (which is a good approximation (Khrapak et al. 1990) for any dusty plasma with highly negatively (positively) charged dust, i.e. for $q_d = sZ_d e$ with Z_d being the number of electrons residing on the dust grain surface and s = 1 (–1) for positively (negatively) charged dust) and $T_i \nabla n_i = -n_i e \nabla \phi$ ($T_e \nabla n_e = n_e e \nabla \phi$) (with ϕ being the electrostatic potential), one can simplify the polarization force as $\mathbf{F}_p = sZ_d e R_j (n_j/n_{j0})^{1/2} \nabla \phi$, where $j = i(e)$ for ion (electron), $R_j = Z_d e^2/4T_j \lambda_{Dj0}$ is a parameter determining the effects of the polarization force (which arises due to interaction between thermal ions (electrons) and highly negatively

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https://doi.org/10.1017/S0022377813000408 Published online by Cambridge University Press

(positively) charged dust grains), n_{j0} is the number density of species j at equilibrium, and $\lambda_{Di(e)0} = [T_i(e)/4\pi n_{i(e)0}e^2]^{1/2}$. It is obvious that (i) the polarization force is directed opposite to the electrostatic force and (ii) in a dusty plasma with highly negatively (positively) charged dust, the polarization force arises mainly due to the polarization of plasma ions (electrons) around the dust grain.

The effects of polarization force on linear propagation of DA waves have also been investigated by Khrapak et al. (1990). Recently, Mamun et al. (2010) have studied the effects of polarization force on dust–acoustic solitary and shock waves in a uniform strongly coupled dusty plasma. The work of Mamun et al. (2010) is valid for a planar geometry. Ashrafi et al. (2010) have then studied non-planar (cylindrical and spherical) dust–acoustic solitary and shock waves in presence of polarization force. Nowadays, polarization force for different dusty plasma situations, viz. non-thermal and trapped ions (Schamel 1972a, b, 1975; Schamel and Bujarbarua 1980; Cairns et al. 1995; Mamun et al. 2004), adiabaticity of electrons and ions (Mamun 2008; Mamun et al. 2008), etc. is also a great deal of interest because of its significant effects on different linear and nonlinear phenomena in space and laboratory plasmas. To the best of our knowledge, the expression for the polarization force available in the existing literature is valid for Maxwellian (isothermal) electrons and ions, and no investigation has been made on the effects of non-isothermal electrons and/or ions, adiabaticity of electrons and/or ions, and polarity of dust. Therefore, in our present work, we have taken into account the effects of non-thermal and trapped ions, adiabaticity of electrons and ions, polarity of dust, etc. on polarization force, which is valid for different dusty plasma situations.

The paper is organized as follows. The modification of polarization force due to the presence of non-thermal ions is described in Sec. 2. The effects of vortex-like ions is analyzed in Sec. 3. The modification due to adiabaticity of electrons and ions is presented in Sec. 4. We finally provide a brief discussion in Sec. 5.

2. Non-thermal ions

We first consider an isolated dust with thermal electrons following Maxwellian distribution (Shukla and Mamun 2002) and non-thermal ions following Cairns distribution (Cairns et al. 1995). These allow us to express electron and ion number densities (n_e and n_i) as follows:

$$n_e = n_{e0} \exp\left(\frac{e\phi}{T_e}\right), \tag{2.1}$$

$$n_i = n_{i0}\left[1 + \frac{\beta e\phi}{T_i} + \frac{\beta e^2\phi^2}{T_i^2}\right]\exp(-e\phi/T_i), \tag{2.2}$$

$$\beta = \frac{4\alpha}{1+3\alpha}, \tag{2.3}$$

where α is a parameter determining the number of fast (non-thermal) ions (Cairns et al. 1995; Mamun 1997). It should be mentioned here that for $\alpha = 0$, n_i reduces to the Maxwellian ion distribution (Mamun et al. 1996).

If we consider positively charged dust, the Debye shilding is mainly due to Maxwellian electrons and the effect of non-thermal ions is negligible. Thus, the polarization force can be approximated as

$$\mathbf{F}_{pn+} = Z_d e R_e (n_e/n_{e0})^{1/2}\nabla\phi, \tag{2.4}$$

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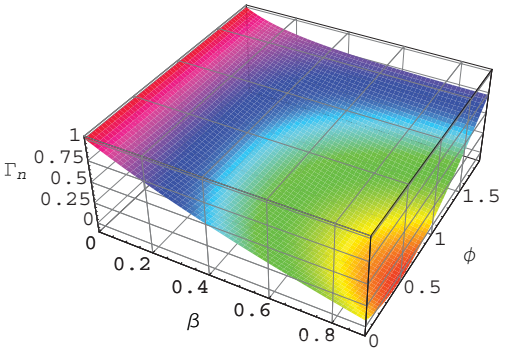


FIGURE 1. (Color online) Showing the variation of Γ_n with β and ϕ for negatively charged dust.

where

$$R_e = Z_d e^2/4T_e\lambda_{De0}. \tag{2.5}$$

However, if we consider negatively charged dust, then the Debye shilding is mainly due to non-thermal ions and the polarization force can be approximated as

$$\mathbf{F}_{pn-} = -Z_d e R_i A(n_{i0}/n_i)^{1/2}\nabla\phi, \tag{2.6}$$

where

$$R_i = Z_d e^2/4T_i\lambda_{Di0}, \tag{2.7}$$

$$A = we^{-e\phi/T_i}, \tag{2.8}$$

$$w = \left[1 - \beta - \frac{\beta e\phi}{T_i} + \frac{\beta e^2\phi^2}{T_i^2}\right], \tag{2.9}$$

$$\lambda_{Di0} = \sqrt{T_i/4\pi n_{i0}e^2(1-\beta)}, \tag{2.10}$$

if $\beta = 0$, then the polarization force is exactly the same as derived by Mamun et al. (2010).

From (2.6), we observe that the polarization force is significantly modified due to the presence of non-thermal ions and negatively charged dust. Figure 1 shows the variation of $\Gamma_n(= F_{pn-}/F_p)$ with β and ϕ for negatively charged dust. For non-thermal ions with negatively charged dust Γ_n decreases with β but increases with ϕ.

3. Vortex-like ions

We next consider an isolated dust with thermal electrons following Maxwellian distribution (Shukla and Mamun 2002) and ions following Schamel distribution (Schamel 1972a, b, 1975). The ion density n_i for Schamel distribution is directly given by Schamel (1972a, b, 1975), Schamel and Bujarbarua (1980), and Mamun et al. (2004),

$$n_i = n_{i0}\left[1 - \frac{e\phi}{T_i} - \frac{4(1-\sigma)}{3\sqrt{\pi}}\left(\frac{-e\phi}{T_i}\right)^{3/2}\right]\exp(-e\phi/T_i), \tag{3.1}$$

where σ, defined as the ratio of the free hot ion temperature to the hot trapped ion temperature, is a trapping parameter that determines the number of trapped ions (Mamun 1998). We note that $\sigma < 0$ represents a vortex-like excavated trapped

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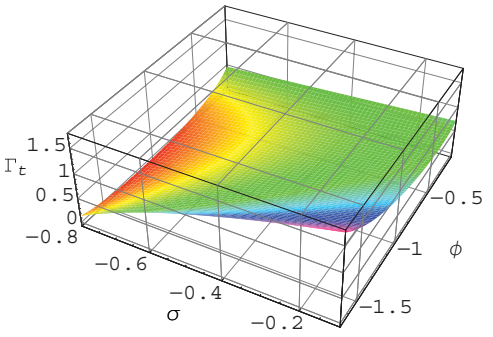


FIGURE 2. (Color online) Showing the variation of Γ_t with σ and ϕ for negatively charged dust.

ion distribution, whereas $\sigma = 1$ ($\sigma = 0$) represents a Maxwellian (flat–topped) ion distribution. We are interested in $\sigma < 0$.

Thus, as before, the polarization force for a system containing positively charged dust, Maxwellian electrons, and vortex-like ions, can be approximated as

$$\mathbf{F}_{pt+} = Z_d e R_e (n_e/n_{e0})^{1/2} \nabla\phi, \tag{3.2}$$

where

$$R_e = Z_d e^2/4T_e\lambda_{De0}. \tag{3.3}$$

Equation (3.2) indicates that in the case of positively charged dust, trapped ion has no significant effect on polarization force.

On the other hand, for negatively charged dust, the polarization force becomes

$$\mathbf{F}_{pt-} = -Z_d e R_i A (n_{i0}/n_i)^{1/2} \nabla\phi, \tag{3.4}$$

where

$$R_i = Z_d e^2/4T_i\lambda_{Di0}, \tag{3.5}$$

$$A = \left[1 + \frac{2(1-\sigma)}{\sqrt{\pi}} \frac{e}{T_i} \frac{1}{\sqrt{\frac{-e\phi}{T_i}}} - \frac{e\phi}{T_i}\right], \tag{3.6}$$

$$\lambda_{Di0} = \sqrt{T_i/4\pi n_{i0} e^2}. \tag{3.7}$$

if $\sigma = 1$, then the polarization force is exactly the same as derived by Mamun et al. (2010).

Equation (3.4) is the modification of the polarization force due to trapped ions and negatively charged dust. Figure 2 shows the variation of $\Gamma_t (= F_{pt-}/F_p)$ with σ and ϕ for negatively charged dust. From Fig. 2, we see that the polarization force is significantly increased by the presence of trapped ions and by the increase of magnitude of electric potential in the case of negatively charged dust.

4. Adiabatic electrons and ions

We finally consider an isolated dust with adiabatic electrons and ions. The adiabatic electron and ion number densities (n_e and n_i) are directly given by Mamun (2008)

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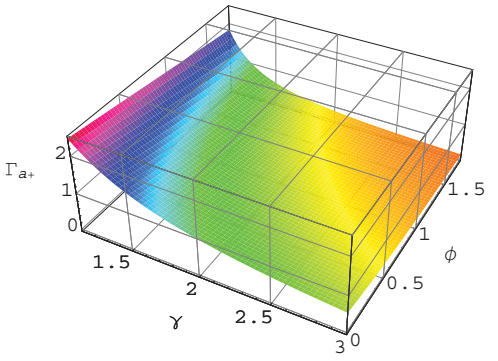


FIGURE 3. (Color online) Showing the variation of Γ_{a+} with γ and ϕ for positively charged dust.

and Mamun et al. (2008),

$$n_e = n_{e0}\left[1 + \frac{(\gamma-1)}{\gamma}\frac{e\phi}{T_{e0}}\right]^{\frac{1}{(\gamma-1)}}, \tag{4.1}$$

$$n_i = n_{i0}\left[1 - \frac{(\gamma-1)}{\gamma}\frac{e\phi}{T_{i0}}\right]^{\frac{1}{(\gamma-1)}}. \tag{4.2}$$

Thus, as before, the polarization force for a system containing positively charged dust, adiabatic electrons, and ions can be approximated as

$$\mathbf{F}_{pa+} = Z_d e R_e A (n_{e0}/n_e)^{1/2} \nabla\phi, \tag{4.3}$$

where

$$R_e = Z_d e^2/4T_{e0}\lambda_{De0}, \tag{4.4}$$

$$A = \frac{1}{\gamma}\left[1 + \frac{(\gamma-1)}{\gamma}\frac{e\phi}{T_{e0}}\right]^{\frac{2-\gamma}{\gamma-1}}, \tag{4.5}$$

$$\lambda_{De0} = \sqrt{\gamma T_{e0}/4\pi n_{e0} e^2}. \tag{4.6}$$

On the other hand, for negatively charged dust, the polarization force becomes

$$\mathbf{F}_{pa-} = -Z_d e R_i A (n_{i0}/n_i)^{1/2} \nabla\phi, \tag{4.7}$$

where

$$R_i = Z_d e^2/4T_{i0}\lambda_{Di0}, \tag{4.8}$$

$$A = \frac{1}{\gamma}\left[1 - \frac{(\gamma-1)}{\gamma}\frac{e\phi}{T_{i0}}\right]^{\frac{2-\gamma}{\gamma-1}}, \tag{4.9}$$

$$\lambda_{Di0} = \sqrt{\gamma T_{i0}/4\pi n_{i0} e^2}, \tag{4.10}$$

The modification of polarization force due to adiabatic electrons and ions is displayed in Figs. 3 and 4. Figure 3 shows variation of $\Gamma_{a+}(= F_{pa+}/F_p)$ with γ and ϕ for positively charged dust. On the other hand, Fig. 4 shows variation of $\Gamma_{a-}(= F_{pa-}/F_p)$ with γ and ϕ for negatively charged dust. Figures 3 and 4 imply that the polarization force is significantly decreased by the adiabaticity of electrons and ions in the case of both positively and negatively charged dust whereas it is significantly increased

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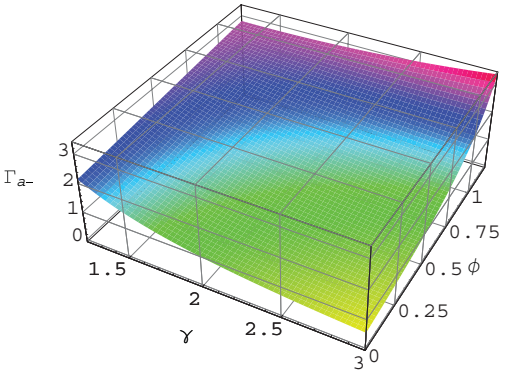


FIGURE 4. (Color online) Showing the variation of Γ_{a-} with γ and ϕ for negatively charged dust.

(decreased) by increase of the magnitude of electric potential in the case of negatively (positively) charged dust.

5. Discussion

To summarize, we have investigated the polarization force for different dusty plasma situations, viz. non-thermal and trapped ions, adiabaticity of electrons and ions, etc. The magnitude of the polarization force is significantly decreased by the presence of non-thermal ions and by the adiabaticity of electrons and ions. On the other hand, it is significantly increased by the presence of trapped ions. It has been also shown that the magnitude of the polarization force is significantly increased (decreased) by the increase of the magnitude of electric potential in the case of negatively (positively) charged dust.

To conclude, the results of the present investigation should be useful for understanding different linear and nonlinear features in laboratory and space plasmas where these effects are very important.

Acknowledgements

The research grant for research equipment from the Third World Academy of Sciences (TWAS), ICTP, Trieste, Italy is gratefully acknowledged. The constructive suggestions of anonymous referee are also gratefully acknowledged.

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