Meteoroid impacts and dust particles in near-surface lunar exosphere

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Abstract. It is shown that for consideration of dust particle release from the lunar surface one has to take into account (among other effects) both adhesion and meteoroid impacts. The effect of surface roughness on the adhesion intensity on the Moon is discussed. The rate of meteoroid impacts with the lunar surface per unit area is determined. The strength of the regolith due to the adhesion effect is estimated. The processes occurring when a high-speed meteoroid impacts with the lunar surface are described. In particular, the characteristic parameters of zones of evaporation of the substance, its melting, destruction of particles constituting lunar regolith, their irreversible deformations, and elastic deformation of the regolith substance are found. A possibility of the rise of micrometer-sized dust particles above the lunar surface is shown. It is demonstrated that most of the particles rising over lunar surface due to the meteoroid impact originates from the elastic deformation zone. The number of dust particles raised over the lunar surface as result of meteoroid impacts is calculated. The size-distribution function of particles released from the lunar surface due to meteoroid impacts is determined. It is noted that micrometeoroid impacts can result in rise of dust particles of the size of a few µm up to an altitude of about 30 cm that explains the effect of “horizon glow” observed by Surveyor lunar lander.

1. Introduction
It is now almost universally accepted that the dust in the lunar exosphere is a component of a plasma-dust system (see, e.g., [1–14]). The discovery of the dust in the lunar exosphere was made in post-sunset Surveyor lunar lander TV camera images of the lunar horizon. These Surveyor images revealed the presence of a near-surface (e.g., scale height of \∼\ 10–30 cm) glow [15]. This effect was related to sunlight scattering giving rise to “horizon glow” and “streamers” in the lunar exosphere [16]. Subsequent investigations have shown that the sunlight was most likely scattered by electrostatically charged micrometer dust grains originating from the lunar surface [17]. During the Apollo missions, 0.1 µm scale dust was observed up to about 100 km altitude. Similar conclusions can be made from recent observations of the LADEE lunar orbital spacecraft [18].
There are also some indirect manifestations of lunar dust. The Soviet Luna 19 and 22 spacecraft conducted a series of radio occultation measurements to determine the line-of-sight electron column concentration, or total electron content, above the limb of the Moon as a function of tangent height \[19, 20\]. From these measurements they inferred the presence of a “lunar ionosphere” above the sunlit lunar surface with peak electron concentrations \(n_e \sim 500–1000 \text{ cm}^{-3}\) and scale heights of \(\sim 10–30 \text{ km}\). These values are broadly consistent with those inferred from lunar occultation measurements of the Crab Nebula in which radio waves were refracted in the vicinity of the Moon \[21, 22\]. The electrically charged exospheric dust could contribute to such high electron density populations \[3\].

The description \[4–14\] makes clear some features of dusty plasma system over the Moon. However, there are unsolved problems concerning its parameters and manifestations \[11\]. In particular, significant uncertainty exists as to the physical mechanism through which dust particles are released from the surface of the Moon. Adhesion has been identified as a significant force in the dust particle launching process which should be considered to understand particle launching methods \[23\]. The problem of the dust particle release from the lunar surface can be solved, for example, by considering meteoroid impacts onto the surface of the Moon. Here, we consider lunar dust particle launching process due to meteoroid impacts. A significant attention is paid to the importance of the adhesive force.

### 2. The force of adhesion

In \[23\] dust particles with smooth surfaces have been considered. The effect of surface roughness \[24\] results in significant attenuation of the effect of adhesion in comparison with the results given by \[23\]. Indeed, the calculation \[25\] of the force of adhesion between a plane with an asperity of the radius \(r\) and a spherical particle of radius \(a\) gives

\[
F_{\text{adh}} = \frac{AS^2}{24\Omega^2} \left( \frac{ra}{r+a} + \frac{a}{1 + rS^2/(2\Omega)} \right),
\]

where \(A\) is the Hamaker’s constant, \(S\) is the surface cleanliness, and \(\Omega = 0.132 \text{ nm}\) characterizes the diameter of oxygen ion. For lunar regolith Hamaker’s constant is \(4.3 \times 10^{-20} \text{ J}\); surface cleanliness varies in the range of 1 to 0 and for lunar dayside is calculated as \(S = 0.88\) while for lunar nightside \(S = 0.75\) \[26\] that is determined by the gas constituents in the lunar exosphere. Equation (1) corresponds to the fact that adsorption characterized by the surface cleanliness influences strongly the adhesion properties of surfaces. On the Moon (under the conditions of low pressures) small width \(t \equiv \Omega/S\) of layers of adsorbed atoms and molecules results in large magnitudes of adhesion attraction forces. Adequate consideration of the adhesion effect is important for the description of the plasma-dust system in the lunar exosphere which will be studied in the future space missions Luna-25 and Luna-27 \[5, 11\].

Calculations based on the equation (1) show that the effect of roughness results in two-three orders of magnitude attenuation of the effect of adhesion in comparison with the case (considered in \[23\]) of a smooth particle (figure 1). Nevertheless, even considering the roughness of lunar regolith particles, the electrostatic forces required to launch dust particles from the lunar surface, as a rule, do not exceed the adhesive forces. Dust particle launching can be explained \[9\] if the dust particles rise at a height of about dozens of nanometers owing to some processes (e.g., meteoroid impacts, etc.). This is enough for the dust particles to acquire charges sufficient for the dominance of the electrostatic force over the gravitational and adhesive forces, and finally to rise above the lunar surface.

### 3. Meteoroid impacts

The number of impact events with the lunar surface is determined by the meteoroid flux. In \[27\], the dependencies of \(F_i(m_i)\) of the meteoroid flux density in Earth’s space environment (which
Figure 1. Dependence of the normalized force of adhesion (to that in the absence of asperity \([23]\)) on asperity size \(r\) for the particles with the sizes of 100 nm, 1 \(\mu\)m, and 10 \(\mu\)m under the conditions of the dusty plasma system at the lunar surface.

is analogous to the flux of impactors with the lunar surface) are given for meteoroids with the masses larger than \(m_i\). We use these dependencies for our analysis. We represent the distribution function of the impactors over the masses and the speeds as the product of the function \(f_m(m_i)\), which depends on the meteoroid mass \(m_i\), and the function \(f_u(u_i)\), which depends on the meteoroid speed \(u_i\). In this approximation we have

\[
F_i(m_i) = \int_{m_i}^{+\infty} f_m(m)dm \int_0^{+\infty} u f_u(u)du, \tag{2}
\]

where \(f_u(u_i)\) is the normalized velocity-distribution function

\[
\int_0^{+\infty} f_u(u)du = 1, \tag{3}
\]

while \(f_m(m_i)dm_i\) gives the number density of the impactors in the range of \(m_i\) to \(m_i + dm_i\). The averaged impactor speed is determined as

\[
\langle u_i \rangle = \int_0^{+\infty} u f_u(u)du. \tag{4}
\]
The velocity-distribution function \( f_u(u_i) \) of the impactors has three local maxima (at \( u_i = 18, 50, \) and 63 km/s (figure 2). The averaged speed is \( \langle u_i \rangle \approx 27 \) km/s.

The rate of meteoroid impacts with the lunar surface per unit area is determined by the value \( N_i \approx 100 \) m\(^{-2}\)day\(^{-1}\). Most of the impacts is realized by meteoroids of sub-micrometer and micrometer sizes.

We consider an impact of a high-speed meteoroid with the lunar surface when the specific energy of the imactor \( u_i^2 / 2 \) is much larger than the binding energy of atoms and molecules of substances of the impactor and lunar regolith. This assumption is valid because the binding energy is of the order of 10 MJ/kg, while the specific energy of the imactor \( u_i^2 / 2 \sim \langle u_i \rangle^2 / 2 \approx 360 \) MJ/kg. When a high-speed meteoroid impacts with the lunar surface the substances of the impactor and the target are strongly compressed and heated. Under the action of high pressure strong shock wave is formed. The shock propagates and weakens moving away from the impact epicenter. Finally the weakening shock transforms into linear acoustic wave. The zones (around the impact epicenter) of evaporation of the substance (the zone I), its melting (the zone II), destruction of particles constituting lunar regolith (the zone III), their irreversible deformations (the zone IV) are formed due to the propagation of the weakening wave (figure 3). Beyond the zone IV of irreversible deformations the zone V of elastic deformation is created which is characterized by the magnitudes of the pressure in acoustic wave less than dynamic limit of elasticity.

Assuming that the acoustic speed in the unperturbed regolith is \( c_0 = 300 \) m/s, the density in the upper layer of the regolith is \( \rho_0 \approx 1.4 \) g/cm\(^3\), and analyzing the shock wave propagation one can determine the radii of the zones I, II, and IV, \( r_I \approx 0.24 u_i^{2/3} a_i \), \( r_{II} \approx 0.45 u_i^{2/3} a_i \), \( r_{IV} \approx 1.3 u_i^{2/3} a_i \), where \( a_i \) is the impactor radius and \( u_i \) is calculated in units of km/s. The

\begin{figure}
\centering
\includegraphics[width=\textwidth]{velocity_distribution}
\caption{The velocity-distribution function of meteoroids impacting the lunar surface.}
\end{figure}
Figure 3. Scheme characterizing the formation on lunar surface around the impact epicenter of zones of evaporation of the substance (I), its melting (II), destruction of particles constituting lunar regolith (III), their irreversible deformations (IV), elastic deformation of the regolith substance (V).

maximum pressure $p_m$ in the acoustic wave at the distance of $r_{IV}$ from the impact epicenter is

$$p_m(r_{IV}) = \rho_0 c_0^2 \approx 0.13 \text{ GPa}. \quad (5)$$

4. Dust particle release

The size-distribution of the lunar regolith particles is in a good agreement [4] with the Kolmogorov distribution

$$\Phi_K(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left(-\frac{y^2}{2}\right) dy, \quad (6)$$

which characterizes materials subjected to multiple crushing. Here, $t = (\ln a - \ln(a_K))/\sigma_K$, $a$ is the characteristic size of the particle, $a_K = 61.56 \mu m$, $\sigma_K = 1.29$. $\Phi_K(t)$ is the probability to find a particle of lunar regolith with the radius less than $a$. 
Table 1. The number of particles released from the lunar surface per unit of time and unit of area due to meteoroid impacts at different altitudes.

| h, m | 0.1 | 1   | 10  |
|------|-----|-----|-----|
| N, m$^{-2}$day$^{-1}$ | 65  | 20  | 7   |

Let us introduce the normalized size-distribution function $\phi_0(a)$ of particles in the surface layer of the lunar regolith,

$$
\phi_0(a) = \frac{d\Phi_K}{dt} \frac{dt}{da} = \frac{1}{\sqrt{2\pi\sigma_Ka}} \int_{-\infty}^{t} \exp\left(-\frac{(\ln(a) - \ln(a_K))^2}{2\sigma_K^2}\right)dy,
$$

(7)

$$
\int_0^\infty \phi_0(a) da = 1.
$$

(8)

The knowledge of the distribution function $\phi_0(a)$ allows us to determine the strength of the lunar regolith caused by the adhesion forces (1). These forces prevent a particle to be separated from the lunar surface. The strength of the regolith is

$$
\sigma_{adh} = 2n_0 \int_0^\infty F_{adh} a \phi_0(a) da,
$$

(9)

where $n_0$ is the number density of particles in the lunar regolith. Calculating the value of $\sigma_{adh}$ for $\rho_0 \approx 1.4$ g/cm$^3$ we find for the lunar surface $\sigma_{adh} \approx 7 \times 10^{-3}$ Pa.

Considering the balance between the maximum force of pressure in the blast wave, which is characterized by the relationship (5), and the sum of the adhesive force, which is characterized by the relationship (9), electrostatic and gravitational forces, we determine the radius $r_B$ of the zone around the impact epicenter which restricts the region where dust particles are released from the surface of the Moon due to meteoroid impacts. For $c_0 = 300$ m/s and $\rho_0 \approx 1.4$ g/cm$^3$ we find $r_B \approx 1.8 \times 10^3 u_r^{2/3} a_i$. This value is much larger than $r_{IV}$. Thus one can conclude that most of the particles rising over lunar surface due to the meteoroid impact originates from the elastic deformation zone. Following [28] we estimate the depth of spallation layer, i.e. the layer where fragments from the surface of lunar rock are separated by interaction with a compression wave

$$
w = 0.5c_0 \tau_+ \quad \text{if} \quad r > r_{IV},
$$

(10)

where $\tau_+$ is the time of positive phase ($u_r > 0$) in the blast wave, $u_r$ is the horizontal component of velocity in the blast wave. We note that in addition to the compression wave the rarefaction wave is formed when propagating the blast wave. The interaction of the compression and rarefaction waves results in an appearance of vertical component of velocity $u_z$ in the blast wave. For $r > r_{IV}$ we have $u_r = (1 - 1.5)u_z$ [28]. Thus in our calculations we assume $u_r \sim u_z$.

Knowing the depth of spallation layer $w$ and the averaged flux of meteoroids to the lunar surface we calculate the number $N$ of dust particles raised over the lunar surface per unit of time and unit of area due to meteoroid impacts. Table 1 presents the results of the calculation of $N$ at different altitudes $h$.

We see the dependence of $N$ on the altitude $h$. This dependence is caused by different vertical velocities in the blast wave at different stages of its propagation.
Figure 4. The size-distribution function of particles released from the lunar surface due to meteoroid impacts.

The normalized (by unity) size-distribution of the particles raised over the lunar surface as a result of meteoroid impacts is close to the normalized size-distribution function of particles of the surface layer of lunar regolith. Thus using the equation (7), we can determine the normalized (by unity) size-distribution function of particles released from the lunar surface due to meteoroid impacts. Such a distribution function is shown in figure 4.

The normalized distribution function that is shown in figure 4 is valid at different altitudes points out the existence of micrometer-sized dust particles above the lunar surface. This differs the particles raised over the lunar surface as a result of meteoroid impacts from those typical for the consideration of dusty plasmas in the lunar exosphere [6] where dust particles levitating over the lunar surface have nano-scale or sub-micrometer sizes. Consideration of only typical for dusty plasmas processes (excluding strong perturbations like meteoroid impacts) allows us to explain the existence of 2–3 $\mu$m dusts only over the lunar terminator [13]. In all other cases the levitating dust particles are either nano-scale or sub-micrometer those. Thus meteoroid impacts provide a significant source of micrometer-sized dust particles in the lunar exosphere. The sunlight scattered by such micrometer-sized dust grains originated due to meteoroid impacts with the lunar surface can explain the effect of “horizon glow” observed by Surveyor lunar lander.

5. Summary
Thus we have shown that for consideration of dust particle release from the lunar surface one has to take into account (among other effects) both adhesion and meteoroid impacts. We have discussed the effect of surface roughness on the adhesion intensity on the Moon. We have determined the rate of meteoroid impacts with the lunar surface per unit area and estimated the strength of the lunar regolith due to the adhesion effect. We have described the processes
occurring when a high-speed meteoroid impacts with the lunar surface. We have found the characteristic parameters of zones of evaporation of the substance, its melting, destruction of particles constituting lunar regolith, their irreversible deformations, and elastic deformation of the regolith substance. We have shown a possibility of the rise of micrometer-sized dust particles above the lunar surface. In particular, micrometeoroid impacts can result in rise of dust particles of the size of a few µm up to an altitude of about 30 cm that explains the effect of “horizon glow” observed by Surveyor lunar lander. We have demonstrated that most of the particles rising over lunar surface due to the meteoroid impact originate from the elastic deformation zone. We have calculated the number of dust particles raised over the lunar surface as result of meteoroid impacts. We have determined the size-distribution function of particles released from the lunar surface due to meteoroid impacts.

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