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DUST PARTICLE CHARGING AND FORMATION OF DUST STRUCTURES IN THE UPPER ATMOSPHERE

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We investigate the dust particle charging process in the Earth's upper atmosphere. Calculating the spectra of solar radiation we study the influence of the photoelectric effect on the charging process. We show that both positively and negatively charged dust particles are present in the upper atmosphere. We consider the mechanisms which can be responsible for the formation of dust structures like noctilucent clouds and polar mesosphere summer echoes.

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Earth's upper atmosphere reveals some layered structures which are known as noctilucent clouds (NLC) and polar mesosphere summer echoes (PMSE). These structures are believed to be associated with the presence of a large amount of charged dust or aerosol in the upper atmosphere. The problem of formation of dust structures in the Earth's upper atmosphere is considered now in dusty plasma community as one of the key problems. Furthermore, the great interest to these structures is due to their possible connection with the Earth global warming process.

NLC consist probably of particles of ice nature. Their appearance is confined to the summer season at the mesospheric altitudes close to 80–85 km at high and midlatitudes, when the temperature drops down below about 155 K [e.g. 1]. Under these conditions the formation of ice particles occurs. Polar mesosphere summer echoes are strong radar echoes which appear to be also associated to dust [2]. PMSE occur in well defined layers in the 80 to about 95 km altitude region [3]. Because NLC and PMSE observed at the same season, and at the altitude region close to the mesopause, one can assume that NLC and PMSE have the same origin. Both NLC and PMSE are small-scale mesospheric structures. Their width L_c is far less than the height scale H of the atmosphere: $L_c \ll \ll H$; $L_c \simeq 100$ m $\div$ 1 km, $H \approx 7$ km. Many questions remain to be answered about NLC and PMSE, the most important one being the width of the structures.

In the present study we propose the model of NLC as a layer of a charged dusty plasma illuminated by solar radiation [4]. We calculate spectra of solar radiation at NLC altitudes, determine charges of the dust particles, and analyze the possibilities of the formation of dust particle structures. For brevity the mesospheric dust structures are referred to as "NLC".

We choose the following parameters of the mesosphere and dust particles: the characteristic dust particle size is $a \sim 10^{-7} \div 10^{-5}$ cm, the dust number density is $n_d \sim 10 \div 10^3\,\mathrm{cm}^{-3}$, the altitudes of NLC formation are $h \simeq 82 \div 83$ km, the width of NLC is $L_c \sim 100$m $\div$ 1 km, the vertical optical depth is $L \ll 1$, the neutral number density is $n_n \simeq 2\cdot 10^{14}\ \mathrm{cm}^{-3}$, the water vapour number density is $n_w \sim (10^8 \div 10^9)\ \mathrm{cm}^{-3}$, the temperature of neutrals is $T_n \leq 155$ K.

The mesospheric ion composition is rather complicated [5]. Different sorts of both positive and negative ions are present. Here we take into account only positive ions[1] of two kinds. The first one is related to light primary ions like NO^+, N_2^+, O_2^+, while the second one to the so-called proton hydrate ions (PHs) $(H^+(H_2O)_n, n \leq 10)$. We note that the electron-ion recombination coefficient α_{rec} depends strongly on the kind of the ions. The light primary ions have the effective recombination coefficient $\alpha_{rec}^p \sim 10^{-7}$ $cm^3 \cdot s^{-1}$, while $\alpha_{rec}^c \sim 10^{-5}$ $cm^3 \cdot s^{-1}$ for PHs ions. Here and below the superscript p and c are referred to the primary and PHs ions, respectively.

The temperatures of ions and electrons are believed to be equal to the neutral temperature $T_i = T_e = T_n$. The ionization rate is $q_e \sim 0.1 \div 10$ $cm^{-3} \cdot s^{-1}$.

We have calculated the solar spectra at NLC altitudes using Phodis code [6]. Fig.1 shows the spectrum variations with altitude and solar zenith angle. It is seen clearly that the typical solar spectrum decreases sharply for the wavelengths less than approximately 170 nm (that corresponds to the photon energy ≈ 7.3 eV) – the cut off of energetic photons occurs.

The work function of pure ice is about 8.9 eV. Thus taking into account the form of the solar spectrum at NLC altitudes we conclude that the photoelectric effect is not significant in the charging prosess of pure ice grains. However, if (even ice) dust particles contain impurities then the work function of the substance of the dust can be far less than the cut off of the solar spectrum. In this case the photoelectric effect can be very important (even dominant) in the charging process. The effect leads to the existence of both positively and negatively charged dust particles in the mesosphere.

Even under twilight conditions the solar flux is large enough, so that the ionization rate due to the photoelectric effect can be comparable to the value of q_e and even greater than this value. In this case it is nesessary to include the photoelectric effect to determine charges of the dust particles in NLC. We note that solar radiation does not affect (with electron production) on all dust particles. The origin of the dust particle appears to play the crucial role in the effect. One believes that the dust grain is created in the cold summer mesosphere via two various mechanisms. a) The base for the grain creation is the PHs ion. The ions $H^+(H_2O)_n$ are effective seeds for the nucleation processes in the mesosphere [7]. In this case the dust grain appears to consist of pure ice. b) The base for the grain creation is a small dust particle of meteoritic or volcanic eruption nature. In this case the grains consist of contaminated ice, so that the photoelectric work function can be reduced significantly for such particles. In both cases the growth of the dust particle is due to fast absorption of water molecules by the particle.

To evaluate the dust particle charging under NLC conditions we use the model which describes the evolution of the electron density n_e, of the ion density of both kinds n_i^p, n_i^c, and of the dust charge variation. Neglecting the chemistry of negative ions and using the local approximation, we present the set of equations, which describes the dust particle

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[1] The role of the negative ions at NLC altitudes can be evaluated in the following manner. The primary negative ion is O_2^-. The ion is created via the process $e + 2O_2 \rightarrow O_2^- + O_2$ (the rate constant is $k_1 \simeq 5 \cdot 10^{-31}$ $cm^6 \cdot s^{-1}$). Main sinks of the O_2^- ion are: a) photodetachment $O_2^- +$ photon $\rightarrow O_2 + e$ (the rate constant is $\delta_{photo} \sim 0.3$ s^{-1}); b) collisional destruction $O_2^- + O \rightarrow O_2 + O + e$ (the rate constant is $k_2 \simeq 3 \cdot 10^{-10}$ $cm^3 \cdot s^{-1}$). Balancing the processes we can estimate easily the O_2^- concentration at NLC altitudes: $[O_2^-] \sim k_1[O_2]^2 n_e/(\delta_{photo} + k_2[O]) \sim 0.1 \div 1$ cm^{-3}. This value is far less than the positive ion number density. Thus we can neglect the role of the negative ions in the mesospheric dust charging process.

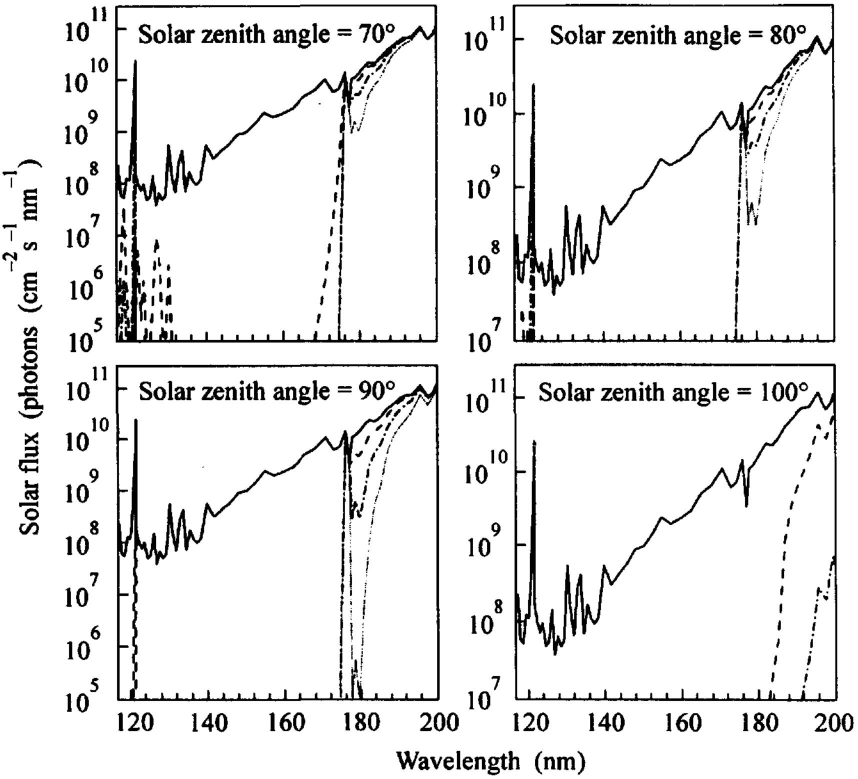

Fig.1. Solar spectra at mesospheric altitudes for various solar zenith angles. Spectra correspond to the altitude of 100 km (solid line), 90 km (dashed line), 80 km (dash-dotted line), and 70 km (dotted line)

charge, in the following form:

$$\frac{\partial n_e}{\partial t} = q_e + \sum_j q_{photo,j} n_d^j - \sum_j \nu_{e,j} n_d^j - \alpha^p_{rec} n_e n_i^p - \alpha^c_{rec} n_e n_i^c,$$

$$\frac{\partial n_i^p}{\partial t} = q_e - \sum_j \nu^p_{i,j} n_d^j - \alpha^p_{rec} n_e n_i^p - \beta_c n_i^p,$$

$$\frac{\partial n_i^c}{\partial t} = \beta_c n_i^p - \sum_j \nu^c_{i,j} n_d^j - \alpha^c_{rec} n_e n_i^c, \qquad \frac{\partial Z_{d,j}}{\partial t} = q_{photo,j} + \nu^p_{i,j} + \nu^c_{i,j} - \nu_{e,j}.$$

Here ν_e, ν_i are the charging rates due to electron and ion collisions with dust particles, q_{photo} is the charging rate due to the photoelectric effect, β_c is the rate of conversion of the primary ions into the PHs ions, the index j – describes the dust particles of different sizes. The typical values of β_c under NLC conditions are $\beta_c \sim 0.1$ cm^3/s [7]. In the case of the negative dust charge we have [8]

$$\nu_e \approx -\pi a^2 \left(8T_e/\pi m_e\right)^{1/2} n_e \exp\left(eq_d/aT_e\right),$$

$$\nu_i = \sqrt{\frac{\pi}{2}} a^2 v_{Ti} e n_i \left[2\exp\left\{-\frac{v_i^2}{2v_{Ti}^2}\right\} + \right.$$

$$\left. + \frac{\sqrt{2\pi}\left(1 + v_i^2/v_{Ti}^2\right) \operatorname{erf}\left\{v_i/\sqrt{2}v_{Ti}\right\}}{v_i/v_{Ti}} - \frac{2eq_d}{am_i v_{Ti}^2} \frac{\sqrt{2\pi} \operatorname{erf}\left\{v_i/\sqrt{2}v_{Ti}\right\}}{v_i/v_{Ti}} \right].$$

For the situation of the positive dust charge the charging rates are [9]

$$\nu_e \approx -\pi a^2 \left(8T_e/\pi m_e\right)^{1/2} n_e \left(1 + eq_d/aT_e\right),$$

$$\nu_i = \sqrt{\frac{\pi}{2}} a^2 v_{Ti} n_i \left\{ 2\exp\left(-\frac{v_i^2 + v_{\min,i}^2(q_d)}{2v_{Ti}^2}\right)\cosh\left(\frac{v_i v_{\min,i}(q_d)}{v_{Ti}^2}\right) + \right.$$

$$\left. + \sqrt{\frac{\pi}{2}} \frac{v_{Ti}}{v_i}\left(1 + \frac{v_i^2}{v_{Ti}^2} - \frac{2eq_d}{am_i v_{Ti}^2}\right)\left[\operatorname{erf}\left(\frac{v_{\min,i}(q_d) + v_i}{\sqrt{2}v_{Ti}}\right) - \operatorname{erf}\left(\frac{v_{\min,i}(q_d) - v_i}{\sqrt{2}v_{Ti}}\right)\right]\right\}.$$

In the above formulas $q_d = -Z_d e$ is the dust particle average charge, $-e$ is the electron charge, $v_{\min,i}(q_d) = (2eq_d/am_i)^{1/2}$, m_α is the mass of the particle of the kind α, and $\operatorname{erf}(x)$ is the error function.

The photoelectric rate q_{photo} is given by the formula

$$q_{photo} = \frac{\pi\beta a^2}{\hbar} \int\limits_{\omega_R-(e^2 Z_d/a\hbar)}^{\infty} \frac{\Phi(\omega)}{\omega} d\omega.$$

Here $\Phi(\omega)$ is the solar flux at the mesospheric altitudes, β is the probability of emission of the electron due to the action of one photon on dust particle surface, $\hbar$ is the Planck's constant, $\hbar\omega_R$ is the photoelectric work function. The limits of integration correspond to the fact that only photons with frequencies $\omega > \omega_R - (e^2 Z_d/a\hbar)$ can result in photoelectric current generation (i.e., the electrons emitted due to the action of these photons can go away from the dust grain surface to infinity). In our case $\hbar\omega_R$ is equal to several eV, while $e^2 Z_d/a \sim kT_n \sim 0.01$ eV $\ll \hbar\omega_R$. Thus the dependence of the lower limit of the integral on the dust particle charge is negligible.

Fig.2 shows the temporal dependences of the ion and electron number densities and the dust charge variation for two different ionization rates $q_e = 0.1\,\mathrm{cm}^{-3}\cdot\mathrm{s}^{-1}$ and $q_e = 10\,\mathrm{cm}^{-3}\cdot\mathrm{s}^{-1}$. The dust parameters are $n_d \simeq 10^3\,\mathrm{cm}^{-3}$, $a \simeq 10^{-5}\,\mathrm{cm}$ for both cases.

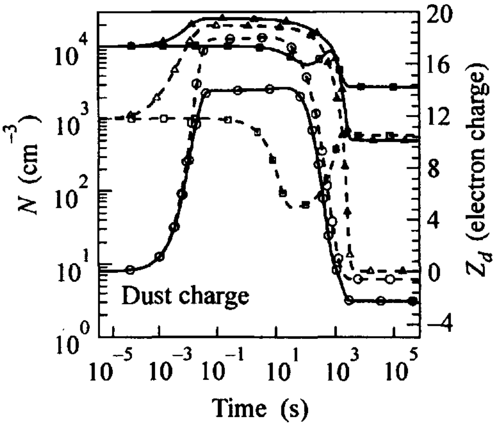

Fig.2. Ions (square), electron (delta) number densities and dust charge (circle) variations versus time at polar summer mesosphere. Solid and dashed lines correspond to various (10^3 cm^{-3} and 10^4 cm^{-3}) initial plasma densities, respectively. The number dust density is $n_d \simeq 10^3$ cm^{-3}, the dust size is $a \simeq 10^{-5}$ cm. The dust photoelectric work function is 7 eV

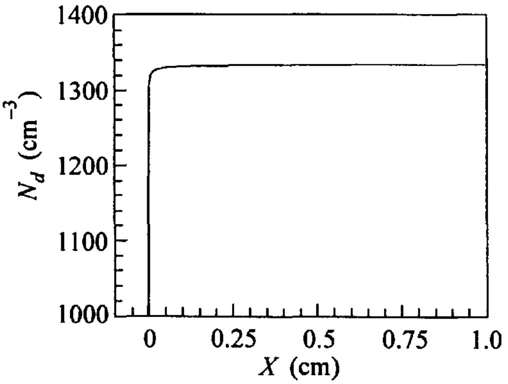

Fig.3. Spatial dependence of the dust number density, showing sharp boundary of NLC

In steady state and in the absence of charged dust particles the densities of electrons and ions at NLC altitudes are determined by the ionization rate q_e and the mean recombination coefficient α_{rec}: $n_e \simeq n_i \simeq \sqrt{q_e/\alpha_{rec}}$. To take into account both day and night conditions the initial time is chosen to be just before twilight. When the dust particles immerse into the mesosphere, they acquire the charges q_d which can be positive even under twilight conditions, the charges are negative at night. The typical values of q_d for NLC parameters are $q_d/e \sim 10 \div 20$ at day time and twilight time, and $q_d/e \simeq -2$ at night.

As it has been mentioned above NLC is accompanied by the presence of dust particles and, moreover, they can be associated with dust layers. Significant electron depletion occurs in the region occupied by the dust particles at night. The presence of solar radiation results in significant depletion of ions, the magnitude of the electron density in this case being larger than the equilibrium one. The depletions create the diffusion fluxes of electrons (ions) on the dust layer at night (day) time. We note that both positively and negatively charged dust grains and the corresponding depletions were observed in the polar summer mesosphere [e.g. 10]. We believe that the depletions play a definite role in the process of NLC formation.

Let us consider the spatial evolution of the dusty layer under the mesospheric conditions. For simplicity we assume that the dust particles have the same sizes. Below we omit the index j in the equations.

We use the one-dimensional model (the axis x is directed down) which is to some extent analogous to the model of self-organizing dusty layer [11], but has the important differences from the latter model. In our case the dusty layer can be charged both positively and negatively depending of solar zenith angle. If the dusty layer is charged positively then the significant depletion of ions inside the layer occurs and the diffusive ion flux affects the dusty layer. Furthermore, the negatively charged pure ice particles tend to squeeze the dusty layer. If the layer is charged negatively (at night), the depletions of electrons and ions appear and the layer (being under the action of the fluxes of electrons and ions) also have a tendency to squeeze. To describe the spatial evolution of such a dusty layer we use the continuity equation for the dust particles, the local approximation for both electrons and ions, and the Poisson equation. The local approximation gives four nonlinear algebraic equations

$$q_e + q_{photo}n_d = \nu_e n_d + \alpha^p_{rec} n_e n^p_i + \alpha^c_{rec} n_e n^c_i,$$

$$q_e = \nu^p_i n_d + \alpha^p_{rec} n_e n^p_i + \beta_c n^p_i,$$

$$\beta_c n^p_i = \alpha^c_{rec} n_e n^c_i + \nu^c_i n_d,$$

$$q_{photo} + \nu^p_i + \nu^c_i = \nu_e.$$

The life time of electrons (ions) $\tau_{e(i)}$ is determined mainly by the charging process $\tau_{e(i)} \sim \sim \nu^{-1}_{e(i)}$. The life time $\tau_{e(i)}$ is far less than the characteristic diffusion time $\tau^{e(i)}_d$, where $\tau^{e(i)}_d \sim L^2_c/D_{e(i)} \sim L^2_c n_n \sigma^{e(i)}_n / v_{e(i)}$, $\sigma^{e(i)}_n$ is the cross section of elastic collisions between electrons (ions) and neutrals. Thus the local approximation is suitable under NLC conditions.

Using the assumption of the stationary dust particle structure we present the continuity equation for the dust particles in the form

$$\partial(n_d u_d)/\partial x = \nu_d n_d.$$

Here the term $\nu_d n_d$ describes the accretion processes. We note that the existense of both positively and negatively charged dust particles accelerates the accretion processes.

For the dust particles we take into account the momentum transfer in collisions with other dust particles, ions, and neutrals (the momentum transfer in collisions with electrons is negligibly small):

$$m_d n_d u_d \frac{\partial u_d}{\partial x} = -eZ_d n_d \frac{\partial \varphi}{\partial x} - \nu_i m_i n_i (u_i - u_d) + m_d n_d g,$$

where φ is the electrostatic potential, u_α is the velocity of the particles of the kind α, g is the gravity.

The Poisson equation takes the form

$$\partial^2 \varphi / \partial x^2 = 4\pi e (n_e + Z_d n_d - n_i).$$

Assuming that the dust particles have zero velocity we can evaluate the electric fields in the mesosphere under NLC conditions

$$E_x = -\partial \varphi / \partial x \simeq m_d g / e Z_d \sim 1 \text{ V/m}.$$

We note, that such electric fields were observed in the lower mesosphere and in the vicinity of NLC [12]. Fig.3 shows the spatial structure of the dust layer calculated on the basis of the above set of equations. We note that the dust structure has sharp boundaries.

As for the width L_c of NLC, the value can be estimated as $L_c \sim v_\alpha / \nu_{\alpha,d}$, where v_α is the velocity of the charged particles of the kind α, $\nu_{\alpha,d}$ is the particle-dust collision rate (it is assumed that the fluxes of the particles of the kind α result in the squeeze of the dusty layer (cf. [11])). For electrons and ions it gives $L_c \sim d^2_{e,i}/a$. Under the mesospheric conditions $L_c \sim 10^5$ cm. This value is of the order of the observable width of NLC. The scaling will be discussed in far more detail in the following publications.

Solar spectrum at NLC altitudes has a cut off at wavelengths less than $\simeq$ 170 nm due to atmospheric absorption of solar radiation. Since the photoelectric work function for the dust particles varies strongly (from about a few eV for contaminated dust up to about 9 eV for pure ice) depending on the particle origin, we conclude that there are both positively and negatively charged dust particles in the polar summer mesosphere. This fact can be important both for NLC formation and for understanding of V/m mesospheric electric fields nature.

Charging of the dust particles results in significant electron depletion at the night time, while significant ion depletion occurs at day time and even twiligth time. In both cases the diffusive fluxes of electrons and ions are created, the fluxes having a tendency to squeeze the dusty layer. We have shown the mesospheric dusty layers have sharp boundaries and their width is of the order of the observable width of NLC.

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