J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Ambipolar diffusion in laboratory and ionospheric dusty plasmas

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(Received: 21 August 2008 / Accepted: 10 December 2008)

A self-consistent model of the ambipolar diffusion of electrons and ions in dusty plasmas accounting for the local electric fields, the dust grain charging process, and the interaction of the plasma particles with the dust grains and neutrals is presented. The dependencies of the diffusion coefficient on the interaction of the electrons and ions with the dust grains as well as with the neutrals are investigated. It is shown that increase of the dust density leads to a reduction of the diffusion scale length, and this effect is enhanced at higher electron densities. The dependence of the diffusion scale length on the neutral gas pressure is found to be given by a power law, where the absolute value of the power exponent decreases with increase of the dust density. The electric field gradient and its effects are shown to be significant and should thus be taken into account in studies of dusty plasmas with not very small dust densities. The possibility of observing localized coherent dissipative nonlinear dust ion-acoustic structures in an asymmetrically discharged double-plasma and the importance of the ambipolar diffusion in ionospheric dusty plasmas are discussed.

Keywords: dusty plasma, ambipolar diffusion, electric field gradient, dust ion-acoustic nonlinear wave structures, noctilucent clouds

1. Introduction

A phenomenon unique to weakly ionized plasmas is that of ambipolar diffusion [1]. It occurs when collisions of the charged plasma particles (electrons and ions) with each other are negligible in comparison to that with the neutral particles. The diffusion of the electrons and the ions are in this case highly correlated because of the appearance of a space-charge electric field [2].

Most naturally occurring weakly ionized plasmas are dusty plasmas since besides the electrons, ions, and neutral atoms and/or molecules, they also contain massive electrically charged (dust) grains or microparticles in solid or liquid phase. An important property of a dusty plasmas is the dust-grain charging process. Usually a dust grain is negatively charged because of the much higher (with respect to the ion) electron mobility, since its charge is determined by the fluxes (grain currents) of electrons and ions flowing onto its surface. Since the grain currents strongly depend on the local plasma parameters, the grain charge can be both space and time dependent. It also strongly depends on the recombination of the electrons and ions that hit the grain surface, as well as the momentum loss by the plasma particles from (including Coulomb) collisions with the grain. These processes are the most important relaxation mechanisms in a dusty plasma [3]. Since diffusion, especially ambipolar diffusion, is often responsible for the formation of stationary or quasistationary plasma states [1], processes associated with dust charging, which strongly affect the diffusion of the electrons and ions, can significantly affect a plasma containing dust grains.

Earlier works on the diffusion of electrons and ions in dusty plasmas [4, 5] give theoretical results which roughly agree with some experimental data. For example, the presence of dusts in a plasma can lead to an appreciable reduction in the diffusion scale length [4]. But these studies are based on the plasma quasineutrality assumption. An empirical momentum-transfer rate, which determines the diffusion coefficient, of the plasma particles, was also used. It includes only the nonelastic (impact) collisions of the electrons and ions with the dust grains, but not the elastic Coulomb collisions. The purpose of the present paper is to develop a more self-consistent model for the ambipolar diffusion of electrons and ions in a dusty plasma by taking into account the dust charging process, the interaction of the plasma particles with the dust grains and neutrals, the resulting self-consistent electric field, etc. The model is then used to consider propagation of localized nonlinear structures such as dust ion-acoustic wave (DIAW), shocks and solitons [6, 7] in an inhomogeneous dusty plasma as well as to describe the ambipolar diffusion process near a contact of the regions containing negatively and positively charged dust grains in the dusty ionosphere.

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2. Self-Consistent Model

Here, we describe the theoretical model [8] which is used in this paper. We are interested in the ambipolar diffusion of the plasma electrons and ions, which are much lighter than the dust grains. Accordingly, we assume that the dust grain distribution remains stationary and its density profile flat. Furthermore, since we are interested in ambipolar diffusion, we shall assume that electron-ion, electron-electron, and ion-ion collisions are negligible.

The diffusion coefficients of the electrons (D_e) and ions (D_i) satisfy the Einstein relations [1, 2]

$$D_e = T_e\mu_e/e \quad \text{and} \quad D_i = T_i\mu_i/e, \tag{1}$$

where $T_{e,i}$ and $\mu_{e,i}$ are the temperatures and mobilities of the electrons and ions, respectively, and $-e$ is the electron charge. The electron and ion mobilities relate the drift velocities of the electrons and ions to the self-consistent electric field $\mathbf{E}$. Taking into account the interaction of the plasma particles with the microparticles and neutrals, we obtain

$$\mu_e = e/m_e\nu_e^{\text{eff}} \quad \text{and} \quad \mu_i = e/m_i\nu_i^{\text{eff}}, \tag{2}$$

where m_e and m_i are the electron and ion masses, $\nu_e^{\text{eff}} = \nu_{en} + \nu_{ed}$, $\nu_i^{\text{eff}} = \nu_{in} + \nu_{id}$, ν_{en} and ν_{in} are the electron-neutral and ion-neutral collision frequencies, respectively, and ν_{ed} and ν_{id} are the momentum-transfer rates due to electron and ion collisions, respectively, with the dust grains.

We shall assume that the electron drift velocity $\mathbf{u}_e$ is much smaller than its thermal velocity $v_{Te} = \sqrt{T_e/m_e}$, and the ion drift velocity $\mathbf{u}_i$ can be arbitrary. The momentum-transfer rates due to the interaction of the plasma particles with the dust grains are then [7]

$$\begin{aligned}\nu_{ed} = (2\sqrt{2\pi}/3)a^2 v_{Ti} n_d (n_i/n_e)(1+z\tau) \\ \times\left[4 + 2z + z^2\exp(z)\Lambda_{ed}\right],\end{aligned} \tag{3}$$

$$\begin{aligned}\nu_{id}^{\text{coll}} = \sqrt{2\pi}a^2 v_{Ti} n_d \tilde{u}^{-2} \\ \times\Big\{\sqrt{\pi/2}\,\text{erf}(\tilde{u}/\sqrt{2})\tilde{u}\big[1+\tilde{u}^2+(1-\tilde{u}^{-2}) \\ \times(1+2\tau z)\big]+(1+2\tau z+\tilde{u}^2)\exp(-\tilde{u}^2/2)\Big\},\end{aligned} \tag{4}$$

$$\begin{aligned}\nu_{id}^{\text{orb}} = \sqrt{2\pi}a^2 v_{Ti} n_d (2\tau z)^2 \Lambda_{id}(\tilde{u})\tilde{u}^{-3} \\ \times\left[\sqrt{\pi/2}\ \text{erf}(\tilde{u}/\sqrt{2}) - \tilde{u}\exp(-\tilde{u}^2/2)\right],\end{aligned} \tag{5}$$

where $\nu_{id} = \nu_{id}^{\text{coll}} + \nu_{id}^{\text{orb}}$, ν_{id}^{coll} is the ion momentum-transfer frequency due to the collection (absorption) of the ions by the dust grain, ν_{id}^{orb} is the ion momentum-transfer rate of elastic ion Coulomb scattering in the dust-grain field, a is the dust radius, $v_{Ti} = \sqrt{T_i/m_i}$ is the ion thermal velocity, n_d, n_e, and n_i are the dust, electron, and ion densities, respectively, $z = Z_d e^2/aT_e$ is the dust surface potential in units of T_e/e, $q_d = -Z_d e$ is the dust charge, $\tau = T_e/T_i$ is the electron-to-ion temperature ratio, $\tilde{u} = |\mathbf{u}_i|/v_{Ti}$ is the normalized ion drift velocity,

$$\begin{aligned}\Lambda_{ed} = \int_0^\infty e^{-x}\ln\left(1 + 4\frac{\lambda_D^2}{a^2}\frac{x^2}{z^2}\right)dx \\ -2\int_z^\infty e^{-x}\ln\left(\frac{2x}{z} - 1\right)dx\end{aligned} \tag{6}$$

is the Coulomb logarithm for electron-dust collisions [9], $\Lambda_{id}(\tilde{u}) \sim \ln[(1+\beta)/(a/\tilde{\lambda}_D(\tilde{u}) + \beta)]$ is the Coulomb logarithm for ion-dust collisions [10], $\beta(\tilde{u}) = z\tau(a/\tilde{\lambda}_D(\tilde{u}))(1+\tilde{u}^2)^{-1}$, $\tilde{\lambda}_D(\tilde{u})$ is the effective screening length defined by $\tilde{\lambda}_D^{-2} = \lambda_{Di}^{-2}(1+\tilde{u}^2)^{-1} + \lambda_{De}^{-2}$, $\lambda_D = \tilde{\lambda}_D(\tilde{u}))|_{\tilde{u}=0}$, and $\lambda_{De,i} = \sqrt{T_{e,i}/4\pi e^2 n_{e,i}}$ is the electron or ion Debye length.

The electron and ion diffusion fluxes are given by [1]

$$\mathbf{\Gamma}_e \equiv n_e\mathbf{u}_e = -D_e\nabla n_e - \mu_e n_e\mathbf{E}, \tag{7}$$

$$\mathbf{\Gamma}_i \equiv n_i\mathbf{u}_i = -D_i\nabla n_i + \mu_i n_i\mathbf{E}. \tag{8}$$

For ambipolar diffusion, the electron and ion fluxes are equal, or

$$\mathbf{\Gamma}_e = \mathbf{\Gamma}_i = \mathbf{\Gamma}. \tag{9}$$

In the steady state, the electron continuity equation is

$$\nabla\cdot\mathbf{\Gamma} = -\nu_r n_e + \nu_I n_e - \beta_{ei}n_i n_e - \nu_{\text{loss}}n_e, \tag{10}$$

where

$$\nu_{\text{r}} = 2\sqrt{2\pi}a^2 v_{Ti} n_d (n_i/n_e)(1+z\tau), \tag{11}$$

is the rate of electron recombination on the dust grain, ν_I is the ionization frequency, β_{ei} is the rate of recombination in the plasma bulk, and ν_{loss} is a generalized loss rate. Bulk recombination are usually negligible for low-pressure discharges, so that Eq. (11) can be rewritten in the form

$$\nabla\cdot\mathbf{\Gamma} = -\nu^* n_e, \tag{12}$$

where $\nu^* = \nu_r - \nu_I + \nu_{\text{loss}}$. In the following we shall concentrate on the Eq. (12).

Ambipolar diffusion is also affected by the dust charging process. Under most experimental conditions the dust-charge variation is mainly due to the variation of the local plasma potential. In this case dust charging can be roughly described by the orbit-motion-limited (OML) theory [11]. In the steady state, the dust charge is then determined by a balance of the local electron (J_e) and ion (J_i) charging fluxes hitting the dust surface, or

$$J_e - J_i = 0, \tag{13}$$

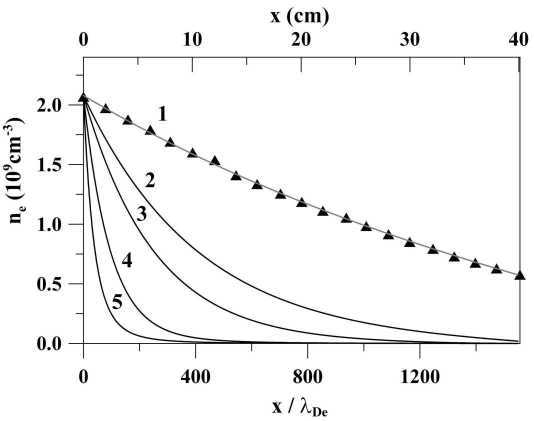

Fig. 1 The diffusion profiles of the electron density for $n_d = 0$ (curve 1), $n_d = 10^2$ cm^{-3} (curve 2), $n_d = 10^3$ cm^{-3} (curve 3), $n_d = 10^4$ cm^{-3} (curve 4), and $n_d = 10^5$ cm^{-3} (curve 5) in an argon plasma with argon gas pressure 0.18 Pa, $n_{e0} = 10^9$ cm^{-3}, $T_e = 1.2$ eV, and $T_i = 0.03$ eV. The dust grain radius is $a = 4.4$ μm. The triangles are from the experiments of Ma et al. [12] for $n_d = 0$.

where

$$J_e = 2\sqrt{2\pi}a^2 v_{Te} n_e \exp(-z) \tag{14}$$

and

$$J_i = \sqrt{2\pi}a^2 v_{Ti} n_i \tilde{u}^{-1}\Big\{\tilde{u}\exp(-\tilde{u}^2/2) + \sqrt{\pi/2}\,\mathrm{erf}(\tilde{u}/\sqrt{2})\left[1+\tau z+\tilde{u}^2\right]\Big\}. \tag{15}$$

Equations (1) – (15) are closed by the Poisson equation,

$$\nabla\cdot\mathbf{E} = 4\pi e(n_i - n_e - Z_d n_d). \tag{16}$$

3. Results of Numerical Simulations

The steady-state diffusion profiles are a solution of the equations (7) – (9), (12), (13), and (16). We solved this set of equations numerically to obtain the properties of an inhomogeneous dusty plasma, in particular that in an asymmetrically discharged double-plasma device [12]. We focused on the effect of the dust grains on the diffusion scale length and the electric field that appears self-consistently because of the diffusion process. For concreteness, we considered an argon plasma with the electron and ion temperatures $T_e = 1.2$ eV and $T_i = 0.03$ eV, respectively. The grain radius is taken to be $a = 4.4$ μm. Figure 1 shows the diffusion generated profiles of the electron density for different dust densities. The argon gas pressure is 0.18 Pa, and the background electron density is $n_{e0} = 10^9$ cm^{-3}. The triangles are the experimental data of Ma et al. [12] for $n_d = 0$. There is a rather good agreement between the theoretical curve 1 (for $n_d = 0$) and the experimental data.

We name in the ambipolar diffusion length λ_a the distance at which an e-fold decrease in the electron density occurs. Increase of the dust density is accompanied by reduction of the diffusion scale length. It is in good agreement with the experimental results [4]. The effect of this reduction is stronger for larger electron densities. This result can be attributed to an increase (due to increase of the dust density) of the contribution of the electron and ion collisions with the dust grains in comparison to that with the neutrals. Figure 2 shows the comparison of the magnitudes of the ambipolar diffusion length calculated on the basis of the set of equations (7) – (9), (12), (13), and (16) (solid curves) with those (dotted curves) calculated on the basis of the theory (see, e.g., [4, 5]) assuming the fulfillment of the quasineutrality condition and $T_i/T_e \ll 1$. We see that the assumption of the quasineutrality leads to incorrect results for high dust particle densities and/or low electron densities. This is related to the fact [8] that for not small dust densities, say, $n_d \gg 10^3$ cm^{-3}, the electric field gradient is not small and should thus be taken into account explicitly in related theoretical studies.

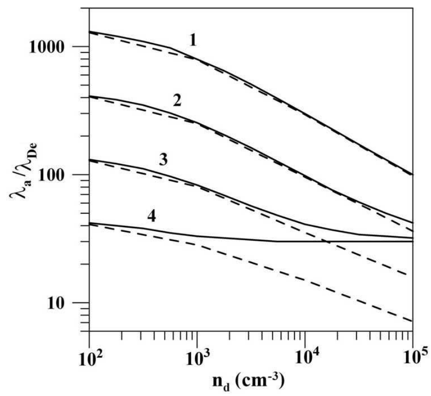

Fig. 2 The ratio λ_a/λ_{De} versus the dust density for $n_{e0} = 10^{10}$ cm^{-3} (curve 1), $n_{e0} = 10^9$ cm^{-3} (curve 2), $n_{e0} = 10^8$ cm^{-3} (curve 3), $n_{e0} = 10^7$ cm^{-3} (curve 4). The other parameters are the same as in Fig. 1.

The dependence of the ratio λ_a/λ_{De} on the pressure P satisfies the power law $\lambda_a/\lambda_{De} \propto P^{-\alpha}$, namely, $\alpha = -0.93$ for $n_d = 10^2$ cm^{-3} (for the argon gas and for $n_{e0} = 10^9$ cm^{-3}), $\alpha = -0.71$ for $n_d = 10^3$ cm^{-3}, and $\alpha = -0.54$ for $n_d = 10^4$ cm^{-3}. The magnitude of the power exponent increases with decrease of the dust density. In particular, we have $\alpha = -1$ for $n_d = 0$, as also found experimentally by Ma et al. [12].

4. Conditions for DIAW Structures

We applied these results to obtain the conditions for the existence of DIAW solitons and shocks in inhomogenious dusty plasma. Double-plasmas have often been used for investigating localized nonlinear structures such as DIAW shocks [13] and solitons [14] in homogeneous plasmas. In most applications, however,

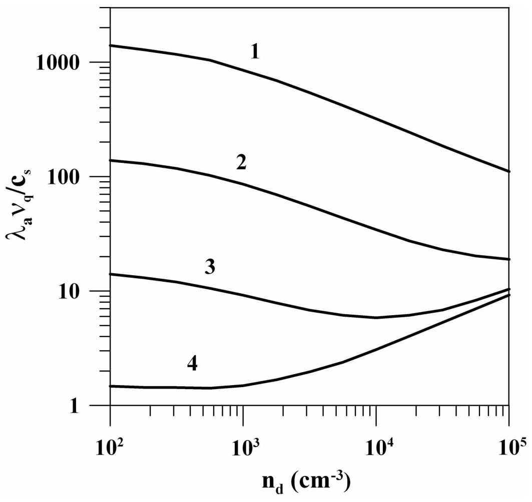

Fig. 3 The ratio $\lambda_a \nu_q / c_s$ versus the dust density for $n_{e0} = 10^{10}$ cm^{-3} (curve 1), $n_{e0} = 10^9$ cm^{-3} (curve 2), $n_{e0} = 10^8$ cm^{-3} (curve 3), $n_{e0} = 10^7$ cm^{-3} (curve 4). The other parameters are the same as in Fig. 1.

the plasma is inhomogeneous. Clearly, a localized structure can be excited in an inhomogeneous plasma only if the diffusion scale length of the plasma is much smaller than its characteristic width.

The width $\Delta\xi_{\text{sol}}$ of a DIAW soliton is mainly determined by the electron Debye length (see, e.g., [15]). For the parameters here we have $\Delta\xi_{\text{sol}} \sim 10\lambda_{De}$. From our results we can conclude that for the asymmetrically discharged double-plasma device [12], namely, $P = 0.18$ Pa, $T_e = 1.2$ eV, $T_i = 0.03$ eV, and $a = 4.4$ μm, DIAW solitons may be observed only for relatively large electron densities, namely, $n_{e0} > 10^8$ cm^{-3} and relatively low dust densities, namely $n_d \ll 10^4$ cm^{-3}.

For the parameters here, one of the most relevant DIAW shocks is that related to anomalous dissipation that originates from the dust charging process [6, 16]. This shock is especially interesting since it involves new physical effects that exist only in dusty plasmas. The width of the shock front $\Delta\xi_{\text{sh}}$ can be estimated by $\Delta\xi_{\text{sh}} \sim Mc_s/\nu_q$ [16], where Mc_s is the speed of the DIAW shock front, M is the Mach number, $\nu_q = \omega_{pi}^2 a(1 + z + T_i/T_e)/\sqrt{2\pi}v_{Ti}$ is the grain charging rate, and $\omega_{pi} = \sqrt{4\pi n_i e^2/m_i}$ is the ion plasma frequency. The Mach number M for DIAW shocks of not too large amplitude as observed in a homogeneous double-plasma is of the order of unity [13]. Thus the necessary condition for these shocks can be excited in inhomogeneous dusty plasmas is $\lambda_a \gg c_s/\nu_q$. Figure 3 shows the dependence of the ratio $\lambda_a \nu_q / c_s$ on the dust density for different electron densities n_{e0}, $a = 4.4$ μm, for the parameters of the inhomogeneous double-plasma of interest here [12]. We see that DIAW shocks associated to anomalous dissipation can only appear if the electron density is large $n_{e0} \gg 10^8$ cm^{-3}.

5. Electric Fields in Dusty Ionosphere

Regions containing dust in the ionosphere can lead to many physical effects having unique observable features [17, 18, 19, 20]. The latter include ionospheric phenomena such as noctilucent clouds (NLC) and polar mesosphere summer echoes (PMSE), where dust grains result, in particular, from condensation of water vapor (see, e.g., [17]). In the ionosphere, dust grains are charged due to the photoelectric effect and the absorption of electrons and ions from the surrounding plasma. Therefore, the plasma of the dusty ionosphere can be considered as a dusty plasma [17, 19].

At the altitudes of 80 to 95 km, where NLC and PMSE exist, there is the cutoff of the solar spectrum corresponding to photon energy of 7.3 eV [18]. This means that pure ice dust grains having the work function equal to 8.7 eV are not subjected to the action of the photoelectric effect and their charges should always be negative. However, if the ice grains contain impurities with the work function less than 7.3 eV then the grains can acquire positive charges [17, 18].

The regions of the pure ice dust grains and the grains containing impurities, which constitute NLC and/or PMSE, can be contiguous. Even in the case of equal sizes of the dust grains (with and without impurities), the densities of electrons and ions in such contiguous regions are different. This results in the ambipolar diffusion in these regions. In Figure 4 the results of calculations of the electron density, the electric field, and the dust particle charge are presented which are formed due to the ambipolar diffusion in the region of the pure ice dust grains for typical parameters [17] of the dusty plasma at the mesospheric altitudes ($n_d = 5 \cdot 10^2$ cm^{-3}, $n_{e0} = 10^4$ cm^{-3}, $T_e = T_i = 155$ K, $P = 0.5$ Pa, $a = 50$ nm, and $a = 500$ nm). We see that the electric fields formed as a result of the ambipolar diffusion in the mesosphere can reach the values $|\mathbf{E}| \sim 1$ V/m. We note that such values of the electric fields were observed in the lower mesosphere and in the vicinity of NLC [21].

6. Summary

In summary, we have introduced a self-consistent model for ambipolar diffusion of electrons and ions in dusty plasmas accounting for the dust grain charging process, the interaction of the plasma particles with the dust grains and neutrals, the resulting self-consistent electric fields, etc., and studied its effect on the properties of an inhomogeneous plasma. The diffusion coefficient is strongly affected by the interaction of electrons and ions with the dust grains as well as the neutrals. It is found that the gradients of the self-consistent electric fields are not negligible and should be taken into account if the dust density is not small ($n_d \gg 10^3$ cm^{-3}). This effect implies the violation of

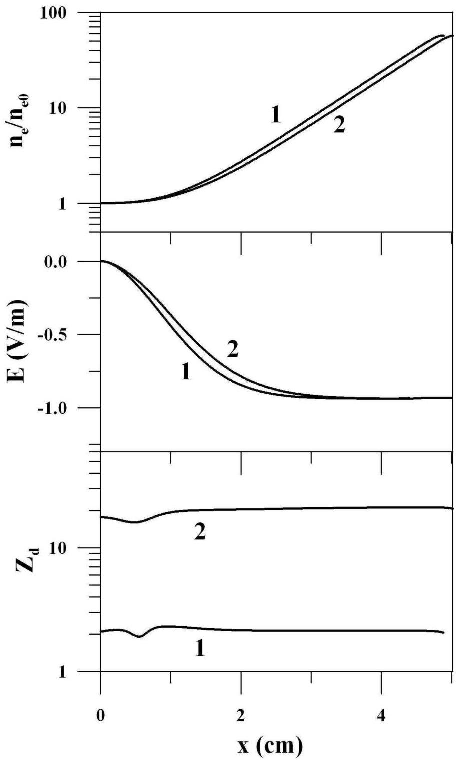

Fig. 4 The profiles of the normalized electron density, the electric field, and the dust particle charge number formed as a result of the ambipolar diffusion at the mesospheric altitudes for two sizes of dust grains: $a = 50$ nm (curves 1) and $a = 500$ nm (curves 2). The plasma parameters are: $n_d = 5 \cdot 10^2$ cm^{-3}, $n_{e0} = 10^4$ cm^{-3}, $T_e = T_i = 155$ K, and $P = 0.5$ Pa.

the quasineutrality condition and is stronger at larger dust densities. The violation of the quasineutrality condition and the importance of the electric field associated with the ambipolar diffusion are confirmed for dust densities as large as $n_d = 10^2$ cm^{-3}. Increase of the dust density leads also to a reduction in the diffusion scale length and this effect is stronger at larger electron densities. It is found that the dependence of the diffusion scale length on the neutral gas pressure is well described by a power law $\lambda_a \propto P^{-\alpha}$, where the magnitude of the power decreases with increase of the dust density. We have also given the conditions for observation of DIAW solitons and shocks in an inhomogeneous plasma from an asymmetrically discharged double-plasma device [12]. It is found that DIAW solitons can be observed only for rather large ($n_{e0} > 10^8$ cm^{-3}) electron densities and rather low ($n_d \ll 10^4$ cm^{-3}) dust densities, while DIAW shocks can appear only at large ($n_{e0} \gg 10^8$ cm^{-3}) electron densities. Furthermore, we have found the profiles of the electron density, the electric field, and the dust particle charge formed as a result of the ambipolar diffusion near the contact of regions of negatively and positively charged dust grains under the mesospheric conditions, and have shown that the electric fields appeared in these regions are of the order of 1 V/m. Such electric fields were observed in the lower mesosphere and in the vicinity of NLC [21].

This work was supported by the Russian Foundation for Basic Research, Project no. 06-05-64826.

[1] F.F. Chen, *Introduction to Plasma Physics* (Plenum, New York, 1974).
[2] E.M. Lifshitz and L.P. Pitaevskii, *Physical Kinetics* (Butterworth-Heinemann, Oxford, 1999).
[3] S.I. Popel, T.V. Losseva, R.L. Merlino, S.N. Andreev, and A.P. Golub', Phys. Plasmas **12**, 054501 (2005).
[4] J.X. Ma, M.Y. Yu, X.P. Liang, J. Zheng, W.D. Liu, and C.X. Yu, Phys. Plasmas **9**, 1584 (2002).
[5] Sh. Amiranashvili and M.Y. Yu, Phys. Plasmas **9**, 4825 (2002).
[6] S.I. Popel, M.Y. Yu, and V.N. Tsytovich, Phys. Plasmas **3**, 4313 (1996).
[7] S.I. Popel, A.P. Golub', T.V. Losseva, A.V. Ivlev, S.A. Khrapak, and G. Morfill, Phys. Rev. E **67**, 056402 (2003).
[8] T.V. Losseva, S.I. Popel, M.Y. Yu, and J.X. Ma, Phys. Rev. E **75**, 046403 (2003).
[9] S.A. Khrapak and G.E. Morfill, Phys. Rev. E **69**, 066411 (2004).
[10] S.A. Khrapak, A.V. Ivlev, G.E. Morfill, and H.M. Thomas, Phys. Rev. E **66**, 046414 (2002).
[11] F.F. Chen, in *Plasma Diagnostic Techniques*, edited by R.H. Huddlestone and S.L. Leonard (Academic, New York, 1965), Chap. 4.
[12] J.X. Ma, Y.-F. Li, D.-L. Xiao, J.-J. Li, and Y.-R. Li, Rev. Sci. Instrum. **76**, 062205 (2005).
[13] Y. Nakamura, H. Bailung, and P.K . Shukla, Phys. Rev. Lett. **83**, 1602 (1999).
[14] Y. Nakamura and A. Sarma, Phys. Plasmas **8**, 3921 (2001).
[15] S.I. Popel and M.Y. Yu, Contr. Plasma Phys. **35**, 103 (1995).
[16] S.I. Popel, A.P. Golub', and T.V. Losseva, JETP Lett. **74**, 362 (2001).
[17] B.A. Klumov, G.E. Morfill, and S.I. Popel, Zh. Éksp. Teor. Fiz. **127**, 171 (2005) [JETP **100**, 152 (2005)].
[18] B.A. Klumov, S.I. Popel, and R. Bingham, Pis'ma Zh. Éksp. Teor. Fiz. **72**, 524 (2000) [JETP Lett. **72**, 364 (2000)].
[19] O. Havnes, in *Dusty Plasma in the New Millenium*, Ed. by R. Bharuthram, M. A. Hellberg, P. K. Shukla, and F. Verheest (AIP, New York, 2002), p. 13.
[20] S.I. Kopnin, I.N. Kosarev, S.I. Popel, and M.Y. Yu, Planet. Space Sci. **52**, 1187 (2004).
[21] A.M. Zadorozhny, A.A. Tyutin, G. Witt, N. Wilhelm, U. Walchli, J. Cho, and W. Swartz, Geophys. Res. Lett. **20**, 2299 (1993).