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Letter to the Editor

Polarization-force-induced dust grain acceleration and intrinsic magnetization of dusty plasmas

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Abstract. It is shown that the polarization force, arising from interactions between thermal ions and highly charged dust grains, can accelerate charged dust grains and can also create spontaneous magnetic fields in a quasi-neutral dusty plasma. The present results are relevant for understanding the origin of dust grain acceleration and the generation of spontaneous magnetic fields in cosmic dusty plasmas.

Charged dust grains and plasmas are ubiquitous in our Universe and in solar system, e.g. near the Earth's atmospheres and mesosphere in the form of charged aerosol nanoparticles and dirty ice particles, in planetary dust rings (e.g. of Saturn and Neptune), in the Martian atmosphere in the form of dust devils, in cometary tails and comae, on the surface of moon (e.g. charged lunar dust arising from the solar wind–moon interactions), as well as in cosmic environments (e.g. in the form of interstellar dust, and in and around clusters of galaxies), and in processing plasmas (in fabrication of microchips in semiconductor industries). Dusty plasmas have been deliberately produced in laboratory discharges for understanding the salient features of dust grain charging and collective dust–plasma interactions at kinetic levels. Specifically, in low-temperature laboratory dusty plasma discharges, many groups around the globe have observed new linear and nonlinear waves (e.g. the dust acoustic wave discovered by Rao et al. [1] and the dust ion-acoustic wave by Shukla and Silin [2], and observed by Barkan et al. [3]), as well as novel soft condensed materials (e.g. organized dust structures in the form of dust Coulomb crystals, as predicted by Ikezi [4] and observed by Chu and Lin [5] and Thomas et al. [6]). There are many textbooks and monographs (e.g. Refs. [7,8]), as well as review articles (e.g. Refs. [9–13]) describing the fundamentals of collective dust–plasma interactions and the progress that has been made during the last two decades.

Recently, the topic of dust grain acceleration has been of significant interest in understanding the dynamics of charged dust grains in cosmic plasmas [14], as well

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as in small-scale laboratory discharges [15] and in tokamaks [16]. Non-uniform acceleration of charged dust particles has important consequences with regards to the generation of radiation from dusty astrophysical environments. Therefore, identifying suitable mechanisms for acceleration of charged dust grains are of paramount interest [17].

In this Letter, we point out possibilities of charged dust grain acceleration and dusty plasma magnetization by the polarization force [18, 19]. The latter results from interactions between thermal positive ions and highly charged dust grains in an electron-ion dust plasma.

Let us consider a non-uniform dusty plasma composed of electrons, positive ions, and negative dust grains. The plasma pressure gradient is ∇P_j, where $P_j(x)$ is the pressure of the particle species j (j equals e for electrons, i for ions, and d for dust grains). We have for the electron pressure $P_e = n_e k_B T_e$, the ion pressure $P_i = n_i k_B T_i$, and for the dust pressure [20] $P_d \simeq (N_{nn}/3)\Gamma n_d T_d (1+\kappa)\exp(-\kappa)$ accounting for the Debye–Hückel–Yukawa-type interacting charged dust grains. Here electrons and ions are weakly coupled, n_j is the number density of the particle species j, T_j is the temperature, k_B is the Boltzmann constant, N_{nn} is determined by the dust structure and corresponds to the nearest neighbors (e.g. in the crystalline state, N_{nn} equals 12 for fcc and hcp lattices and 8 for the bcc lattices), $\gamma = Q_d^2/T_d\Delta$, $\kappa = \Delta/\lambda_D$ is the coupling parameter, $Q_d = Z_d e$ is the dust charge, Z_d is the number of charges residing on a dust grain, e is the magnitude of the electron charge, Δ denotes the mean intergrain distance, $\lambda_D = \lambda_{Di}/\sqrt{1+\lambda_{Di}^2/\lambda_{De}^2}$ is the effective Debye radius of dusty plasmas, and $\lambda_{Di} = \sqrt{k_B T_i/4\pi n_i e^2}$ and $\lambda_{De} = \sqrt{k_B T_e/4\pi n_e e^2}$ are the ion and electron Debye radii, respectively. In the low-temperature dusty plasma, we typically have $T_i \ll T_e$, so that $\lambda_D \simeq \lambda_{Di}$; hence a negative dust grain is screened by positive ions. Furthermore, when dust grains are weakly coupled, one should use $P_d = n_d k_B T_d$. At equilibrium, we invoke the quasi-neutrality condition [21]:

$$n_i = n_e + Z_d n_d. \tag{1}$$

In an unmagnetized dusty plasma, there exist many forces that act on a dust particle. Of our interest here are the gravity force $m_d\mathbf{g}$ which pulls a dust particle downward, the electrostatic force

$$\mathbf{F}_e = -Z_d e\mathbf{E}, \tag{2}$$

which gives an upward thrust/lift (against gravity) to a dust particle in the plasma sheath, the pressure gradient ∇P_d caused by the density and temperature inhomogeneities, and the polarization force [18, 19]

$$\mathbf{F}_p = Z_d e\mathscr{R}\mathbf{E}, \tag{3}$$

arising from interactions between thermal ions and charged dust grains. Here $\mathbf{E}$ is the electric field and $\mathscr{R} = Z_d e^2/4K_B T_i\lambda_D$ for a dusty plasma with $T_i \ll T_e$. We note that $\mathscr{R}$ (could be of order unity) represents the ratio of the Coulomb interaction radius between the ions and dust grains to the dusty plasma Debye radius. The polarization force associated with the electron-ion interactions is $e\mathscr{R}_i\mathbf{E}$, which is much weaker, where $\mathscr{R}_i = e^2/4K_B T_e\lambda_{De}$. The stronger polarization force in a dusty plasma results due to the plasma polarization around a highly charged (Z_d is typically of the order of many hundreds and thousands in laboratory dusty plasma discharges) dust grain, contrary to the polarization force in an electron-ion plasma

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without dust grains. We notice that, for negative dust grains, the direction of the electrostatic and polarization forces acting on a dust grain is opposite to each other.

We assume that the inertialess electrons and ions are Boltzmann distributed, and hence they are held under the action of the electrostatic force and the pressure gradient. We thus have

$$0 = -n_e e\mathbf{E} - \nabla P_e \tag{4}$$

and

$$0 = n_i e\mathbf{E} - \nabla P_i. \tag{5}$$

The dynamics of inertial charged dust particles is governed by

$$\rho_d \frac{\partial \mathbf{u}}{\partial t} = -Z_d n_d e\mathbf{E} - \nabla P_d + Z_d n_d e\mathscr{R}\mathbf{E} + \rho_d \mathbf{g}, \tag{6}$$

where $\rho_d = m_d n_d$ is the dust mass density, m_d is the dust mass, and $\mathbf{u}_d$ is the dust particle velocity vector.

Adding (4), (5), and (6) and using (1), we obtain

$$\rho_d \frac{\partial \mathbf{u}}{\partial t} = -\nabla P + Z_d n_d e\mathscr{R}\mathbf{E} + \rho_d \mathbf{g}, \tag{7}$$

where $P = P_e + P_i + P_d$. It should be noted that the sum of the electrostatic forces factors out from (7) due to the overall quasi-neutrality in our dusty plasma. What remains in (7) are the gradient of the total plasma particle pressure, the polarization force, and the gravity force.

Several comments are in order. First, (7) reveals that the pressure gradient $-\nabla P$ does not accelerate a charged dust particle, while the gravity induced dust grain acceleration is usually weak. The polarization force induced dust grain acceleration is then governed by

$$\frac{\partial \mathbf{u}}{\partial t} = \frac{Z_d e}{m_d}\mathscr{R}\mathbf{E}, \tag{8}$$

which exhibits that the rate of change of the dust particle velocity along the electric field direction is proportional to Z_d^2, $e^2/k_B T_i \lambda_{Di}$ and the strength of the electric field $|\mathbf{E}|$.

Second, in the steady state, we have for the electric field

$$\mathbf{E} = \frac{K_B T_i \lambda_{Di} \nabla P}{Z_d^2 e^2 n_d}, \tag{9}$$

assuming that the polarization force dominates over the gravity force. It then emerges that the polarization force can also produce spontaneous magnetic fields in a non-uniform dusty plasma. The induced magnetic field is determined from the Faraday law

$$\frac{\partial \mathbf{B}}{\partial \tau} = -c\nabla \mathbf{E} = -\frac{c\sqrt{K_B}}{2\sqrt{\pi e^3}} \nabla P \times \nabla \left(\frac{T_i^{3/2}}{Z_d^2 n_d \sqrt{n_i}} \right), \tag{10}$$

which shows that spontaneous non-stationary magnetic fields are created when there is a non-parallel density, temperature, and dust charge gradients in a dusty plasma.

The generalized dust vorticity, driven by the cross-product of the gradient of the plasma pressure and the density gradient, for our purposes reads

$$\frac{\partial (\Omega + \Omega_p)}{\partial \tau} = \frac{1}{m_d n_d^2} \left(\nabla P \times \nabla n_d \right), \tag{11}$$

where $\Omega = \nabla \times \mathbf{u}$ and $\Omega_p = Z_d e\mathscr{R}\mathbf{B}/m_d c$.

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To summarize, we have shown that the polarization force, arising from interactions of thermal ions with highly charged dust grains, is responsible for dust grain acceleration and for intrinsic magnetization of a dusty plasma. It is also found that there exists a generalized dust vorticity on account of the non-parallel plasma pressure and density gradients. The present results are useful for understanding the origin of charged dust grain acceleration and spontaneous magnetic fields in cosmic and laboratory dusty plasmas.

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References

[1] Rao, N. N., Shukla, P. K. and Yu, M. Y. 1990 *Planet. Space Sci.* **38**, 543.
[2] Shukla, P. K. and Silin, V. P. 1992 *Phys. Scr.* **45**, 508.
[3] Barkan, A., Merlino, R. L. and D'Angelo, N. 1995 *Phys. Plasmas* **2**, 3563; Barkan, A., D'Angelo, N. and Merlino, R. L. 1996 *Planet. Space Sci.* **44**, 239.
[4] Ikezi, H. 1986 *Phys. Fluids* **29**, 1764.
[5] Chu, J. H. and Lin, I. 1994 *Phys. Rev. Lett.* **72**, 4009.
[6] Thomas, H., Morfill, G., Demmel, V., Goree, J., Feuerbacher, B. and Möhlmann, D. 1994 *Phys. Rev. Lett.* **73**, 652.
[7] Shukla, P. K. and Mamun, A. A. 2002 *Introduction to Dusty Plasma Physics.* Bristol: IoP.
[8] Morfill, V. E. and Morfill, G. E. 2010 *Complex and Dusty Plasmas: From Laboratory to Space*. London: Taylor & Francis Group.
[9] Shukla, P. K. 2001 *Phys. Plasmas* **8**, 1791; Shukla, P. K. 2003 *Phys. Plasmas* **10**, 1619.
[10] Fortov, V. E., Khrapak, A. G., Khrapak, S. A., Molotkov, V. I. and Petrov, O. F. 2004 *Phys. Ups.* **47**, 447; Fortov, V. E., Ivlev, A. V., Khrapak, S. A., Khrapak, A. G. and Morfill, G. E. 2005 *Phys. Rep.* **421**, 1.
[11] Horanyi, M., Hartquist, T. W., Havnes, O., Mendis, D. A. and Morfill, G. E. 2004 *Rev. Geophys.* **42**, RG4002.
[12] Shukla, P. K. and Eliasson, B. 2009 *Rev. Mod. Phys.* **81**, 25.
[13] Morfill, G. E. and Ivlev, A. V. 2009 *Rev. Mod. Phys.* **81**, 1353.
[14] Bingham, R. and Tsytovich, V. N. 1999 *Astropart. Phys.* **12**, 35.
[15] Ticos, C. M., Wang, Z., Wurden, G. A., Montgomery, D. S., Dorf, L. A. and Shukla, P. K. 2008 *Phys. Rev. Lett.* **100**, 155002.
[16] Ratynskaia, S. et al. 2008 *Nucl. Fusion* **48**, 015006; 2008 *Plasma Phys. Control. Fusion* **50**, 124046; Rudakov, D. L. et al. 2009 *Nucl. Fusion* **49**, 085022.
[17] Shukla, P. K. and Tsintsadze, N. L. 2008 *Phys. Lett.* A **372**, 2053.
[18] Hamaguchi, S. and Farouki, R. T. 1994 *Phys. Rev.* E **49**, 4430; 1994 *Phys. Plasmas* **1**, 2110.
[19] Khrapak, S. A., Ivlev, A. V., Yaroshenko, V. V. and Morfill, G. 2009 *Phys. Rev. Lett.* **102**, 245004.
[20] Gozadinos, G., Ivlev, A. V. and Boeuf, J. P. 2003 *New J. Phys.* **5**, 32.
[21] Shukla, P. K. and Rosenberg, M. 1999 *Phys. Plasmas* **6**, 1038; Mendonça, J. T., Rao, N. N. and Guerreiro, A. 2001 *EPL* **54**, 741.