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**Letter to the Editor**

# Potential distribution around a charged dust grain in an electronegative plasma

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**Abstract.** The potential distribution around a charged dust grain in an electronegative plasma is obtained by using the appropriate dielectric susceptibilities for the Boltzmann distributed electrons and negative ions, and for the inertial positive ions that are streaming from the bulk plasma into the electronegative plasma sheath. The existence of oscillatory ion wakefields is shown. Positive ions are trapped/focused in the ion wakefields, and subsequently the negative dust particles are attracted to each other, forming ordered dust structures.

It is well known that a stationary test charge is shielded in plasmas, and that the near-field potential follows the Debye–Hückel–Yukawa law [1]. Furthermore, it has been shown [2–4] that the far-field potential of a moving test charge in a collisionless electron-ion plasma decreases as the inverse cube of the distance $r$ from the test charge. On the other hand, the far-field potential in a collisional electron-ion plasma [5–8] decays as $r^{-2}$.

When neutral dust grains are immersed in an electropositive plasma, they usually get negatively charged [9,10] due to the high mobility of the electrons that reach the dust grain surface. Several authors [11–13] have investigated the potential around a charged dust grain in a dusty plasma whose constituents are electrons, positive ions and negative dust grains. Besides, the Debye–Hückel–Yukawa potential, there appear long-range oscillatory wakefields [12,13] due to collective interactions between the test charge and the dust ion-acoustic [14] and dust acoustic [15] waves in dusty plasmas with equilibrium drifts of the ions and the dust grains. Since oscillatory wakefields have both positive and negative potential distributions, the background positive ions are trapped/focused in the negative part of the oscillatory wake potential. It turns out that negative dust grains are attracted to each other as they are glued by positive ions. The underlying physics of this scenario is similar to that

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of the Cooper pairing of electrons in superconductors, where phonons do the job of gluing electrons in lattices.

However, in industrial plasmas, negative ion-containing plasmas (known as the electronegative plasmas [16, 17]) have been extensively used in dry etching and plasma-enhanced thin-film deposition processing. In electronegative plasmas, the charge state of a dust particle is greatly affected by the presence of negative ions [19–22]. Electronegative plasmas are composed of electrons, positive inertial ions, and a fraction of negative ions, which typically follow the Boltzmann density distribution [23–25] in the electrostatic potential. In this Letter, we present an investigation of the potential distribution around a charged dust grain in an electronegative plasma sheath [23]. Such an investigation is of significant interest with regard to creating soft condensed materials in plasma-processing technologies [18].

The electrostatic potential around a test dust particle (with charge $Q$) moving with a constant velocity $\mathbf{v}_t$ is [2]

$$\phi(\mathbf{R},t) = \frac{Q}{2\pi^2}\lim_{\epsilon\to 0}\int \frac{d\mathbf{k}\exp(i\mathbf{k}\cdot\mathbf{r}-\epsilon k)}{k^2 D(\mathbf{k},-\mathbf{k}\cdot\mathbf{v}_t)}, \tag{1}$$

where $\mathbf{r} = \mathbf{R} - \mathbf{v}_t t$, $D(\mathbf{k}, \omega = -\mathbf{k}\cdot\mathbf{v}_t)$ is the dielectric constant of the electronegative plasma, and $\mathbf{k}$ is the wave vector of the low-frequency ion oscillations in the electrostatic potential. Following Montgomery et al. [2], the term $\lim_{\epsilon\to 0}\exp(-\epsilon k)$ has been included to ensure proper convergence of the integrals.

The dielectric constant of an electronegative plasma with Boltzmann distributed electrons and negative ions, as well as inertial positive ions and static charged dust grains for $|\mathbf{k}\cdot\mathbf{v}_t| \ll kV_{Te,T-}$ reads

$$D(\mathbf{k},-\mathbf{k}\cdot\mathbf{v}_t) = 1 + \chi_e + \chi_- + \chi_+, \tag{2}$$

where $V_{Tj} = (k_B T_j/m_j)^{1/2}$ is the thermal speed of the particle species $j$ ($j$ equals $e$ for electrons, $-$ for negative ions and $+$ for positive ions). The dielectric susceptibilities for our purposes are

$$\chi_e \approx \frac{k_e^2}{k^2}, \tag{3}$$

$$\chi_- \approx \frac{k_-^2}{k^2}, \tag{4}$$

and

$$\chi_+ = -\frac{\omega_{p+}^2}{(\mathbf{k}\cdot\mathbf{v}_t - k_z u_0)^2 - 3k^2 V_{T+}^2}. \tag{5}$$

Here $k_B$ is the Boltzmann constant, $T_j$ is the temperature, $m_j$ is the mass and $u_0$ is the equilibrium axial (along the $z$-axis) speed of the positive ions entering the electronegative plasma sheath from the bulk plasma. The inverse Debye radii of electrons and negative ions are defined as $k_e = \lambda_e^{-1} = (T_e/4\pi n_{e0}e^2)^{-1/2}$ and $k_- = \lambda_-^{-1} = (T_-/4\pi n_{-0}Z_-^2 e^2)^{-1/2}$, respectively, where $e$ is the magnitude of the electron charge, and the equilibrium densities $n_{j0}$ are related by the quasi-neutrality condition [26] $n_{e0} + Z_- n_{-0} = Z_+ n_{+0} - Z_d n_{d0}$. Here $Z_{-,+}$ is the ion charge state, and $Z_d$ is the number of electrons residing on a charged dust grain, which are assumed to be spherical. The dust number density and the plasma frequency of the positive ions are denoted by $n_{d0}$, and $\omega_{p+} = (4\pi n_{+0} Z_+^2 e^2/m_+)^{1/2}$, respectively. Assuming that our test dust charge is stationary, *viz.* $\mathbf{v}_t = 0$, we have from (2)–(5),

$$\frac{1}{D} \approx \frac{k^2\lambda_D^2}{(1+k^2\lambda_D^2)}\left[1+\frac{\omega_s^2}{(k_z^2u_0^2-\omega_s^2)}\right], \tag{6}$$

where $\lambda_D = \lambda_e\lambda_-/(\lambda_e^2+\lambda_-^2)^{1/2}$ is the effective Debye radius of the electronegative plasma, $\omega_s = kC_s/(1+k^2\lambda_D^2)^{1/2} \gg kV_{T+}$, and $C_s = \omega_{p+}\lambda_D$ is the effective ion sound speed in the electronegative plasma with $T_e \gg T_+$.

Substituting (6) into (1) and carrying out the integration in a straightforward manner, we readily obtain [12, 13] the potential around a stationary charged dust grain

$$\phi = \phi_D + \phi_W, \tag{7}$$

where the Debye–Hückel–Yukawa and wake potentials are, respectively,

$$\phi_D = \frac{Q}{r}\exp\left(-\frac{r}{\lambda_D}\right) \tag{8}$$

and

$$\phi_W(\rho=0,z) \approx \frac{2Q}{|z|(1-M^{-2})}\cos(|z|/L_*). \tag{9}$$

Here $M = u_0/C_s$ is the Mach number, $|z| > L_*$, where $L_* = \lambda_D\sqrt{M^2-1}$ is the effective length and $\rho$ and $z$ are the cylindrical coordinates of the field point of the test charge. We note that $L_*$ is positive for $M^2 > 1$, and the wake potential is attractive for $\cos(|z|/L_*) < 0$. The attractive potential can dominate over the Debye–Hückel–Yukawa potential because of the rapid decrease of the latter beyond the shielding cloud.

In summary, we have presented a simple investigation of the potential distribution around a stationary charged dust grain in an unmagnetized electronegative plasma composed of electrons and negative ions following the Boltzmann density distribution, as well as positive ions that stream from the main body of the plasma into the electronegative plasma sheath where the charged dust grains are levitated/confined due to a balance between the sheath electric and gravity forces. By using appropriate susceptibilities for the plasma particles of our electronegative plasma, we have deduced expressions for the potential distributions around a static charged dust grain. We have found an oscillatory wakefield potential, besides the short-range Debye–Hückel–Yukawa potential, when the positive ions have supersonic speeds (*viz.* $M > 1$). Due to the presence of the oscillatory ion wakefields, negative dust particles can be attracted to each other and form dust lattices/dust crystals in an electronegative plasma.

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