Dusty plasma in Earth's mesosphere: formation and evolution of polar mesospheric clouds

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One important feature of the polar ionosphere under summer conditions is the presence of dust layers (very thin on the atmospheric scale) located at altitudes of 80 to 85 km (noctilucent clouds, or NLC) or about 90 km (polar mesospheric summer echoes, or PMSE). NLC consist of submicron-sized particles. They can be seen by the naked eye at sunset, whereas PMSE (apparently consisting of charged nanometer-sized particles) cannot be observed by optical methods and manifest themselves by strong radio reflections observed with radars at frequencies between 50 and 1000 MHz. In the literature, NLC and PMSE are frequently grouped together under the common term polar mesospheric clouds (PMC).

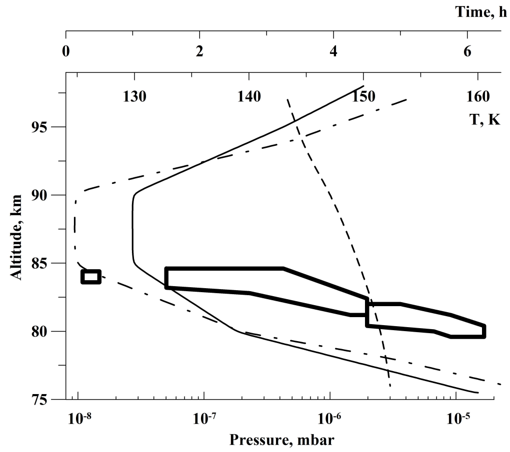

Figure 1: Qualitative estimates for vertical profiles of air temperature (solid curve), partial pressure of water vapor (dashed curve), and pressure of saturated water vapor (dash-dot curve). Water vapor is supersaturated at altitudes of 77 to 94 km. Bold solid lines characterize (in accordance with the data [4]) temporal evolution of the altitude range in which NLC are observed.

Interest to the description of dusty structures in the ionosphere has significantly increased since the 2000s [1 – 3] owing to the development of the methods of investigation of dusty plasmas. Furthermore, the great interest to these structures is due to their possible connection with climate change and, in particular, with the Earth global warming process.

The formation of NLC and PMSE takes place in the polar atmosphere at mesospheric altitudes (80–100 km) between the end of May and the end of August. In this period, the ambient air temperature there falls below 150 K, and water vapor supersaturates. This leads to conditions favoring the growth of dust grains. The dominant nucleation mechanism appears to be the condensation of water molecules on nanometer-scale particles, which are always present at mesospheric altitudes. The characteristic grain size is a few nanometers, and their concentration typically is 10 to 1000 cm^{-3}. Figure 1 illustrates the summer conditions in the polar ionosphere that are important for the physics of PMCs.

Here, we perform further development of a theoretical model [2] that provides a self-consistent description of the process taking place in NLC and PMSE including their formation. The model describes, in particular, sedimentation of dust grains in the middle atmosphere, their growth in a supersaturated water vapor, and microparticle charging processes, allowing for variations of the ion-subsystem composition in the polar mesosphere and photoelectric emission. In the present paper we pay the main attention to the processes of condensation as well as to the initial conditions. Using the modified model we show the influence of initial distributions of fine particles as well as of the processes of condensation and water molecule absorption by fine particles on the formation of NLC and PMSE. We illustrate also a possibility of the formation of layered structure and sharp boundaries of NLC.

We use the following equations. A kinetic equation for the dust particle velocity distribution function $f_d(h,a,v,t)$ at the altitude h is

$$\frac{\partial f_d}{\partial t} + \frac{\alpha_w m_{\mathrm{w}} v_{\mathrm{w}}^{th}\left(n_{\mathrm{w}} - n_{\mathrm{w}}^{s}\right)}{4\rho_d}\frac{\partial f_d}{\partial a} + v\frac{\partial f_d}{\partial h} + \left(g - \frac{\pi \rho c_s a^2 F_d (v + v_{\mathrm{wind}})}{m_d}\right)\frac{\partial f_d}{\partial v} = 0. \quad (1)$$

Here, a is the characteristic dust particle size, m_d is the dust particle mass, m_{w} is the water molecule mass, α_w is the accommodation coefficient for water molecules colliding with a dust grain (normally, $\alpha_w \sim 1$), v_{w}^{th} is the thermal speed of water molecules, c_s is the local acoustic speed, ρ and ρ_d denote the densities of the ambient air and grain material, n_{w}^{s} and n_{w} are the number densities of saturated water vapor over the dust particle surface and of water vapor in the mesosphere, v_{wind} and v are the upward components of the wind and dust particle velocity, respectively, the factor F_d (of the order of unity) reflects the effect of grain geometry, g is the gravity of Earth.

An equation characterizing the relationship between the pressure P_S of the saturated water vapor over a dust particle of the size a, possessing the surface charge q_d, and the pressure P_0 of the saturated water vapor over a flat surface is

$$v_d\left(P_S - \frac{N_A \mu_D q_d}{\mu_g a^2 v_d} L\left(\frac{\mu_D q_d}{T a^2}\right) - P_0\right) - \frac{N_A T}{\mu_g}$$
$$\times \ln\left\{\frac{P_S}{P_0}\right\} + \frac{2\sigma v_d}{a} + \frac{q_d^2 v_d}{8\pi a^4}\left(\frac{1}{\varepsilon} - 1 + \nu(\lambda, a)\right) = 0, \quad (2)$$

where

$$\nu(\lambda,a) = \int_a^{\infty} \frac{a^2(\lambda + r)^2}{r^2} \cdot \frac{2a\exp\{2(a-r)/\lambda\}}{\lambda(\lambda+a)^3} dr, \quad (3)$$

λ is the characteristic screening length of Yukawa potential characterizing the electric field of a dust particle, ε is the dielectric function of the grain material, v_d is the specific volume of the dust particle, N_A is the Avogadro number, μ_D is the dipole moment of water molecule, μ_g is the molar mass of water vapor, T is the temperature, $L(x)$ is the Langevin function, σ is the surface tension coefficient. Solution of Eq.(2) allows us to determine the number density n_{w}^s (included in Eq. (1)) by means of the relationship $n_{\mathrm{w}}^s = P_S/T$.

An equation describing the dynamics of the water vapor is

$$\frac{\partial n_w}{\partial t} + \frac{\partial \Gamma_w}{\partial h} = -P_w - n_w L_w - \pi \alpha_w v_w^{th} n_w \left\langle a^2 n_d \right\rangle , \quad (4)$$

where Γ_w is the vertical diffusion flux of water vapor [5], P_w, L_w are photochemistry sources and sinks of water vapor in the mesosphere, the last term on the right-hand-side (4) describes absorption of water molecules by dust particles. The rest equations of the model which describe the plasma properties of the the polar atmosphere at mesospheric altitudes are given in [2].

We have used two profiles shown in Fig. 6 of [6] as initial profiles of the height distribution of dust particles. One of them represents a distribution of dust particles of relatively small number density at the altitudes of 90–95 km. Another one corresponds to relatively thin dust layer of sufficiently high number density ($n_d = 100 - 1000\,\mathrm{cm}^{-3}$) at the altitudes of 85–87 km.

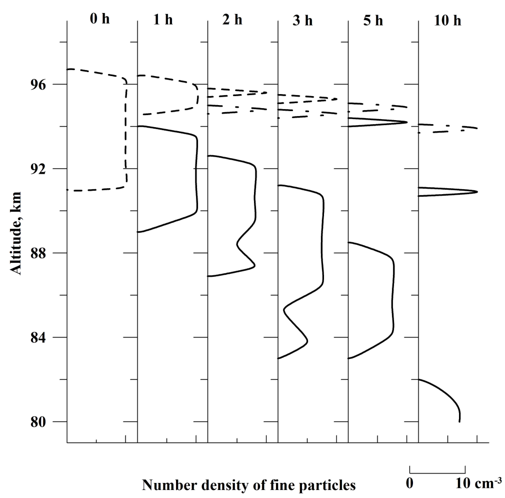

Figure 2: Evolution of the initial trapeziform profile of dust particle number density $n_d = 10\,\mathrm{cm}^{-3}$ *vs* altitude for different moments of time ($t = 0, 1, 2, 3, 5, 10$ h). Dashed, dash-dot, and solid curves denote the profiles of number density for the particles with the sizes smaller than 20 nm, between 25 nm and 75 nm, and more than 80 nm, respectively.

In calculations, the first distribution is approximated by trapeziform profile, so that one considers the initial number density of dust particles equal to $n_d = 10\,\mathrm{cm}^{-3}$ at the altitudes between 91 and 96 km and the initial radii of the particles are equal to 10 nm. Evolution of such an initial profile is given in Figure 2. The particles being initially higher than 94 km grow rather slowly, therefore they levitate at the altitudes of 90 to 95 km during several hours. The reason for such their behavior is that the layers existing below 94 km are initially in the condensation zone, *i.e.*, in the zone where water vapor is supersaturated (see Figure 1). They gather (on their surfaces) the main part of water vapor and sediment downward together with the absorbed water molecules. Those particles which are initially higher than 94 km (even when reaching the condensation zone in some time) cannot grow significantly because of only small amount of the residual water molecules in this zone. These small-size-particles exist at the altitudes of 90–93 km during hours, that explains the phenomenon of PMSE.

The formation of the layered structure of NLC is illustrated (Figure 3) by the evolution of the observed initial bell-shaped dust particle distribution [6]. The lower part of the bell-shaped distribution which passes first through the layer of water vapor sediments, acquires some speed, and gather almost all water molecules. As a result, the second (upper) part of the distribution moves slower and finally the second hump appears on the total distribution.

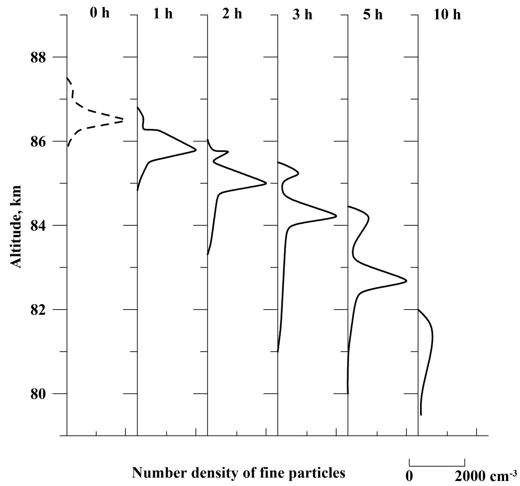

Figure 3: Evolution of the initial [6] bell-shaped dust particle height distribution for different moments of time ($t = 0, 1, 2, 3, 5, 10$ h).

Thus we have described briefly a self-consisted model of dusty plasma structures such as NLC and PMSE. Calculations based on the model illustrate an influence of the initial dust distributions on the formation of NLC and PMSE, show why two types of dusty structures, namely NLC and PMSE, are formed, and justify a possibility of the formation of layered structure and sharp boundaries of NLC.

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References

[1] B.A. Klumov, S.I. Popel, and R. Bingham, JETP Letters **72**, 364 (2000).

[2] B.A. Klumov, G.E. Morfill, and S.I. Popel, J. Experim. Theor. Phys. **100**, 152 (2005).

[3] A.Yu. Dubinskii and S.I. Popel, JETP Letters **96**, *No.*1 (2012).

[4] N. Kaifler, G. Baumgarten, J. Fiedler, *et al.*, Atmos. Chem. Phys. Discuss. **10**, 25081 (2010).

[5] B.J. Murray and J.M.C. Plane, Atmos. Chem. Phys. **5**, 1027 (2005).

[6] K. Amyx, Z. Sternovsky, S. Knappmiller, *et al.*, J. Atmos. Solar-Terr. Phys. **70**, 61 (2008).