Lunar dusty plasma: A result of interaction of the solar wind flux and ultraviolet radiation with the lunar surface

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Abstract. One of the main problems of future missions to the Moon is associated with lunar dust. Solar wind flux and ultraviolet radiation interact with the lunar surface. As a result, there is a substantial surface change and a near-surface plasma sheath. Dust particles from the lunar regolith, which turned in this plasma because of any mechanical processes, can levitate above the surface, forming dust clouds. In preparing of the space experiments “Luna-Glob” and “Luna-Resource” particle-in-cell calculations of the near-surface plasma sheath parameters are carried out. Here we present some new results of particle-in-cell simulation of the plasma sheath formed near the surface of the moon as a result of interaction of the solar wind and ultraviolet radiation with the lunar surface. The conditions of charging and stable levitation of dust particles in plasma above the lunar surface are also considered.

1. Introduction

Usually, when an object immersed in a plasma environment, the equilibrium charge of its surface is determined by the primary electron and ion currents to the surface. However, there are some environments where secondary electron currents from the surface, such as, photoemission, thermionic emission and secondary electron emission, are the main charging mechanisms [1, 2].

The surface of the Moon, as well as the surface of any space body without an atmosphere, is subjected to the solar wind and ultraviolet radiation induced photoemission. As a result, a charge appears on the surface (positive on the illuminated side and negative on the night side) and electric fields near it are induced [1,3]. Dust particles from the lunar regolith occurring in the near-surface plasma owing to certain mechanical processes (e.g., action of micrometeorites or electrostatic forces) can levitate over the surface, forming dusty plasma clouds [4]. The existence of electrostatic mass transfer of lunar dust was assumed long before the first flight to the Moon [5]. The first experimental data confirming the presence of levitating dust particles over the surface of the Moon were obtained by the Surveyor 5 lunar lander and the astronauts of Apollo 17 [6, 7]. The aggressive action of the lunar dust is one of the main problems for future missions to the Moon [8, 9]. Charged microparticles of lunar regolith adhere to any surface,
contaminating it and reducing the service life of mechanisms and devices [9]. Furthermore, lunar dust is very dangerous to human health [8,10]. Therefore, new experimental and numerical data on the electrodynamic properties of the medium and conditions of levitation of dust particles near the surface of the Moon are necessary.

In this work, a photoinduced plasma layer near the surface of the Moon has been numerically simulated for various parameters of the solar wind. The conditions of the charging and stable levitation of dust particles near the illuminated surface of the Moon are analyzed.

Since the photoelectron current dominates in the process of charging of the illuminated part of the surface of the Moon, the calculation results depend significantly on the choice of the photoemission parameters. It is noteworthy that the existing data on the photoemission properties of lunar soil are diverse. In particular, the photoemission properties of the lunar regolith samples delivered by the Apollo missions were experimentally studied in [11]. The integration of the quantum yield and energy distribution of photoelectrons from lunar dust particles irradiated by monochromatic radiation with the spectrum of moderate solar radiation showed that the photoelectron current density is $j_{pe,0} = 4.5 \times 10^{-10}$ A/cm$^2$, and the energy spectrum of photoelectrons can be approximated by the Maxwellian distribution function with the temperature $T_{pe} \approx 2$ eV. At this photocurrent, the density of photoelectrons near the normally illuminated surface can be estimated as $n_{pe,0} = 2j_{pe,0}m_e/2T_{pe} \approx 100$ cm$^{-3}$ (where $m_e$ is the mass of the electron). In this case, the screening length is $\lambda_{pe,0} \approx 100$ cm.

2. Numerical simulation

The plasma layer formed near the surface of the Moon because of the action of ultraviolet radiation and solar wind was simulated with the 2D(XZ) version of the KARAT relativistic electromagnetic code including all three components of electromagnetic fields and momenta of particles [12]. This code is based on the particle-in-cell method and was developed to simulate electrodynamic plasma processes. The computational cell was a rectangle whose lower boundary corresponds to the lunar surface, has photoemission properties, and absorbs all particles incident on it, accumulating a surface charge. The flux of electrons and ions of the solar wind with certain distribution functions was injected to the upper boundary (generally, at the angle $\theta$ to it). Periodic boundary conditions were specified along the horizontal direction. The calculations were performed for the time $t \approx 100/\omega_{sw}$ (where $\omega_{sw}$ is the plasma frequency of the unperturbed solar wind), which is necessary for the effective damping of plasma oscillations appearing at the initial stage of the solution of the problem. For the correct calculation of the boundary photoelectron layer, the grid step did not exceed $\sim 0.2\lambda_{pe,0}$. In this case, the distance between the upper and lower boundaries of the calculation region $L_z$ was determined by the condition $L_z \gg \max[\lambda_{pe,0}, \lambda_{sw}]$ (where $\lambda_{sw}$ is the screening length in the plasma of the quasi neutral solar wind). In our case, it varied from 60 to 100 m. The computational cell is shown in figure 1. In this stage of the work, the problem was solved in the quasi 1D formulation, where variation of physical quantities in the horizontal direction was disregarded. We consider only the case of the normal incidence of the flux of the solar wind on the flat surface ($\theta = 90^\circ$).

The simulated photoelectron flux from the surface had a half-Maxwellian distribution with the temperature $T_{pe} = 2$ eV and photocurrent density $j_{pe,0} = 4.5 \times 10^{-10}$ A/cm$^2$. In order to analyze the effect of the solar wind on the formation of the surface photoelectron layer, a quasi neutral electron-ion (proton) flux with a half-Maxwellian distribution and drift velocity was introduced to the system through the upper boundary of the calculation region. The flux of the solar wind is conditionally divided into fast and slow components. The fast wind originates from the solar poles and the source of the slow wind is the equatorial region [13]. In our calculations, electrons and ions imitating the flux of the slow solar wind were introduced into the calculation region with the temperatures $T_{we} = 8$ eV and $T_{wi} = 16$ eV, respectively; drift velocity $u = 350$ km/s; and initial concentrations $n_{we,0} = n_{wi,0} = 12$ cm$^{-3}$. The fast solar wind was simulated
with the plasma parameters $T_{we} = 12$ eV, $T_{wi} = 4$ eV, $u = 750$ km/s, and $n_{we,0} = n_{wi,0} = 4 \times 10^{3}$ cm$^{-3}$. We also performed calculations with the averaged parameters of the solar wind [13] $T_{we} = T_{wi} = 10$ eV, $u = 550$ km/s, and $n_{we,0} = n_{wi,0} = 10$ cm$^{-3}$. The effects of the interaction of the lunar surface with the plasma of the Earths magnetosphere tail are neglected because this interaction is significant only for the dark side of the Moon. The phase diagram illustrating the dependence of the vertical component of the velocity $V_z$ of plasma particles on the distance from the lower boundary of the calculation region is shown in figure 2. It can be easily seen that electrons of the solar wind near a positively charged surface are accelerated, whereas the dynamics of supersonic ions does not change.

3. Results and discussion
The calculated vertical density distribution of plasma components (photoelectrons, electrons, and ions of the solar wind) is shown in figure 3a. It was found that the quasi neutrality of the electron ion flux is violated at a distance of $\sim 30\lambda_{pe,0}$ from the surface. For comparison, the photoelectron density distribution obtained numerically in the absence of a directed flux of ions and electrons is added in figure 3a. At heights above $(5\div6)\lambda_{pe,0}$, the solar wind noticeably affects the density of the photoelectron layer. The dependence of the electric field $E$ on the distance from the surface $z$ is shown in figure 3b. Here and below, the electric field strength is treated as its vertical component. In contrast to the problem including only a single component photoelectron plasma (see, e.g., [14, 15]), the inclusion of the flux of the solar wind results in the appearance of a height range where the electric field is negative (see inset in figure 3b). The stable levitation of positively charged lunar dust particles is impossible in this range. Such a nonmonotonic behavior of the electric field was analytically predicted in [16].

For the stable levitation of charged lunar dust particles appearing in the plasma layer near the surface of the Moon owing to certain processes, the balance condition $Mg = qE$ for the gravitational and electrostatic forces should be satisfied. Here, $M$ is the mass of a dust particle and $g = 1.62$ m/s$^2$ is the gravitational acceleration on the lunar surface. The equilibrium
Figure 3. Vertical distributions of (a) the density of plasma particles and (b) electric field. The thick lines correspond to the numerical model including the average flux of electrons and protons of the solar wind (SW). The thin line is a one component plasma model (only photoelectrons).

The charge $q$ of the particle is determined by zero sum of microscopic currents of photoelectrons emitted by the particle, electrons and ions of the solar wind, and photoelectrons of the near-surface photoelectron sheath. To calculate the charge $q$ and to determine the height of its stable levitation over the lunar surface, we used well-known equations for instantaneous microscopic currents of electrons and ions to a spherical dust grain [1], [14], [17] and the obtained KARAT data on plasma density.

Figure 4 shows how stable levitation height of a dust particle depends on its size (diameter) for various parameters of the solar wind. We took a value of $3 \text{ g/cm}^3$ for the lunar regolith density. Dust particles may stably levitate at altitudes from $\sim 2$ to $\sim 15$ meters, depending on particle sizes and plasma parameters. Stable levitation is possible only for particles smaller than $\sim 0.5$ microns at that. The upper limit of the altitude range is related to the negative electric field zone (in which levitation of positively charged particles is not possible) related to interaction of the solar wind with the photoelectron sheath (see figure 3b). The lower limit is due to a high concentration of photoelectrons, which reduce the grain charge.

For comparison, figure 4 shows the stable levitation height of dust particles calculated in [18] for various photocurrents corresponding to various periods of the solar cycle (at the maximum of solar activity, the photocurrent can increase to $j_{pe,0} = 15 \times 10^{-10}$ A/cm², whereas it can reach $j_{pe,0} = 40 \times 10^{-10}$ A/cm² during solar flares). Our numerical data are in qualitative agreement with the results obtained previously in [18]. Their quantitative difference is explained by the fact that the problem was solved in [18] in the 1D formulation, where the anisotropy of the semi-infinite plasma near the absorbing surface was not taken into account. In such a plasma, particles from the tail of the Maxwellian distribution moving along the normal perish on the surface more rapidly than particles moving along the surface. Therefore, the inclusion of all three components of the momentum of particles is important for the correct simulation. Furthermore, the energy distribution of photoelectrons in [18] differed from the Maxwellian distribution primarily in the absence of particles with energies $> 6$ eV, which should lead to a relatively lower electric field.

In addition, figure 4 also shows the equilibrium positions of a dust particle in the photoelectron
Figure 4. Stable levitation height of a dust particle and its size. The thick lines are our numerical calculations for the photocurrent corresponding to a moderate solar activity ($j_{pe,0} = 4.5 \times 10^{-10}$ A/cm$^2$) and various parameters of the solar wind (SW). The thin lines are data [18]. The points are the results of calculations [14] for the photoelectron layer.

sheath which parameters were calculated analytically in [14]. In this case, the stable levitation height of charged particles has no upper bound because the system of equations consisting of the kinetic equation for the photoelectron distribution function and the Poisson equation for the electrostatic potential was solved in [14] excluding the ion and electron components of the solar wind. Another reason for the differences between the values of stable levitation heights of dust particles is that the authors of [14] have estimated the photocurrent on the basis of the semi-empirical model of the photoelectron quantum yield of the Earth’s basalt rocks [15]. The quantum yield in [15] for photons with energies close to the work function is six or seven orders of magnitude different from the value experimentally measured for lunar soil samples in [11]. A detailed discussion of the problem of the parameters of photoelectrons emitted from the lunar surface is beyond the scope of this work. We emphasize that this problem is still open and requires further investigations.

4. Conclusions
To summarize, we have obtained new numerical data on the parameters of the dusty plasma layer formed near the surface of the Moon under the action of ultraviolet radiation, as well as the fast and slow solar wind. The conditions of the charging and stable levitation of dust particles in the surface plasma layer of the Moon have been analyzed. The numerical calculations including the photoemission properties of the lunar regolith sample delivered to the Earth have been compared to the estimates within the known theoretical models. It has been shown that the flux of the solar wind noticeably affects the photoelectron density distribution and electric field near the illuminated part of the lunar surface. In contrast to the existing analytical models of the photoelectron layer developed in the single component plasma approximation, according to the self-consistent numerical calculation of the surface photoelectron layer including the plasma flux of the solar wind, the region where the electric field changes sign and stable levitation of positively charged dust particles is impossible is formed at heights where the photoelectron density becomes lower than the electron density of the solar wind. It is shown that the height range of stable levitation and the maximum size of levitating dust particles are equally depend on both cyclic changes in the ultraviolet part of the solar spectrum, and variations of the solar wind parameters.
Acknowledgments
This work was supported by the Ministry of Education and Science (grant No. MK-7932.2015.8), the Russian Foundation for Basic Research (grant No. 15-32-21159) and by the Presidium of the Russian Academy of Sciences.

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