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The influence of multi-ion streaming on the variation of dust particle surface potential with Maxwellian/non-Maxwellian dusty plasmas

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Dust grain potential variation influence by positive ion streaming as well as negative ion streaming is presented in a complex (dusty) plasma following the Maxwellian/non-Maxwellian (kappa distribution and Cairns distribution) function. The components of complex plasma are the electrons, ions [positive and negative], and dust grains having negative charge. For this purpose, the mathematical statement (equation) of currents is derived for dust grains having negative charge to fulfill the equilibrium state (viz., $q_D = \text{constant}$). It is observed numerically that positive ion streaming speed as well as negative ion streaming speed has a significant influence on the surface potential of dust particles, e.g., by increasing the positive ion and negative ion streaming speed, the magnitude of dust particle surface potential increases. The relevance to low-temperature research center in a non-equilibrium complex (dusty) plasma is precisely discussed by associating oxygen ion (negative and positive) species. *Published by AIP Publishing.*
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I. INTRODUCTION

Dusty plasmas or complex plasmas comprise ions, electrons, and massive charged (negative/positive) dust particles (grains). Complex plasmas have attracted great attention in the beginning of this decade. The size of the dust grains may range up to few microns and they are normally around 10 to 12 orders of magnitude heavier than plasma species. The characteristic length-scales linked with dusty-plasma are of the ordering $r_D \ll d$ and $\lambda_\mathbf{D} \ll L$, where r_D, d, $\lambda_\mathbf{D}$, and L represent dust-grain radius, distance between dust grains, effective Debye-length, and dimension of the plasma-system, respectively.[1] In principle, when $\lambda_D/L \to 0$, the interactions corresponding to the plasma-surface split into a two scale problem comprising a quasi neutral presheath and a collision-free sheath.[2] The dusty plasma is regularly found in the circumstellar mists, planetary rings, interstellar clouds, and nebulae, interplanetary media the Earth's domain.[3,4] Complex plasma also occurs in the lab during the effect of high Z-impurities from the wall tokamak and in addition the impurity which is produced by MHD power generators.[1,5] The modes of dusty plasma have also been examined theoretically[6] and experimentally[7,8] as well as by simulation.[9] The utmost essential acoustic like modes in the Maxwellian complex plasma[10] were initially investigated[11] known as dust acoustic wave (DAW) by taking into account the cohesionless liquid model. Later on, it was examined theoretically[12] that an ion acoustic wave was found in a dusty plasma, when temperature of the electrons is equalized to ion temperature and declared it as the dust ion acoustic wave (DIAW). In addition, the lab study[13–16] was also examined.

The negative ions were seen to be an extra constituent (naturally occurring or infused from an external source) in the complex plasma (both in space and lab).[17] The presence of negative ions in an electro-negative plasma is the result of the phenomena where free electrons gain by neutral atoms. The dust grains charged negatively or positively mostly depend on the charging mechanism,[13,18–20] for example, secondary emission, photo-electric emission, and thermionic emission resulting in positive charge on dust particles (grains). It has been observed through experiments conducted in the low temperature lab that thermal velocity of electrons is greater than that of ions; the resulting electrons are captured by dust grains and attain negative charge. The electron current as well as ion current flows on the surface of the dust grains; as a result of this, dust charge/potential variation occurs. Because of negatively charged dust grains, electron current (I_e) is decreased and hence positive ion current increases (I_i) until the steady state value is achieved (viz$|I_e| = |I_i|$. The dust charging process was first examined by Barkan[21] to study the dust particle potential (surface) experimentally as well as theoretically. Likewise, the influence of negative ions on the charging of dust grains in Maxwellian Plasma has been observed by Mamun and Shukla.[22] Later on, the significance of non- Maxwellian plasma species (κ–distribution) was also studied.[23]

In principle, the component species in the plasma system do collision among themselves continuously and as a result, they attain different velocities. Alternatively, in order to move towards thermal equilibrium the plasma species exchange Kinetic-energy and Momentum among them and at last thermal equilibrium is established. To describe the plasma species

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in equilibrium, Maxwellian distribution is the natural choice.[24,25] There are several plasmas in the space systems where the plasma particles (electrons/ions) are not under thermal equilibrium (non-Maxwellian distribution). On the basis of this point, around 47 years prior,[26] the electron energy spectra of the plasma sheet were analyzed and an empirical function of high energy electrons to model the velocity distribution was acquainted. It has been investigated that the velocity distribution of high energy electrons is not like a Maxwellian distribution and hence, another distribution termed as kappa distribution to study the behavior of high energy electrons in the plasma system.[26] The kappa distribution was considered because of wave particle correlation and external forces acting by the space environment,[27] e.g., ionosphere, interstellar medium, solar wind, magnetosphere, thermosphere, etc. Various observations[28–31] have been made to clarify mutual interactions (correlation) in the plasma particles by using the κ–distributed plasma species. Where κ stands for the spectral index and shows the deviation from Maxwellian distribution of plasma species to non-Maxwellian distribution, while the value of the spectral index (κ) is always greater than 3/2. It has been noticed that for small values of spectral index kappa, the tails of velocity distribution curves correspond to high energy particles. By applying the limit (kappa) $\kappa \to \infty$, the kappa distribution exactly coincides to a Maxwellian distribution.[24,25] In 1995, the Ferja satellite[32] and Viking spacecraft[33] made observations regarding the rarefaction of ion number density (cavitons). Using these observations, Cairns and his collaborators[34] made a non-thermal distribution which is identified as Cairns distribution in the literature. Observations reported by the Viking spacecraft[33] demonstrate that inside the auroral-zone the distribution-function describing the electrons corresponds to the shoulder of the distribution-function. The Cairns distribution involves the spectral-index α which corresponds to the number of energetic-particles on the shoulder of distribution-function in the plasma system. Using the limit $\alpha \to 0$ in the Cairns-distribution function, the Maxwellian distribution[24,25] is re-established.

In this article, the expressions for the dust particle potential (surface potential) have been documented, while using the current balance equations (for electrons, positive/negative ions streaming) for dust particles, for the cases of Maxwellian and non-Maxwellian (kappa distribution and Cairns distribution) functions. We have concentrated on the influence of positive/negative ion streaming velocity on the negatively charged dust particle potential (surface) and its possible outcomes.

The manuscript is arranged as follows: in Sec. II, an attempt has been made to investigate the dust grain surface potential containing electron and ion (negative/positive) streaming effects. In the equilibrium condition, the dust charging statement formulates the balance equation of the current that can be utilized to describe the dust-particle surface-potential variation and the dust grain charging mechanism for the case of both Maxwellian and non-Maxwellian (κ–distribution) functions is shown in Secs. II A and II B, respectively. And finally the numerical results and discussion are documented in Sec. III.

II. THE DUST PARTICLE SURFACE POTENTIAL HAVING NEGATIVE/POSITIVE ION STREAMING SPEED

We consider a plasma system having no magnetic field in the background, consisting of dust grains (spherical nature), electrons, and positive/negative ions. The plasma system like this can be described by both Maxwellian and non-Maxwellian (Kappa/Cairns) distributions. In principle, the Orbit Motion limited (OML) is utilized to find the upper cutoff on the charging-currents. OML is used only when the particle-radius is smaller than the Debye-length (thick-sheath).[35] Indeed, the plasma species from an infinite-distance, approach towards spherical dust-grains and by entering its Debye sphere, interact electrostatically with the dust grain's surface to generate either positive or negative charge on the dust.[25] In this respect, the dust charging process is accounted for the negatively charged dust due to the currents of electrons and ions (including both the positive and negative ions) in a Maxwellian and non-Maxwellian distributed plasma and can be expressed by an equation[36] as follows:

$$\frac{\partial q_D}{\partial t} = \sum_{j=e,i,n} I_j, \tag{1}$$

where q_D is termed as the mean charge of the dust grains and I_j is termed as the current of the plasma jth species ($j = e$ stands for electrons, i stands for positive ions, and n stands for negative ions) flowing on the dust particle which can be stated[37] as

$$I_j = \sum_{j=e,i,n} q_j \int V_j \sigma_j^D f_j(V_j) d^3\mathbf{V}_j. \tag{2}$$

Here, q_j and $f_j(V_j)$ represent the charge and distribution function of plasma jth species, respectively. V_j represents the minimum value of the plasma particle (electrons and ions) velocity with which the particle hits the dust grain. Where the σ_j^D stands for the charging cross section due to collisions among the dust particles and plasma species (e, i, n) can be formulated[36,38] as

$$\sigma_j^D = \left(1 - \frac{2q_j\phi_D}{m_j V_j^2}\right)\pi r_D^2, \tag{3}$$

$m_j(r_D)$ is the mass of plasma species (radius of dust grains) and ϕ_D is the dust grain surface potential.

A. Dust-charge fluctuation using Maxwellian distribution function in the presence of negative/positive ion streaming speed

The plasma species collide continually with each other and move with different velocities, and because of these collisions, plasma species may inter-change their kinetic energy and momentum to achieve thermal equilibrium (balance). The most widely recognizable distribution is the Maxwellian distribution $[f_j^M(V_j)]$ for the plasma species which depends exponentially on the species velocity. The Maxwellian distribution[25,39] is given by

$$f_j^M(\mathbf{V}_j) = \frac{n_j}{\pi^{3/2}V_{tj}^3}\exp\left(-\frac{V_j^2}{V_{tj}^2}\right), \quad (4)$$

where V_j and n_j are the velocity and number density of the plasma species, respectively, and $V_{tj}(=\sqrt{2T_j/m_j})$ stands for the thermal speed of jth plasma species with m_j and T_j being mass and temperature (in energy units), respectively. This sort of distribution is only applicable to the plasma system (framework) which obeys the condition of thermal equilibrium.

By inserting Eqs. (3) and (4) into Eq. (2) and using the volume element $d^3V_j = \mathbf{V}_i^2 dV_j d\phi d\mu$ in spherical-coordinates, the dust charging current for electrons (I_e^M) and positive/negative ions for dust grains (negatively charged) can be written as, respectively,[1,22,36] in the form

$$I_e^M = -4\pi r_D^2 n_e e\left(\frac{T_j}{2\pi m_j}\right)^{\frac{1}{2}}\exp\left(\frac{2e\phi_D}{m_i V_{te}^2}\right), \quad (5)$$

$$I_i^M = 4\pi r_D^2 n_i Z_i e V_i\left(1-\frac{2Z_n e\phi_D}{m_n V_i^2}\right), \quad (6)$$

and

$$I_n^M = -4\pi r_D^2 n_n Z_n e V_n\left(1+\frac{2Z_n e\phi_D}{m_n V_n^2}\right), \quad (7)$$

where Z_i (Z_n) stands for the positive (negative) ion charging state. Equation (5) shows that electron thermal velocity is greater than electron streaming speed, it is because the mass of electrons is negligibly small as compared to ion mass. Equations (6) and (7) show that the positive ion (negative ion) streaming speed V_i (V_n) is much greater than its thermal speed V_{ti} (V_{tn}). Under the steady state condition, $\partial q_D/\partial t = 0$ and Eq. (1) takes the form

$$\sum_{j=e,i,n} I_j = I_e^M + I_i^M + I_n^M = 0. \quad (8)$$

The charge-neutrality condition is given by

$$n_e + Z_n n_n = Z_i n_i + q_D n_D/e. \quad (9)$$

Now using the zero net current condition [Eq. (8)], charge-neutrality condition [Eq. (9)] and the relationship $\phi_D = q_D/r_D$, [in CGS unite system] the surface potential for the dust particles having Maxwellian distributed Positive/negative ion streaming speeds can be formulated as

$$\sqrt{S_{i0}} - \frac{Z_i}{\sqrt{S_{i0}}}U - \frac{\zeta}{2\pi}\exp(U)\left(1-\chi\frac{Z_n}{Z_i}+PZ_iU\right) = \sqrt{S_{n0}}Z_n\chi\left(1+\frac{Z_nU}{S_{n0}}\right)\frac{\beta}{Z_i}, \quad (10)$$

where $S_{i0} = m_iV_i^2/2T_e$, $S_{n0} = m_nV_n^2/2T_e$, $\chi = n_n n_i^{-1}$, $\beta = \sqrt{m_i/m_n}$ and $\zeta = \sqrt{m_i/m_e}$. The dust grain surface potential measured relative to the plasma potential is symbolized by $U = e\phi_D/T_e$ and the dust number density (normalized) by $P = n_D r_D 4\pi\lambda_0^2$ with $\lambda_0 = \sqrt{T_e/4\pi Z_i^2 e^2 n_i}$. Equation (10) contains the effect of negative/positive ion streaming velocity on variations in the dust grain potential (surface potential), and is a function of parameter P.

B. Dust-charge fluctuation using non Maxwellian κ–distribution function having negative/positive ion streaming speed

The three dimensional (kappa) κ–distribution function[26] can be written for jth plasma species as

$$f_j^\kappa(\mathbf{V}_j) = C_{j\kappa}\frac{1}{\theta_j^3}\left(1+\frac{V_j^2}{\kappa\theta_j^2}\right)^{-(\kappa+1)}, \quad (11)$$

where $C_{j\kappa} = n_j\kappa^{-3/2}\Gamma(1+\kappa)/\pi^{3/2}\Gamma(\kappa-1/2)$, κ (kappa) is the spectral index which shows the conversion from thermal equilibrium to non-thermal-equilibrium in the limit $\kappa > 3/2$, $\theta_j[=\sqrt{2\kappa-3)/\kappa}V_{tj}]$ is the realistic effective thermal speed, and Γ stands for the gamma function. We note that the kappa distribution [given by Eq. (11)] reduces to a Maxwellian distribution [given by Eq. (4)] for $\kappa\to\infty$.

Utilizing the same mathematical strategy as followed in Sec. II A, we can compose electron-current (I_e^κ), positive ion-current (I_i^κ), and negative ion-current (I_n^κ) [it is noticed that for the positive ions $V_i \gg \theta_i$ and for negative ions $V_n \gg \theta_n$, (where $V_i(V_n)$ is streaming velocity of positive (negative) ions)] for the κ–distribution case[23,36] as

$$I_e^\kappa = -2\sqrt{\pi}r_D^2 n_e\theta_e\frac{\kappa}{\kappa-1}\frac{\Gamma(\kappa-1)}{\kappa^{\frac{3}{2}}\Gamma\left(\kappa-\frac{1}{2}\right)}\left(1-\frac{2e\phi_D}{\kappa m_e\theta_e^2}\right)^{-\kappa+1}Z_ie, \quad (12)$$

$$I_i^\kappa = 2\sqrt{\pi}r_D^2 n_i V_i\frac{\kappa}{\kappa-1}\frac{\Gamma(\kappa-1)}{\kappa^{\frac{3}{2}}\Gamma\left(\kappa-\frac{1}{2}\right)}\left(1-\frac{2(\kappa-1)}{\kappa}\frac{2Z_ie\phi_D}{m_iV_i^2}\right)Z_ie, \quad (13)$$

and

$$I_n^\kappa = -2\sqrt{\pi}r_D^2 n_n V_n\frac{\kappa}{\kappa-1}\frac{\Gamma(\kappa-1)}{\kappa^{\frac{3}{2}}\Gamma\left(\kappa-\frac{1}{2}\right)}\left(1+\frac{2(\kappa-1)}{\kappa}\frac{2Z_ne\phi_D}{m_nV_n^2}\right)Z_ne. \quad (14)$$

By using the charge-neutrality condition [Eq. (8)], the zero net current condition [Eq. (9)] and the relationship $\phi_D = q_D/r_D$, the equilibrium dust particle surface potential having non Maxwellian κ–distributed Positive/negative ion streaming speed can be formulated as

$$\sqrt{S_{i0}} - \frac{2(\kappa-1)}{\kappa}\frac{Z_iU}{\sqrt{S_{i0}}} - \left(1-\frac{2U}{2\kappa-3}\right)^{-\kappa+1} \frac{\zeta}{\sqrt{2}}\left(\frac{2\kappa-3}{\kappa}\right)^{\frac{1}{2}}\left(1-\chi\frac{Z_n}{Z_i}+PZ_iU\right) = \sqrt{S_{n0}}Z_n\chi\left(1+\frac{2(\kappa-1)}{\kappa}\frac{Z_nU}{S_{n0}}\right)\frac{\beta}{Z_i}. \quad (15)$$

Equation (15) presents the variations in the dust-grain potential (surface-potential) with the parameter P in the existence of non-Maxwellian Kappa distribution plasma species. It is noticed that by using the limit $\kappa \to \infty$, Eq. (15) reduces to Eq. (10) presenting the dust particle potential with a Maxwellian complex-plasma.

C. Dust-charge fluctuation using the Cairns distribution function having negative/positive ion streaming speed

The three dimensional Cairns distribution function for jth plasma species is given as[34,40]

$$f_j^C(\mathbf{V}_j) = \frac{n_j}{(3\alpha+1)\pi^{\frac{3}{2}}V_{tj}^3}\left(1+\alpha\frac{V_j^4}{V_{te}^4}\right)\exp\left(-\frac{V^2}{V_{tj}^2}\right), \quad (16)$$

where α measures the number of energetic particles within the plasma system under consideration. Following the same mathematical strategy as we have used in Sec. II A, electron-current (I_e^c), positive ion-current (I_i^c), and negative ion-current (I_n^c) [it is noticed that for the positive ions $V_i \gg V_{ti}$ and for negative ions $V_n \gg V_{tn}$ (where $V_i(V_n)$ is streaming velocity of positive (negative) ions)] for the Cairns distribution case[23,36] can be written as

$$I_e^\alpha = \frac{-2\sqrt{\pi}en_e r_D^2}{3\alpha+1}V_{te}\left[\exp\left(\frac{2e\phi_D}{m_eV_{te}^2}\right)+6\alpha+\frac{2e\phi_D}{m_eV_{te}}2\alpha\right], \quad (17)$$

$$I_i^\alpha = \frac{2\sqrt{\pi}r_D^2Z_ieV_i}{3\alpha+1}\left[1+6\alpha-\frac{2Z_ie\phi_D}{m_iV_i^2}(1+2\alpha)\right], \quad (18)$$

$$I_n^\alpha = \frac{-2\sqrt{\pi}r_D^2Z_neV_n}{3\alpha+1}\left[1+6\alpha+\frac{2Z_ne\phi_D}{m_nV_n^2}(1+2\alpha)\right]. \quad (19)$$

By using the charge-neutrality condition, the zero net current condition, and the relationship $\phi_D = q_D/r_D$, the equilibrium dust particle surface potential having Cairns distributed positive/negative ion streaming speed can be expressed as

$$\sqrt{S_{i0}} - 6\alpha - \frac{Z_iU}{\sqrt{S_{i0}}}(1+2\alpha) - \zeta\left(1-\chi\frac{Z_n}{Z_i}+Z_iPU\right)[6\alpha+2\alpha U+\exp(U)] = \frac{Z_n}{Z_i}\chi\beta\sqrt{S_{n0}}1+6\alpha+\frac{Z_nU(1+2\alpha)}{S_n}. \quad (20)$$

Equation (20) shows the variations in the dust-grain potential (surface-potential) with the parameter P in the presence of non-Maxwellian Cairns distribution plasma species. It is noticed that by using the limit $\alpha = 0$, Eq. (20) reduces to Eq. (10) presenting the dust particle potential with a Maxwellian complex-plasma. In order to investigate the connection between the dust particle surface-potential and the dust number density parameter in the presence of both positive and negative ions streaming under the condition of thermal/non-thermal equilibrium conditions, Eqs. (10), (15), and (20) can be further studied numerically.

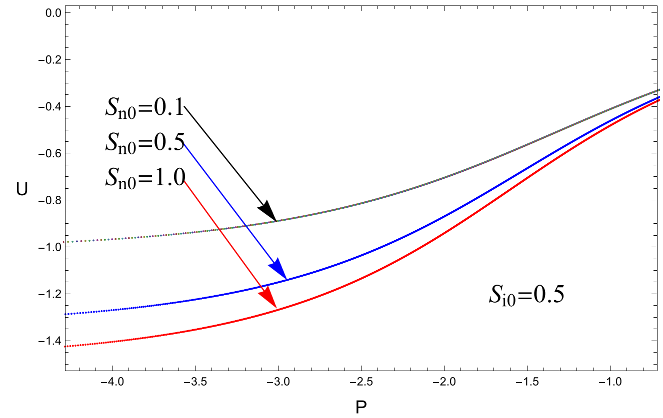

FIG. 1. The relationship between dust grain surface potential $(U = e\phi_D/T_e)$ and the dust grain density parameter $(P = \lambda_0^2 n_D 4\pi r_D)$ [see Eq. (10)] for different values of negative ion streaming speed $S_{n0}(=0.1,\ 0.5,\ 1.0)$ with $S_{i0} = 0.5$. Other parameters utilized here are $Z_i = 1$, $\chi = 0.4$, $\beta = 1$, and $Z_n = 2$.

III. NUMERICAL RESULTS AND DISCUSSION

Here, an attempt has been made to observe numerically Eqs. (10), (15), and (20) to study dust particle surface-potential (U) [measured relative to the plasma potential] versus dust number density (normalized) parameter P [ratio of dust number-density (n_D) to ion number density (n_i)] in log scale. The influence of positive/negative ion streaming speed on dust surface-potential for the case of Maxwellian/non Maxwellian (kappa distribution and Cairns distribution) dusty plasmas has also been discussed. These plasma systems contains negative ions of oxygen (O_2^-), positive ions of oxygen (O_2^+), electrons and isolated negatively charged dust grains. Here, the following data have been used for numerical analysis:[17,22,41,42] $\beta = 1$, $\alpha = 0.4$, $S_{i0} = 0.3$–0.9, $S_{n0} = 0.1$–1.0, $Z_i = 1$, and $Z_n = 2$.

Figure 1 displays the effects of negative ion streaming speed (U_{n0}) on the dust-grain surface potential (normalized) $U = e\phi_D/T_e$ as a function of the dust number density parameter (normalized) $P = 4\pi n_D r_D \lambda_0^2$ [see Eq. (10)] for the fixed values of $\alpha = 0.4$, $\beta = 1$, $Z_n = 2$, $\zeta = 242.8$, and $Z_i = 1$. It is observed that as we increase the values of negative ion

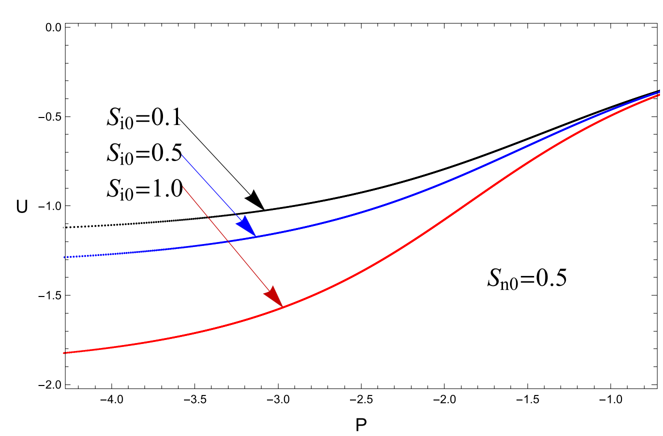

FIG. 2. The relationship between U and P [see Eq. (10)] for different values of positive ion streaming speed $S_{i0}(=0.1,\ 0.5,\ 1.0)$ with $S_{n0} = 0.5$. Other parameters utilized here are the same as in Fig. 1.

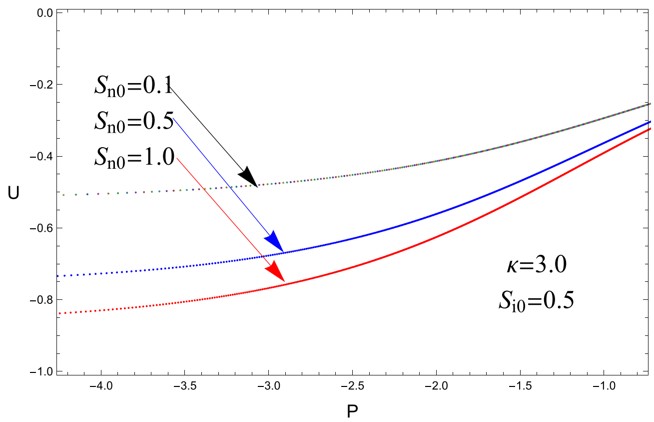

FIG. 3. The relationship between U and P [see Eq. (15)] for different values of negative ion streaming speed S_{n0}(=0.1, 0.5, 1.0) with $S_{i0} = 0.5$ and $\kappa = 3$. Other parameters utilized here are the same as in Fig. 1.

streaming $S_{n0}(= 1.0,\ 0.5,\ 0.1)$ while keeping positive ion streaming S_{i0} fixed with the value $S_{i0} = 0.5$, the strength of dust grain surface potential ($|\phi_D|$) increases and the effect becomes significant when P is less than –1.75. The same effect has been observed for the case of positive ion streaming speed in Fig. 2. From Fig. 2, we can see that by increasing the positive ion streaming speed S_{i0}(=0.1, 0.5, 1.0) with the fixed value of $S_{n0} = 0.5$, the strength of dust grain surface potential ($|\phi_D|$) increases. Figure 3 (Fig. 4) represents how the negative (positive) ion streaming speed amends the dust particle surface potential or dust-charge in the presence of non-Maxwellian κ–distribution. It is investigated that as we increase the value of negative-ion streaming-speed S_{n0}(0.1, 0.5, 1.0) with the fixed value of $S_{i0} = 0.5$ and $\kappa = 3$, the magnitude of dust grain surface potential ($|\phi_D|$) increases. On the other hand, by increasing the value of positive ion streaming speed S_{i0}(0.1, 0.5, 1.0) with $S_{n0} = 0.5$ and $\kappa = 3$, the magnitude of dust-grain surface-potential ($|\phi_D|$) enhances because positive ion streaming gradually increases the relative potential between positive ions and the negative charge of dust grains. Similarly, Figs. 5 and 6 show the effect of negative ion streaming speed and positive ion streaming speed on dust particle surface potential ($|\phi_D|$) having non-Maxwellian Cairns distribution, respectively. It is observed that by increasing both negative ion streaming speed and positive ion streaming-speed magnitude of dust surface-potential increases. The influence of spectral indices κ and α has been studied with Figs. 7 and 8, respectively. It has been investigated that by increasing the values of κ and α, the dust

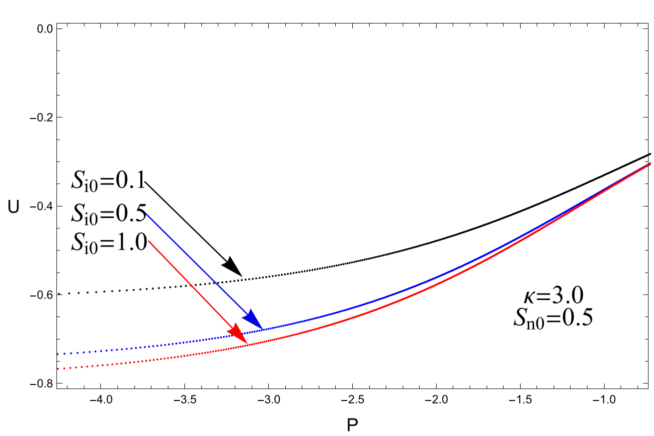

FIG. 4. The relationship between U and P [see Eq. (15)] for different values of positive ion streaming speed S_{i0}(=0.1, 0.5, 1.0) with $S_{n0} = 0.5$ and $\kappa = 3$. Other parameters utilized here are the same as in Fig. 1.

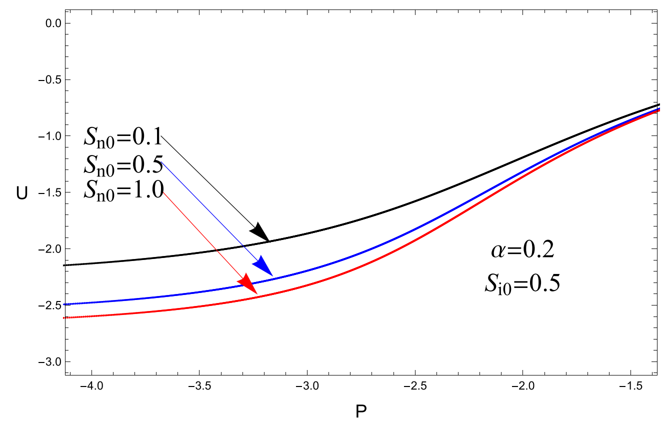

FIG. 5. The relationship between U and P [see Eq. (20)] for different values of negative ion streaming speed S_{n0}(=0.1, 0.5, 1.0) with $S_{i0} = 0.5$ and $\alpha = 0.2$. Other parameters utilized here are the same as in Fig. 1.

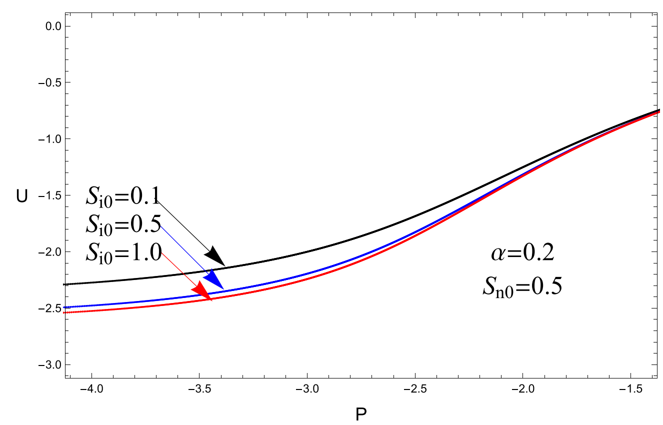

FIG. 6. The relationship between U and P [see Eq. (20)] for different values of positive ion streaming speed S_{i0}(=0.1, 0.5, 1.0) with $S_{n0} = 0.5$ and $\alpha = 0.2$. Other parameters utilized here are the same as in Fig. 1.

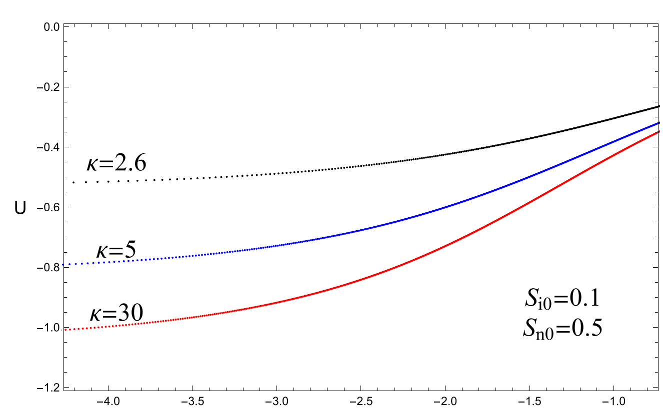

FIG. 7. The relationship between U and P [see Eq. (15)] for different values of spectral index κ(=2.6, 5, 30) with $S_{n0} = 0.5$ and $S_{i0} = 0.1$. Other parameters utilized here are the same as in Fig. 1.

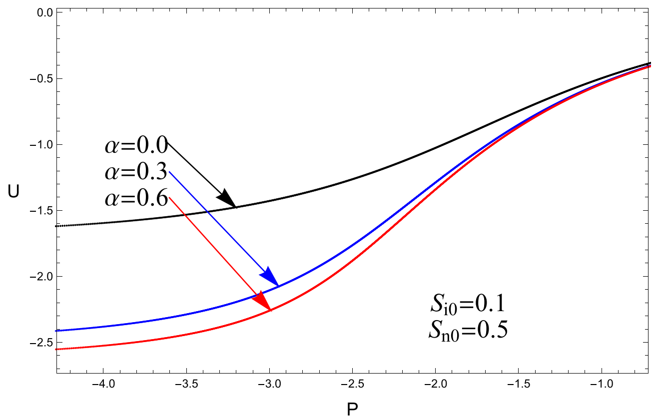

FIG. 8. The relationship between U and P [see Eq. (20)] for different values of spectral index α(=0, 0.3, 0.6) with $S_{i0} = 0.1$ and $S_{n0} = 0.5$. Other parameters utilized here are the same as in Fig. 1.

grain surface potential increases. Figure 7 shows that as we increase the value of κ, our result follows the curve plotted, using Maxwellian-distribution. But the opposite effect has been observed in Fig. 8, as we decrease the value of α, our result approaches the Maxwellian curve.

In conclusion, we have observed a dust surface potential variation by taking into account the positive ion streaming as well as negative ion streaming in the presence of Maxwellian/non-Maxwellian (κ–distribution) distributed plasma species. We formulated the mathematical statement of currents when dust charge accomplishes its balance state (viz., $q_d = \text{constant}$) for positive/negative ion streaming, and the dust particle surface potential. Numerical calculations show that the variation of plasma variables, for example, S_{i0} and S_{n0}, significantly affects the dust grain surface potential (i) by increasing the negative ion streaming speed, the strength of dust surface potential ($|\phi_D|$) increases. (ii) By increasing the values of positive ion streaming speed, the dust grain surface potential ($|\phi_D|$) increases. The physical reason for the observed trend is because positive/negative ion streaming gradually increases the relative potential between ions and the negative charge of dust grains. The accumulation of dust charges seems to appear due to relative streaming of ions; the dust surface potential has been increased. It has been also studied that by increasing spectral index κ and α dust grain surface potential relative to plasma potential increases.

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[1]P. K. Shukla and A. A. Mamun, *Introduction to Dusty Plasma Physics* (Institute of Physics, Bristol, UK, 2002).
[2]K.-U. Riemann, J. Phys. D: Appl. Phys. **24**, 493 (1991).
[3]H. Horanyi and D. A. Mendis, J. Astrophys. **91**, 355 (1986).
[4]C. K. Goertz, Rev. Geophys. **27**, 271, doi:10.1029/RG027i002p00271 (1989).
[5]V. E. Fortov, A. V. Ivlev, S. A. Khrapak, A. G. Khrapak, and G. E. Morfill, Phys. Rep. **421**, 1 (2005).
[6]R. K. Varma, P. K. Shukla, and V. Krishan, Phys. Rev. E **47**, 3612 (1993).
[7]R. L. Merlino, A. Barkan, C. Thompson, and N. D'Angelo, Phys. Plasmas **5**, 1607 (1998).
[8]A. Barkan, R. L. Merlino, and N. D'Angelo, Phys. Plasmas **2**, 3563 (1995).
[9]D. Winske and M. S. Murillo, Phys. Rev. E **59**, 2263 (1999).
[10]P. K. Shukla, Phys. Plasmas **8**, 1791 (2001).
[11]N. N. Rao, P. K. Shukla, and M. Y. Yu, Planet. Space Sci. **38**, 543 (1990).
[12]P. K. Shukla and V. P. Silin, Phys. Scr. **45**, 508 (1992).
[13]J. B. Pieper and J. Goree, Phys. Rev. Lett. **77**, 3137 (1996).
[14]A. Barkan, N. D'Angelo, and R. L. Merlino, Planet. Space Sci. **44**, 239 (1996).
[15]H. R. Prabhakara and V. L. Tanna, Phys. Plasmas **3**, 3176 (1996).
[16]V. I. Molotkov, A. P. Nefedov, V. M. Torchinskii, V. E. Fortov, and A. G. Khrapak, J. Exp. Theor. Phys. **89**, 477 (1999).
[17]H. Amemiya, B. M. Annaratone, and J. E. Allen, Plasma Sources Sci. Technol. **8**, 179 (1999).
[18]E. C. Whipple, T. G. Northrupt, and D. A. Mendis, J. Geophys. Res. **90**, 7405, doi:10.1029/JA090iA08p07405 (1985).
[19]B. Young, T. E. Cravens, T. P. Armstrong, and R. J. Friauf, J. Geophys. **99**, 2255 (1994).
[20]S. J. Choi and M. J. Kushner, J. Appl. Phys. **75**, 3351 (1994).
[21]A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Rev. Lett. **73**, 3093 (1994).
[22]A. A. Mamun and P. K. Shukla, Phys. Plasmas **10**, 1518 (2003).
[23]A. A. Abid, S. Ali, and R. Muhammad, J. Plasma Phys. **79**, 1117 (2013).
[24]J. C. Maxwell, Philos. Mag. **S4**(19), 19–32 (1860); **S4**(20), 21–37 (1860).
[25]F. F. Chen, *Introduction to Plasma Physics* (Plenum Press, New York, 1974).
[26]V. M. Vasyliunas, J. Geophys. Res. **73**, 2839, doi:10.1029/JA073i009p02839 (1968).
[27]V. Pierrad and M. Lazar, Sol. Phys. **267**, 153 (2010).
[28]R. L. Mace and M. A. Hellberg, Phys. Plasmas **2**, 2098 (1995).
[29]D. Summers and R. M. Thorne, Phys. Fluids B **3**, 1835 (1991).
[30]M. A. Hellberg, R. L. Mace, T. K. Baluku, I. Kourakis, and N. S. Saini, Phys. Plasmas **16**, 094701 (2009).
[31]T. K. Baluku and M. A. Hellberg, Phys. Plasmas **15**, 123705 (2008).
[32]P. O. Dovner, A. I. Eriksson, R. Bostrom, and B. Holback, Geophys. Res. Lett. **21**, 1827, doi:10.1029/94GL00886 (1994).
[33]R. Bostrom, G. Gustafsson, B. Holback, G. Holmgren, H. Koskinen, and P. Kintner, Phys. Rev. Lett. **61**, 82 (1988).
[34]R. A. Cairns, A. A. Mamun, R. Bingham, R. Bostrom, R. O. Dendy, C. M. C. Nairn, and P. K. Shukla, Geophys. Res. Lett. **22**, 2709, doi:10.1029/95GL02781 (1995).
[35]S. Hamaguchi and R. T. Farouki, Phys. Rev. E **49**, 4430 (1994).
[36]N. Rubab and G. Murtaza, Phys. Scr. **73**, 178 (2006).
[37]B. Walch, M. Horanyi, and S. Robertson, Phys. Rev. Lett. **75**, 838 (1995).
[38]L. Spitzer, *Physical Processes in the Interstellar Medium* (Wiley, New York, 1978).
[39]N. A. Krall and A. W. Trivelpiece, *Introduction to Plasma Physics* (MacGraw-Hill, Tokyo, 1973), p. 362.
[40]A. A. Abid, M. Z. Khan, Q. Lu, and S. L. Yap, Phys. Plasmas **24**, 033702 (2017).
[41]H. Amemiya, B. M. Annaratone, and J. E. Allen, J. Plasma Phys. **60**, 81 (1998).
[42]V. Vyas, G. A. Hebner, and M. J. Kushner, J. Appl. Phys. **92**, 6451 (2002).