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Study of obliquely propagating dust acoustic solitary waves in magnetized tropical mesospheric plasmas with effect of dust charge variations and rotation of the plasma

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The characteristics of obliquely propagating Dust Acoustic Waves (DAWs) in rotating and magnetized dusty plasma in the dayside tropical mesosphere are examined by incorporating adiabatic dust charge fluctuations. A Korteweg-de Vries equation is derived, which may support a nonlinear dust acoustic wave on a very slow time scale. The meteoritic dust in mesospheric plasmas on the dayside is charged positively due to photo- and thermionic emissions. The dynamics of the DAW with electronic, ionic, thermionic, and photoelectric currents along with obliqueness and effective gyrofrequency are studied. It is observed that the amplitude of the soliton depends directly on the obliqueness θ and dust charge variation, respectively, while the width is modified inversely with these parameters. It is also observed that the effective gyrofrequency modifies the width inversely. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2206547]

I. INTRODUCTION

Thousands of millions of interplanetary meteoroids enter the Earth's atmosphere daily with initial velocities in the range of 11.2–72.8 km s^{-1}. While the critical size of the meteoroid to become dust depends on the entry velocity, those with radii typically in excess of about 10 μm produce observable luminous phenomena ("meteors"). During their impact with the Earth's atmosphere, the meteoroids vaporize and recondense into dust particles suspended in the Earth's mesosphere.[1]

The very first instrument launched to study charged dust in the tropical mesosphere detected a layer of fine dust (radius ≈ 10 nm) near the mesopause. The dust in the thinner lower part of the layer carried a negative charge and the dust in the thicker upper part carried a positive charge.[2] The negative charge on the dust was expected, while the positive charge was not, because the observation was taken half hour after local astronomical sunset. The observers sought to resolve the problem by suggesting that the positive grains were still carrying their pre-sunset positive charge acquired by photoemission. Mendis *et al.*[3] have reinvestigated this phenomenon to explain the positive charge on the upper part of the layer. They have suggested that micrometeoroids that enter the Earth's atmosphere at sufficient entry speeds, even on the night side, acquire substantial positive charges due to thermionic electron emission high up in the mesospheric region before they start ablating in the mesopause region. According to 3 the charging equation of a micrometeoroid entering the earth's atmosphere on its night side is $dQ/dt=I_e+I_i+I_{th}+I_s$, where Q is the total charge on the micrometeoroid and I_e, I_i, I_{th} are the electron collection, ion collection, and thermionic (electron) collection currents, respectively, and I_s is the ablating (secondary) electron current that has been introduced because the frictionally heated micrometeoroid surface evaporates, and the evaporated particles carry away the accumulated surface charge at a certain rate. Mendis *et al.*[4] and Sorasio *et al.*[5] have also studied the positively charged dust grain due to the thermionic emission of electrons from a fractionally heated meteoroid, as it enters the Earth's atmosphere. It may be pointed out that these authors limit their treatment to the night side of the Earth so as to avoid the role of photoemission while emphasizing the role of thermionic emission, but our consideration here in this work is relevant to the Earth's dayside, where the contribution to the current from photoemission is also taken into account.

Collective waves in dusty plasmas have attracted a great deal of attention in recent years. Among them, a new acoustic mode (i.e., dust-acoustic wave) on a very slow time scale of dust dynamics emerged as a result of the balance between dust grain inertia and plasma pressure.[6] Such dust acoustic waves can easily become highly nonlinear.[7] It has recently been shown by several authors that these nonlinear waves can form solitons of either positive or negative electrostatic (ES) potential.[6,8–10] It has also been shown theoretically and observed experimentally that dust charge fluctuations introduce new eigenmodes[11–16] both in the linear and nonlinear regimes. In plasmas with positive dust particles, the electron density would be larger than that of ions, and different types of instabilities and waves are likely to occur.[17,18] Plasmas with positive charged particles occur widely in space and also in the Earth's mesosphere.[19,20]

In this paper, we present an analytical model for obliquely propagating DAWs in a rotating magnetized dusty plasma with adiabatic dust grain charge variations in the dayside tropical mesospheric region. We employ the reductive perturbation technique to derive the Korteweg-de Vries (KdV) equation for these waves. Finally, we discuss the ef-

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fects of obliqueness and effective gyrofrequency on the dynamics of this wave.

II. BASIC EQUATIONS

Consider a one-dimensional, rotating magnetized electropositive dusty plasma whose constituents are Boltzmann-distributed electrons and ions, and cold dust grains having charge fluctuation. The external magnetic field is directed along the x axis, i.e., $\mathbf{B}_0 = B_0\hat{x}$ and the plasma is taken to be rotating along the magnetic field due to the Coriolis force with a rotational frequency Ω_0. The normalized basic equations for low phase velocity DAWs are as follows.

The continuity equation:

$$\frac{\partial n_d}{\partial t} + \nabla \cdot (n_d \mathbf{v}_d) = 0. \tag{1}$$

The equation of motion in a frame rotating with angular frequency Ω_0 can be written as

$$\frac{\partial v_d}{\partial t} + (\mathbf{v}_d \cdot \nabla)\mathbf{v}_d = -(1+\Delta Q)\nabla\varphi + (1+\Delta Q)\Omega_{cd}(\mathbf{v}_d \times \hat{x}) + 2\Omega_o(\mathbf{v}_d \times \hat{x}) \tag{2}$$

and the Poisson's equation

$$\nabla^2\varphi = \mu e^{\varphi} + (1-\mu)e^{-\rho\varphi} - (1+\Delta Q)n_d. \tag{3}$$

In deriving these equations, we use the charge neutrality condition $en_{i0} = en_{e0} - Q_{d0}n_{d0}$, where $Q_{d0}(=Z_{d0}e)$ is the dust charge at equilibrium, ΔQ is the perturbed part of the normalized dust charge Q_d, i.e., $Q_d = 1 + \Delta Q$, Z_{d0} is the number of charged particles on the dust surface at equilibrium, and n_{j0} is the equilibrium number density of the jth species here, $j = e, i, d$ (electron, ion, dust). The number density n_j is normalized by equilibrium density n_{j0}. The dust fluid velocity v_d and electrostatic wave potential φ are normalized by dust acoustic speed $c_{sd} = (Z_{d0}T_e/m_d)^{1/2}$ and T_e/e, respectively. The dust charge Q_d is normalized by the equilibrium value Q_{d0}. The rotational frequency $\mathbf{\Omega}$ and the dust gyrofrequency $\Omega_{cd} = Z_{d0}eB_0/m_dc$ are normalized by dust plasma frequency $\omega_{pd} = \sqrt{(4\pi n_{d0}Z_{d0}^2e^2/m_d)}$. The space and time coordinates are normalized, respectively, by Debye length, $\lambda_D = \sqrt{T_e/4\pi Z_{d0}n_{d0}e^2}$ and the dust plasma period ω_{pd}^{-1}. We note that $\rho = T_i/T_e$, where $T_e(T_i)$ is the electron (ion) temperature, $\mu = 1/(1-p)$ and $p = n_{i0}/n_{e0}$.

We assume that dust sized micrometeoroid is charged positively when it enters the earth's atmosphere on the day side. So for $Q_d > 0$ the normalized dust charging equation is

$$\frac{\omega_{pd}}{\nu_{ch}}\partial_t\Delta Q = \frac{I_e + I_i + I_{th} + I_p}{Z_{d0}e\nu_{ch}}. \tag{4}$$

Here I_e, I_i, I_{th} are the electron collection, ion collection, and thermionic (electron) collection currents, respectively. Here I_p is the photoelectric current of electrons emitted from the dust grain surface due to the action of solar radiation. The normalized expressions of these currents for spherical dust grain of radius r_d are[3,5,21]

$$\begin{aligned} I_e &= -J_e n_e(1 + zQ_d), \\ I_i &= J_i n_i \exp(-\rho z Q_d), \\ I_{th} &= J_{th}(1 + \alpha z Q_d)\exp(-\alpha z Q_d), \\ I_p &= J_p \exp(-\delta z Q_d), \end{aligned} \tag{5}$$

where $J_l = 4\pi r_d^2 e\beta_l$ $(l = e, i, \text{th}, p)$, $\alpha = T_e/T_d$, $\delta = T_e/T_p$ (T_p is the average temperature of the grain during the photoemission process). Here $\beta_e = n_{e0}(V_{the}/\sqrt{2\pi})$, $\beta_i = n_{i0}(V_{thi}/\sqrt{2\pi})e^{-\rho z}$, $\beta_{th} = \sqrt{2/\pi}(m_eT_e/2\pi\hbar^2)^{3/2}V_{the}$ $\exp(-W_f/T_d - \alpha z)$, $\beta_p(=J_pY/4)\exp[-\delta z]$ are the coefficients due to I_e, I_i I_{th}, and I_p currents, respectively. In the expressions of β_{th} and β_p, W_f denotes the work function of dust material, J_p is the photon flux, Y_p is the yield of photoelectrons, and h is Plank's constant. Also, $z = eQ_{d0}/4\pi\epsilon_0 r_d T_e$ denotes the nondimensional dusty plasma parameter. In expression (4) $\nu_{ch} = \alpha_o[\alpha^2 z\beta_{th}\exp(-\alpha z) + \delta\beta_p\exp(-\delta z) + \beta_e + \rho\beta_i\exp(-\rho z)]$, is the dust-charging frequency, with $\alpha_0 = 4\pi r_d e^2/k_BT_e$.

We are interested in dust perturbations in mesospheric plasmas which lead to soliton formation. KdV solitons are formed as a balance between the nonlinearity and dispersion effects. However, in the present context of a complex plasma we take into account the dust grain charging processes, which are faster (typically of the order of 10^{-8} seconds) than other characteristic processes (tens of milliseconds for microsized dust grain) of the DA wave formation and propagation. Therefore on a hydrodynamic time scale, the dust charge quickly reaches local equilibrium, which means that the dust grain charge will be fixed in each point of the DA soliton and determined there by the plasma parameters at this point. Thus, at different points of the soliton the dust grain charges will be, in general, different. It follows that $\omega_{pd}/\nu_{ch} \approx 0$, and this reduces the current balance equation[22,26,27] to

$$I_e + I_i + I_{th} + I_p \approx 0. \tag{6}$$

In this case the dust charge instantaneously reaches its equilibrium value at each space-time point determined by the local electrostatic potential $\varphi(r,t)$ and hence does not give rise to any dissipative effect, and this is known as adiabatic dust charge variation. Equation (6), in terms of ΔQ_d and φ, can be written as

$$\beta_{th}(1 + \alpha z\,\Delta Q)e^{-\alpha z\,\Delta Q} + \beta_p e^{-\delta z\,\Delta Q} - \beta_e e^{\varphi}(1 + z\,\Delta Q) + \beta_i e^{-\rho\varphi}e^{(-\rho z\,\Delta Q)} \approx 0. \tag{7}$$

In order to examine the dynamics of finite amplitude obliquely propagating dust acoustic wave in the presence of adiabatic dust charge variation, we derive an evolution equation from Eqs. (1)–(3) and Eq. (7) by employing the reductive perturbation technique that entails the introduction of stretched coordinates, $\xi = \epsilon^{1/2}(l_xx + l_yy + l_zz - \lambda t)$ and $\tau = \epsilon^{3/2}t$, where ϵ is a small parameter characterizing the strength of the nonlinearity, λ is the normalized solitary wave velocity, and l_x, l_y, and l_z are the direction cosines of the wave vector

k along the x, y, and z axis, respectively, so that $l_x^2+l_y^2+l_z^2=1$. The dependent variables are expanded as

$$\Theta = \Theta_{(0)} + \sum_{i=1}^{\infty} \epsilon^i \Theta_i,$$

where $\Theta \equiv [n_d, v_{dx}, \varphi, \Delta Q]^T$ and $\Theta_{(0)}=[n_{d0}, v_{dx0}, \varphi_0, \Delta Q_{d0}]^T =[1,0,0,0]^T$, while transverse velocities are expanded as

$$v_{ds} = \sum_{\chi=2}^{\infty} \epsilon^{(\chi+1)/2} v_{s(\chi-1)}.$$

Here $s=y,z$, applying the perturbation scheme given previously to Eqs. (1)–(3) and Eq. (7) and then collecting terms of different powers of ϵ. In the lowest order we obtain $v_{1x}=(l_x/\lambda)\varphi_1$, $n_{d1}=(l_x/\lambda)^2\varphi_1$, $\Delta Q_1=-\gamma_1\varphi_1$, $v_{1z}=\Omega_c^{-1} l_y(\partial\varphi_1/\partial_\xi)$ and $v_{1y}=-\Omega_c^{-1} l_z(\partial\varphi_1/\partial\xi)$. Here $\gamma_1=[\beta_e(z+1)+\beta_i\rho)/z(\alpha^2 z\beta_{\text{th}}+\delta\beta_p+\rho\beta_i+\beta_e]$ is the coefficient due to dust charge fluctuation in the linear regime and $\Omega_c=(\Omega_{cd}+2\Omega_0)$ is the effective gyrofrequency due to Lorentz and Coriolis forces. Combining these results with lowest order terms of the Poisson equation given by Eq. (3),

$$\lambda = \frac{l_x}{\sqrt{\mu - \rho(1-\mu) + \gamma_1}}. \tag{8}$$

The previous expression is the linear dispersion relation and λ is the normalized linear phase velocity of the DAW, which is modified due to the dust charge variation γ_1 and obliqueness θ with respect to the external magnetic field B_0. For θ and $\gamma_1=0$, we get the relation (17) of 23 in the limit $(k^2\lambda_D^2 \ll 1)$. It is shown in Fig. 1 that for given values of β_i and β_e the phase velocity λ is higher in the presence of photoelectric and thermionic currents. Generally the effect of positive dust charge variation appears to decrease the wave velocity whatever the changes occur in other parameters. We also note that as obliqueness θ increases the phase velocity decreases.

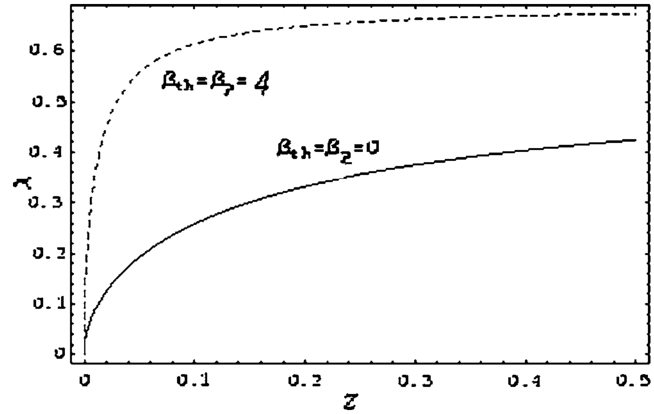

FIG. 1. Linear dependency of phase velocity λ on z for different values of coefficients β_{th} and β_p.

In the next order ($\sim\epsilon^2$) we obtain from Eqs. (1)–(3) and Eq. (7) the following:

$$\begin{aligned}
&-\lambda\frac{\partial v_{1y}}{\partial \xi} - \Omega_c v_{2z} = 0,\\
&-\lambda\frac{\partial v_{1z}}{\partial \xi} + \Omega_c v_{2y} = 0,\\
&\frac{\partial^2\varphi_1}{\partial\xi^2} - \Bigg[[\mu-\rho(1-\mu)+\gamma_1]\varphi_2 - n_{d2}\\
&\qquad + \left(\gamma_2 + \frac{1}{2}\mu + \frac{\rho^2}{2}(1-\mu)\right)\varphi_1^2 + \gamma_1 n_{d1}\varphi_1\Bigg] = 0,\\
&\Delta Q_2 + \gamma_1\varphi_2 + \gamma_2\varphi_1^2 = 0,
\end{aligned} \tag{9}$$

where the coefficient γ_2 is due to dust charge variation and is given by

$$\gamma_2 = \frac{\beta_e(z+1-2\gamma_1 z) + \beta_i(2\gamma_1 z - 1 - z^2\gamma_1^2)\rho^2 + \beta_{th}(\alpha^2 z^2 - \alpha^3 z^3)\gamma_1^2 - \beta_p\delta^2 z^2}{2z(\beta_e + \rho\beta_i + \alpha^2 z\beta_{th} + \delta\beta_p)},$$

and from terms of order $\epsilon^{5/2}$ we obtain the following set of equations:

$$\begin{aligned}
&-\lambda\frac{\partial v_{2x}}{\partial\xi} + l_x\frac{\partial\varphi_2}{\partial\xi} = -\frac{\partial v_{1x}}{\partial\tau} - l_x v_{1x}\frac{\partial v_{1x}}{\partial\xi} - l_x\,\Delta Q_1\frac{\partial\varphi_1}{\partial\xi},\\
&-\lambda\frac{\partial n_{d2}}{\partial\xi} + l_x\frac{\partial v_{2x}}{\partial\xi} = -\frac{\partial n_{d1}}{\partial\tau} - \frac{\partial}{\partial\xi}(v_{1x}n_{d1}) - l_y\frac{\partial v_{2y}}{\partial\xi} - l_z\frac{\partial v_{2z}}{\partial\xi}.
\end{aligned} \tag{10}$$

By eliminating quantities with subscript 2 and terms containing v_{1y} and v_{1z} from Eqs. (9) and (10), we get the nonlinear KdV equation in terms of electrostatic potential and is given by

$$\frac{\partial\varphi_1}{\partial\tau} + A\varphi_1\frac{\partial\varphi_1}{\partial\xi} + B\frac{\partial^3\varphi_1}{\partial\xi^3} = 0, \tag{11}$$

where the coefficients A and B are given by

$$\begin{aligned}
A = &\frac{l_x}{(\mu-\rho+\rho\mu+\gamma_1)^{1/2}}[3(\mu-\rho+\rho\mu+\gamma_1) - \gamma_1\\
&- (\mu-\rho+\rho\mu+\gamma_1)^{-1}(2\gamma_2+\mu+\rho^2-\rho^2\mu)],
\end{aligned}$$

$$B = \frac{l_x}{2(\mu-\rho+\rho\mu+\gamma_1)^{3/2}}\left(1 + \frac{1-l_x^2}{\Omega_c^2}\right).$$

The steady state solution of the KdV equation [Eq. (11)] is obtained by transforming the independent variables ξ and τ into new coordinate $\eta = (\xi - V_0\tau)$, where V_0 is a constant velocity normalized to c_{sd}. Following[24] the steady state solution of Eq. (11) is given by

$$\varphi_1 = \varphi_m \operatorname{sech}^2[(\xi - V_0\tau)/w], \tag{12}$$

where the normalized maximum amplitude φ_m and the width w are

$$\varphi_m = \left(\frac{3V_0}{A}\right), \qquad w = \sqrt{\frac{4B}{V_0}}. \tag{13}$$

The previous results can be used to find an expression for n_1 and v_{1x}, which are

$$n_{d1} = n_m \operatorname{sech}^2[(\xi - V_0\tau)/w], \qquad v_{1x} = v_m \operatorname{sech}^2[(\xi - V_0\tau)/w]. \tag{14}$$

Here $n_m = (l_x^2/V_0^2)\varphi_m$ and $v_m = \frac{l_x}{V_0}\varphi_m$ are, respectively, the peak soliton dust density and peak soliton x component of dust velocity. The soliton energy ε_s can be calculated by using the integral $\varepsilon_s = \int_{-\infty}^{\infty} v_{1x}^2(\eta)d\eta$. By substituting v_{1x} from Eq. (14) in this integral we obtain for the soliton energy

$$\varepsilon_s = \tfrac{4}{3}u_m^2 w. \tag{15}$$

From the expressions of φ_m and w, it is clear that as V_0 increases the soliton amplitude increases, but the width decreases. It is obvious from Eq. (12) that there exists compressive (rarefactive) solitary waves if $A > 0$ ($A < 0$). We have numerically analyzed φ_m and w for parameters corresponding to mesospheric dusty plasma parameters[2,5,25] with $r_d \sim (1-10)$ nm, $n_{d0} = 10^3$ cm^{-3}, $w_f \sim 2-5$ eV, $T_e \simeq T_i = 0.022$ eV. A 1 nm dust mass is 5000 amu, $Z_{d0} \sim 100-500$, $z(=Z_{d0}e^2/r_dT_e)$ lies in the range -1.5 to -2.5 for positively charged dust, and $T_p \sim 1-2$ eV. Values for some parameters are taken arbitrarily, i.e., $u_0 = 1$, $\omega_{cd} = 0.1$, $\Omega_0 = 0.01$, $lx = 0.1$. We found that for the above mentioned parameter values $A > 0$; thus φ_m is always positive (see Fig. 2). This means that for the dusty plasma parameters that we have considered supports only compressive solitary waves (solitary waves with $\varphi_m > 0$), which is in agreement with Ref. 26 for a two component dust-electron plasmas induced by ultraviolet irradiation, and with positively charged dust case in the work by Kopnin *et al.*,[27] in which the different soliton profiles related to different signs of the dust charge have been investigated. In the calculation of Ref. 27, Kopnin *et al.* have studied the positively charged dust case with three currents (electronic, ionic, photoelectric) in an unmagnetized mesospheric plasmas. But in our case we have additionally investigated the effect of thermionic emission in a magnetized plasma. In our case we obtain a larger amplitude soliton as compared to those in Ref. 27, and this is may be due to the additional thermionic current. Figure 2 and Eq. (14) show that due to dust charge variation, the amplitude of the soliton increases, whereas their width decreases.

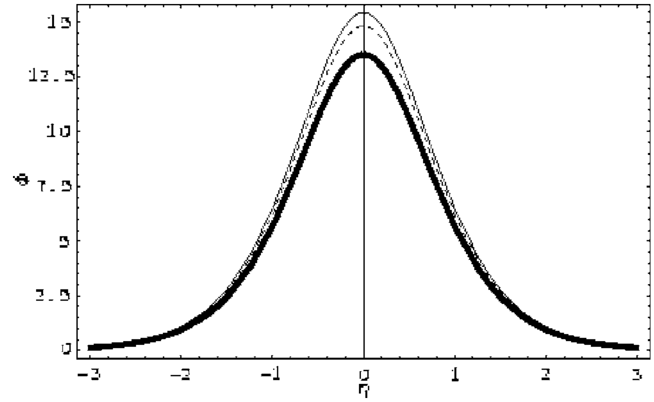

FIG. 2. Effect of dust charge variation on soliton potential φ as a function of η. Bold curve for low values, Dashed curve for intermediate values. Solid curve for higher values of all β's.

It should be noted here that the perturbation method, which is only valid for a small but finite amplitude limit, is not valid for the large propagation angle, θ (which makes the wave amplitude large enough to break the condition $1 < \epsilon n_1$). We also note that as we decrease l_x, i.e., increase the angle between magnetic field (B_0) and propagation vector k, the amplitude of the soliton increases, whereas its width decreases for $\Omega_c \gg (1-l_x)$ and increases for $\Omega_c \ll (1-l_x)$, while for small values of θ the amplitude of the soliton decreases. A decreasing soliton amplitude may therefore be attributed to the decreasing soliton energy, which may be possible due to the reflection of ions and positively dust particles from the electrostatic field generated inside the plasma. Another reason for the decrease of the soliton amplitude may be due to the wave particle energy exchange mechanism, the calculations of which are possible from kinetic theory and are beyond the scope of the present work.

It is seen that the effective gyrofrequency Ω_c has no direct effect on the amplitude of the solitary waves. However, it does have an effect on the width of these solitary waves. It is shown that as we increase the effective gyrofrequency, the width of the soliton decreases, which in turn increases the amplitude and hence the soliton energy. It means that the effective gyrofrequency makes the solitary structures more spiky.

To summarize, we have investigated the properties of DAW with an adiabatic dust charge fluctuation in general and thermionic and photoelectric currents in special, in a magnetized rotating mesospheric plasma. We have also discussed the effect of the obliqueness of propagation and effective gyrofrequency on the dynamics of this wave. It is observed that for given parameter values with mesospheric dusty plasma, DAW admits the compressive soliton structure. Dust charge variations modify the soliton amplitude directly and width inversely. Effective gyrofrequency $\Omega_c(=\Omega_{cd}+2\Omega_0)$ is inversely proportional to the width of the soliton and hence makes the soliton more energetic and spiky as the effective gyrofrequency increases. Rotating magnetized plasmas along with variable charging currents are believed to exist in planetary magnetospheres of Jupiter and Saturn,[28] rotating interstellar clouds, and dusty magnetoplasmas,[29] and of course the tropical mesosphere.

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[1] D. M. Hunten, R. P. Turco, and O. B. Toon, J. Atmos. Sci. **37**, 1342 (1980).
[2] L. J. Gelinas, K. A. Lynch, M. C. Kelley, S. Collins, S. Baker, Q. Zhou, and J. S. Friedman, Geophys. Res. Lett. **25**, 4047 (1998).
[3] D. A. Mendis, W-H. Wong, and M. Rosenberg, Phys. Scr. **T113**, 141 (2004).
[4] D. A. Mendis, W-H. Wong, M. Rosenberg, and G. Sorasio, J. Atmos. Sol.-Terr. Phys. **67**, 1178 (2005).
[5] G. Sorasio, D. A. Mendis, and M. Rosenberg, Planet. Space Sci. **49**, 1257 (2001).
[6] N. N. Rao, P. K. Shukla, and M. Y. Yu, Planet. Space Sci. **38**, 543 (1990); N. D'Angelo, Planet. Space Sci. **38**, 1143 (1990).
[7] A. Barkan, R. L. Merlino, and N. D'Angelo, Phys. Plasmas **2**, 3563 (1995).
[8] A. A. Mamun, R. A. Carins, and P. K. Shukla, Phys. Plasmas **3**, 702 (1996).
[9] S. Mahmood and A. Mushtaq, J. Fusion Energy **21**, 199 (2003).
[10] C. Thompson, A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Plasmas **4**, 2331 (1997); F. Verheest, Planet. Space Sci. **40**, 1 (1992).
[11] Y. N. Nejoh, Phys. Plasmas **4**, 2813 (1997).
[12] M. Rosenberg, Planet. Space Sci. **41**, 229 (1993).
[13] R. K. Verma, P. K. Shukla, and V. Krishan, Phys. Rev. E **47**, 3612 (1993).
[14] S. Nunomura, T. Misawa, N. Ohno, and S. Takamura, Phys. Rev. Lett. **83**, 1970 (1999).
[15] Samrian Ghosh, S. Sarkar, and M. R. Gupta, Phys. Plasmas **7**, 3594 (2000).
[16] A. A. Mamun, P. K. Shukla, and T. Farid, Phys. Plasmas **7**, 2329 (2000).
[17] K. N. Ostrikov, M. Y. Yu, and L. Stenflo, Phys. Rev. E **61**, 782 (2000).
[18] S. I. Popel, A. A. Gisko, A. P. Golub, R. Bingham, and P. K. Shukla, Phys. Plasmas **7**, 2410 (2000).
[19] T. Nitter, O. Havnes, and F. Melandnso, J. Geophys. Res. **103**, 6605 (1998).
[20] O. Havnes *et al.*, J. Geophys. Res. **101**, 10839 (1996).
[21] P. K. Shukla and A. A. Mamun, *Introduction to Dusty Plasma Physics* (Institute of Physics Publishing, Bristol, 2002), pp. 94, 151, 197–212; M. S. Sodha and S. Guha, Adv. Plasma Phys. **4**, 219 (1971).
[22] S. K. El- Labany and W. F. El-Taibany, J. Plasma Phys. **70**, 69 (2004).
[23] P. K. Shukla, Phys. Rev. E **61**, 7249 (2000).
[24] J. Satsuma, J. Phys. Soc. Jpn. **40**, 286 (1976); A. Mushtaq and H. A. Shah, Phys. Plasmas **12**, 012301 (2005).
[25] A. A. Samarian, O. S. Vaulina, A. P. Nefedov, V. E. Fortov, B. W. James, and O. F. Petrov, Phys. Rev. E **64**, 056407 (2001).
[26] Z-X. Wang, Y. Liu, J-Y. Liu, and X. Wang, Phys. Plasmas **12**, 014505 (2005).
[27] S. I. Kopnin, I. N. Kosarev, and S. I. Popel, *Proceeding of 30th EPS Conference on Contr. Fusion and Plasma Physics*, St. Petersburg, 7–11 July 2003.
[28] C. K. Goertz, Rev. Geophys. **27**, 271 (1989); M. Horanyi and D. A. Mendis, J. Geophys. Res. **91**, 355 (1986).
[29] P. K. Shukla, P. K. Dwivedi, and L. Stenflo, New J. Phys. **5**, 22.1 (2003).