The idea of an experiment to explore dust clouds in outer space

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Abstract. The idea of a space experiment to create and explore dust clouds in outer space is described. Some estimations of the charge-dynamic characteristics of dust particles ejected into space near the orbit of the Earth outside its magnetosphere are made. For the model of optically transparent rarefied two-component plasma consisting of dust particles and photoelectrons emitted by them, we calculate the equilibrium surface potential of dust particles, depending on their sizes and materials, and also on solar activity. For the model of two initially uncharged particles in the presence of solar wind and short-wave radiation we estimate the characteristic velocities that closely located particles obtain due to charging and electrostatic interaction between them.

1. Introduction

Plasma that contains particles of condensed dispersed phase (dusty plasma) is the most common type of space plasma. Interplanetary space, comets, planetary rings, surfaces of atmosphereless celestial bodies, noctilucent clouds and interstellar nebulae are the examples of environments where electrons, ions and charged dust particles coexist [1–4].

As a result of interaction with ions, electrons and short-wave radiation, dust particles in space acquire an electric charge. In interplanetary space (beyond planetary atmospheres and magnetospheres), the dominant mechanism for charging dust particles is photoelectric emission caused by short-wave radiation of stars. Dust particles, charged due to photoemission, can levitate in electric fields near the surface of space bodies deprived of the atmosphere [5, 6]. If the flows of electrons and ions from the surrounding plasma to the surface of a particle are significant, as, for example, in the upper layers of planetary atmospheres or in the tails of comets, dust particles can carry a negative charge (because of the higher electron mobility). In some cases, it is possible that positively and negatively charged dust particles can coexist [7, 8].

Previously, dust particles were detected in the upper atmosphere of the Earth [9], near the surface of the Moon [10], in comet tails [11], and in interplanetary space [12, 13]. Currently, it is planned to install on board the Luna-25 landing module (the future Russian automatic interplanetary station) a set of devices for the study of the plasma–dust environment of the moon [14]. However, it is not enough to detect individual dust particles to study dynamic processes and collective phenomena occurring in comic dusty plasmas.
Dust particles do not only change the charge composition of a plasma, but also lead to the emergence of some new effects, for example, associated with the dissipation and recombination of the plasma on the surface of particles, particle charge fluctuation, wave propagation, the development of various instabilities, etc [2, 4]. The presence of dust in the interstellar and interplanetary environment influences the radiation characteristics of studied celestial bodies and signals from space objects. Dust particles weaken the radiation, changing its spectral composition and polarization state [3]. Interstellar dust can also affect the thermal balance of interstellar gas [1]. If the energy of interaction between dust particles turns out to be much more than the energy of their thermal motion, it is possible to form ordered structures [4]. Such conditions can be realized, for example, in planetary rings [2, 4]. Physical modeling of plasma–dust formations in outer space can contribute to the understanding of all these phenomena and related processes. However, such experiments have not been conducted until now.

It should be noted that in 1998 the influence of ultraviolet radiation on the dynamics of the dispersed environment under microgravity conditions was studied on board of Mir orbital station [15]. However, the experimental conditions realized on board an orbital space station are far from the conditions under which dusty plasma exists in outer space.

This article describes the idea of a space experiment to create and explore plasma–dust clouds in outer space. Some estimations of the charge-dynamic characteristics of dust particles ejected into space near the orbit of the Earth outside its magnetosphere are presented.

2. The idea of a space experiment
Dust ejection into space can be carried out with the help of the transport-launching container installed on an automatic interplanetary station or a cargo spacecraft for future lunar missions used in unmanned mode. The optimal experimental platform for conducting space experiments in a low-earth orbit is the Progress cargo spacecraft. In order to ensure the normal operation of all onboard systems, the transport-launching container can be separated from the spacecraft hull to a safe distance, for example, using a retractable rod. After the dust particles are removed from the container, the dust cloud will begin to expand both due to the initial pulses and the electrostatic interaction forces arising as they are charged. Dust cloud monitoring can be carried out on board of the spacecraft using video cameras, as well as by sounding in the radio frequency and optical ranges. A fairly large size of dust particles (\(\sim 1–100~\mu m\)) allows for visual observation of the trajectories of some individual particles. This will allow us to investigate the phenomena occurring in dusty plasma at the kinetic level.

3. Photoelectric charging of dust particles in space
In this article, we restrict ourselves to the charging process of dust particles in outer space outside the magnetosphere of the Earth. Under these conditions, the particles are exposed to both the solar wind flow and solar short-wave radiation.

Short-wave radiation causes photoelectron emission from the illuminated surface of the dust particle. The flux density of photoelectrons from a surface normally exposed to the solar spectrum is equal to \(j_{pe,0} = YJ\), where \(Y\) is some effective value, which depends on the quantum yield and the work function of the electron yield, and about equal close to 1 for metals and about 0.1 for dielectrics, \(J = 2.5\times10^{10}d^{-2}~cm^{-2}s^{-1}\) for medium solar activity [16], where \(d\) is a distance from Sun, measured in astronomical units. Let us note that the solar activity \(J\) may increase more than 3 times at the maximum, and 10 times during a solar flare [17]. Therefore, for further calculations of the dust particle charge in the vicinity of the orbit of the Earth, we will vary the value \(j_{pe,0}\) in the range from \(2.5 \times 10^{9}\) to \(2.5 \times 10^{11}~cm^{-2}s^{-1}\). The average energy of electrons emitted from the surface of particles when exposed to solar radiations may be characterized by a temperature 1–3 eV for most materials [2]. Further, for definiteness, we assume 2 eV.
Solar wind in the vicinity of the orbit of the Earth has an average velocity \( V_{sw} \approx 500 \text{ km/s} \) and the following characteristic concentrations and temperatures of protons (i) and electrons (e) \([18]\): \( T_i \approx T_e \approx 10 \text{ eV} \), \( n_i \approx n_e \approx 5-10 \text{ cm}^{-3} \). Because the thermal velocities of the protons and electrons of the solar wind are approximately 50 and 2000 km/s, respectively, the flow of ions and electrons relatively to the dust particles ejected from the transport container are supersonic (with the Mach number \( M \approx 10 \)) and subsonic, respectively. In this case, the Debye radius is determined only by the parameters of the electron plasma component: \( \lambda = \sqrt{kT_e/4\pi e^2n_e} \approx 1000 \text{ cm} \), where \( e \) is the charge of electron, \( k \) is the Boltzmann constant.

The photoemission current is dominant for the conditions described above. Therefore, the dust particle will have a positive charge. The kinetics of charging is determined by the following equation:

\[
\frac{\partial Z}{\partial t} = I_e + I_i - I_{pe},
\]

where \( Z \) is the number of elementary charges (e) accumulated on the surface of the dust particle, and the currents of ions and electrons of the solar wind \( (I_i \text{ and } I_e) \), as well as photoelectrons \( (I_{pe}) \) are given in the following form \([4, 16]\):

\[
I_e = -\pi a^2 e n_e \sqrt{8kT_e \pi m_e} \left( 1 + \frac{\left| \phi_s e \right|}{kT_e} \right),
\]

\[
I_i = \pi a^2 e n_i \sqrt{2kT_i \pi m_i} \left( 1 - \frac{\left| \phi_s e \right|}{kT_e M^2} \right) \approx \pi a^2 e n_i V_{sw},
\]

\[
I_{pe} = -\pi a^2 j_{pe,0} \exp \left( -\frac{\left| \phi_s e \right|}{kT_{pe}} \right),
\]

provided that the floating potential of the particle surface \( \phi_s = eZ/a \geq 0 \). Here \( a \) is the radius of the dust particle, \( m_e(i) \) is the mass of electrons and protons, respectively. Note that in this work we neglect secondary electron emission, although under certain conditions it can play a significant role \([16]\).

The results of the numerical solution of equation (1) are presented in figure 1 for a micron-size particle with different values of the flux density \( j_{pe,0} \) of photoelectrons from its surface. The charge of the particle changes until the flows of electrons and ions on its surface are equal. The electrostatic potential of the particle surface reaches its equilibrium value through \( \approx 100 \text{ s} \). The time \( \tau \) required to achieve it, unlike the equilibrium potential, depends on the size of the dust particle. Because \( eZ = \phi a \), and \( dZ/dt \propto a^2 \), then \( \tau \propto 1/a \).

Let us now consider an extended optically transparent dust cloud illuminated by the Sun. In order for the dispersed medium to be transparent to external radiation, its optical density must satisfy the condition:

\[
2\pi a^2 n_p H < 1,
\]

where \( n_p \) is the average concentration of dust particles and \( H \) is the characteristic size of the medium. Since photoemission of electrons is the dominant mechanism of charging, for simplicity of subsequent estimates we exclude solar wind from our model. In this case, the system under consideration is a rarefied two-component plasma consisting of dust particles and electrons emitted by them. The equilibrium charge \( Z \) of the particle, expressed in elementary charges, averaged over the ensemble, can be determined from the balance of the emission and external electronic currents:

\[
I_e = I_{pe},
\]

where \( I_e \) is set by equation (2), which now indicates the concentration \( n_e \) of photoelectrons. Then, using the quasineutrality condition

\[
Z n_p = n_e,
\]
Figure 1. The electrostatic surface potential $\phi_s = eZ/a$ of an initially uncharged micron-sized particle ($a = 1 \mu m$) depending on the dielectric properties of the material and the solar activity. Solid blue curve corresponds to dielectric grain under moderate sun, the dashed green curve corresponds to metal grain under moderate sun, dashed red—metal grain and solar flare).

Figure 2. The dependence of the equilibrium surface potential of dust particles $\phi_s^*$ in a cloud on the concentration of dust particles $n_p$ for different particle sizes and materials, as well as the intensity of solar radiation. Bold solid curves demonstrate the potential of particles with $1 \mu m$ size, thin curves—$100 \mu m$. Blue curves correspond with dielectric grains under moderate sun, green—metal grains under moderate sun, red—metal grains and solar flare. The dashed lines indicate the potential corresponding to the value $Z = 1$ for the particles of the appropriate size.
Figure 3. The history of velocities $\dot{x}/2$ that two initially uncharged micron-sized particles ($a = 1 \mu m$) obtain due to charging and electrostatic interaction between them for different initial interparticle distance: $x_0 = 2a$ (bold curves), $x_0 = 200a$ (dashed line). Blue color correspond with metal grains under moderate Sun (material density is 2.7 g/cm$^3$); black—dielectric grains under moderate Sun (1.5 g/cm$^3$); green—metal grains and solar flare (19.35 g/cm$^3$); red—metal grains and solar flare (2.7 g/cm$^3$); yellow—metal grains under moderate Sun (19.35 g/cm$^3$).

and the equality of currents (6), we obtain an equation for the equilibrium surface potential of dust particles $\phi^*_s$ in a cloud:

$$\phi^*_s \left(1 + \frac{e\phi^*_s}{T_e} \right) \exp \left( \frac{e\phi^*_s}{T_e} \right) = \sqrt{\frac{\pi e^2 m_e}{8 T_e}} \frac{j_{pe,0}}{n_0 a},$$

(8)

where it is taken into account that the rate of recombination of electrons on dust particles significantly exceeds the rate of thermal losses of their energy due to collisions with neutrals, $T_e \approx T_{pe}$. The illustration of the dependence of the surface potential $\phi^*_s$ on the concentration of dust particles is shown in figure 2 for different particle sizes, materials and solar activity.

4. Dynamics of two initially uncharged dust particles

Let us consider a system of two identical spherical particles with radius $a$ and masses $m$ located in the vicinity of the Earth in the solar wind and under the influence of ultraviolet radiation. The particles are not initially charged and are at a distance $x_0$ from each other. Solving equations (1)–(4) together with the equation of motion:

$$m\ddot{x} = 2F(t),$$

(9)

we determine the characteristic velocities that the particles can obtain due to electrostatic interaction between them. Here $x(t)$ is the interparticle distance, $F(t) = -eZ\partial \phi/\partial x$ is the force of the interparticle interaction, where $\phi(x)$ is the potential of the electrostatic field generated by the particle.

As it is known, the body moving in a plasma creates a perturbed region (a wake). The space body, which is in the vicinity of the orbit of the Earth, but beyond the limits of the
Figure 4. The resulting velocities $0.5\dot{x}|_{t\to\infty}$ that two initially uncharged particles can obtain depending on the normalized initial interparticle distance $x_0/(2a)$ at $a = 1$ (thick lines) and 100 $\mu$m (thin lines). Blue color corresponds to metal grains under moderate Sun (material density is 2.7 g/cm$^3$); black—dielectric grains under moderate Sun (1.5 g/cm$^3$); red—metal grains and solar flare (2.7 g/cm$^3$); grey—hollow dielectric particles under moderate Sun (0.1 g/cm$^3$).

5. Conclusions

The history of velocities $\dot{x}/2$ and the resulting velocities $0.5\dot{x}|_{t\to\infty}$ that two initially uncharged particles can obtain due to charging and electrostatic interaction between them are shown in figures 3 and 4, respectively, for different conditions of the solar activity, particle sizes, materials and the initial interparticle distances.

Estimates of the charge-dynamic characteristics of dust particles ejected into space in the vicinity of orbit of the Earth outside its magnetosphere are obtained. For the model of optically transparent rarefied two-component plasma consisting of identical dust particles and photoelectrons emitted from them due to solar radiation, we calculated the values of the magnetosphere of the Earth, has an equilibrium surface potential of 5–10 V [16]. This is much less than the kinetic energy of the proton flux, usually $\sim 1$ keV. Therefore, the charge of the dust particle does not affect the structure and shape of the wake, and its characteristic thickness is determined by the size of the dust particle. Therefore, to specify the interparticle interaction in the problem of the dynamics of two particles we can restrict ourselves to the simple Debye–Hückel potential:

$$\phi(x) = \frac{eZ}{x} \exp \left( -\frac{x}{\lambda} \right).$$

(10)

The idea of a space experiment of creation and study of dust clouds in the open space is described. These studies will be for understanding the processes occurring in dust accumulations in space, in the upper layers of planetary atmospheres, near the surfaces of atmosphereless celestial bodies, etc.
equilibrium surface potential of dust particles. According to this model, conductive dust particles will acquire an average charge $Z < 1$ when their concentration exceeds $300 \text{ cm}^{-3}$ at moderate solar activity.

We also considered the dynamics of two initially uncharged particles in the presence of solar wind and short-wave radiation. The characteristic velocities that the closely located aluminum particles with a radius of $1–100 \mu\text{m}$ can obtain at moderate solar activity are $0.4–0.5 \text{ cm/s}$. To study the evolution of a dust cloud due to the forces of electrostatic nature, it is necessary that the initial velocities of particles (resulting from the ejection) are much less than the characteristic values of the velocities acquired by the initially resting particles due to the electrostatic interaction.

It should be noted that when considering the evolution of the dense dust cloud, it is necessary to take into account a non-uniform illumination by the Sun, as well as wake effects associated with the interaction of the solar wind with the cloud. As a result the positively and negatively charged dust particles can coexist in the cloud. The solution of this interesting problem may be the topic for future research.

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