Dusty plasmas in the lunar exosphere: Effects of meteoroids

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Abstract. A possibility of the formation in the lunar exosphere of dust cloud due to meteoroid impacts onto the lunar surface is studied. The main attention is paid to the high altitudes over the lunar surface including the range of the altitudes between 30 and 110 km where the measurements of dust were performed within the NASA LADEE mission. From the viewpoint of the formation of dust cloud at high altitudes over the Moon, the most important zone formed by the meteoroid impact is the zone of melting of substance. Only the droplets originated from this zone have the speeds between the first and second astronautical velocities (for the Moon). Correspondingly, only such droplets can perform finite movement around the Moon. The liquid droplets harden when rising over the lunar surface. Furthermore, they aquire electric charges due to the action, in particular, of the solar wind electrons and ions, as well as of the solar radiation. Thus dusty plasmas exist in the lunar exosphere with the characteristic number density $\lesssim 10^{-2}$ m$^{-3}$ of dust particles with the sizes from 300 nm to 1 $\mu$m which is in accordance with the results of measurements performed by LADEE.

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., [1–17]). 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 $\approx 10–30$ cm) glow [18]. This effect was related to sunlight scattering giving rise to “horizon glow” and “streamers” in the lunar exosphere [19]. Subsequent investigations have shown that the sunlight was most likely scattered by electrostatically charged micrometer dust grains originating from the lunar surface [20]. During the Apollo missions 0.1-$\mu$m-scale dust was observed up to about 100 km altitude.

Similar conclusions can be made from recent observations of the Lunar Atmosphere and Dust Environment Explorer (LADEE) (9/2013–4/2014) at the altitudes between 30 and 110 km [21]. The Lunar Dust Experiment (LDEX) onboard the LADEE mission discovered a permanently present dust cloud engulfing the Moon. LDEX is an impact ionization dust detector, it captures coincident signals and full waveforms to reliably identify dust impacts. LDEX recorded average impact rates of approximately 1 and 0.1 hits/minute of particles with impact charges of...
q > 0.5 fC and q > 5 fC, corresponding to particles with radii of \(a > 0.3 \mu m\) and \(a > 0.7 \mu m\), respectively. These LDEX measurements reveal the presence of a tenuous but persistent cloud of small dust grains, from \(< 0.3 \mu m\) to \(> 0.7 \mu m\) in radius. The observed number densities in the cloud range between \((0.4-4) \times 10^{-3}\) m\(^{-3}\). LDEX found no evidence of the expected density enhancements over the terminators where electrostatic processes were predicted to efficiently loft small grains. Furthermore, intermittent density enhancements were observed during several of the annual meteoroid streams, especially during the Geminids. This indicates the correlation between the formation of the dust cloud and meteoroid impacts onto the surface of the Moon.

There are also some indirect manifestations of lunar dust cloud. 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 [22, 23]. From these measurements they inferred the presence of a “lunar ionosphere” above the sunlit lunar surface with peak electron concentrations \(n_e \approx 500-1000\) cm\(^{-3}\) and scale heights of \(\approx 10-30\) 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 [24, 25]. The electrically charged exospheric dust could contribute to such high electron density populations [3].

Here, we consider a possibility of the formation of dust cloud at high altitudes (\(\approx 10-100\) km) over the Moon due to meteoroid impacts onto the lunar surface. Meteoroid impacts can result in rise of dust particles up to the high altitudes. The number density of dust particles at these altitudes is determined by the flux of particles rising over the lunar surface due to the meteoroid impacts which, in turn, is associated with the number of impact events with the surface of the Moon.

In section 2 we describe impact events with the lunar surface, consider the case of continuous gabbro-anorthosite impactor and porous gabbro-anorthosite target, present the conclusions of calculation of the number of dust particles raised over the lunar surface per unit of time and unit of area due to meteoroid impacts and show that the most important zone from the viewpoint of the formation of dust cloud at high altitudes over the Moon is that where the substance is melted due to a meteoroid impact. Section 3 deals with the melt droplets. We estimate their sizes as well as the flux of the droplets and their number density at high altitudes. In section 4 we summarize our results.

2. Meteoroid impacts

The number of impact events with the lunar surface is determined by the meteoroid flux. In [26] the dependencies of \(F_i(m_i)\) of the meteoroid flux density in Earth’s space environment (which 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

\[
F_i(m_i) = \int_{m_i}^{+\infty} f_m(m)dm \int_{0}^{+\infty} u_f(u)du,
\]

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

\[
\int_{0}^{+\infty} f_u(u)du = 1,
\]

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

\[
\langle u_i \rangle = \int_{0}^{+\infty} u f_u(u)du.
\]
Figure 1. The velocity-distribution function of meteoroids impacting the lunar surface.

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 1). 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 $N_i \approx 100 \text{m}^{-2} \text{day}^{-1}$. 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 impactor $u_i^2/2$ 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.

We perform our calculations for the case of continuous gabbro-anorthosite impactor and porous gabbro-anorthosite target. The densities of the impactor and the target before the impact are supposed to be $\rho_{i0} = 3$ g/cm$^3$ and $\rho_{t0} = 1.4$ g/cm$^3$, respectively. The porosity of the target is $k = \rho_{t0}/\rho_{t0} = 2.14$. We suppose also linear dependences between the shock wave speeds $D_{i,t}$ and the mass velocity behind the shock wave front $u$ (see [27]), $D_{i,t} = C_{i,t} + S_{i,t} u$. Here, the subscripts ‘i’ and ‘t’ correspond to the substances of the impactor and the target, respectively; $C_i = 7.71$ km/s, $S_i = 1.05$, $C_t = C_i k/[1 + S_i (k-1)] = 7.51$ km/s, and $S_t = S_i k/[1 + S_i (k-1)] = 1.02$.

Figures 2 to 5 present the dependences on the impactor velocity $u_i$ of the maximum mass speed $u_{\text{max}}$ and the maximum pressure $p_{\text{max}}$ behind the fronts of the shocks in both the impactor and the target, the maximum internal energy of the substance of target $e_{t,\text{max}}$ and impactor $e_{i,\text{max}}$, as well as the compession ratio for the substances of target $\delta_{t,\text{max}} \equiv \rho_{t,\text{max}}/\rho_{t,0}$ and impactor $\delta_{i,\text{max}} \equiv \rho_{i,\text{max}}/\rho_{i,0}$, where $\rho_{i(t),\text{max}}$ is the maximum density of substance behind the shock front.

The zones (around the impact epicenter) of evaporation of the substance (zone I), its melting (zone II), destruction of particles constituting lunar regolith and their irreversible deformations (zone III), nonlinear elastic deformation of the regolith substance (zone IV which is characterized
Figure 2. Dependences of the maximum mass speed behind the fronts of the shocks in both the impactor and the target on the impactor velocity. Solid (dashed) curve corresponds to porous (continous) gabbro-anorthosite target.

Figure 3. Dependences of the maximum pressure behind the fronts of the shocks in both the impactor and the target on the impactor velocity. Solid (dashed) curve corresponds to porous (continous) gabbro-anorthosite target.

by the magnitudes of the pressure in nonlinear acoustic wave less than dynamic limit of elasticity) are formed due to the propagation of the weakening shock wave (figure 6). Beyond zone IV, zone V of linear elastic deformation is present, where acoustic wave can be considered as the linear one.
Figure 4. Dependences of the maximum internal energy of the substance of target and impactor on the impactor velocity. Solid (dashed) curve corresponds to porous (continuous) gabbro-anorthosite target.

Figure 5. Dependences of the compension ratio for the substances of target and impactor. Solid (dashed) curve corresponds to porous (continuous) gabbro-anorthosite target.

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 $\rho_{0i} \approx 1.4$ g/cm$^3$, and analyzing the shock wave propagation one can determine the radii of zones I, II, III, and IV, $r_1 \approx 0.31u_i^{2/3}a_i$, $r_{II} \approx 0.58u_i^{2/3}a_i$, $r_{III} \approx 0.93u_i^{2/3}a_i$, $r_{IV} \approx 1.3u_i^{2/3}a_i$ (confer [16, 17]), where $a_i$ is the impactor radius and $u_i$ is calculated in units of km/s.
Figure 6. 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 and their irreversible deformations (III), nonlinear (IV) and linear elastic deformation of the regolith substance (V). Arrows indicate the ejection of material (in particular, dust particles) at high velocities from the surface of the Moon from zones I to V.

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. In the zone of elastic deformation of the regolith substance (V) the depth of spallation layer is [16, 17]

\[ w_c = 0.5c_0\tau_+, \quad \text{if } r > r_{IV}, \]  

(4)

where \( \tau_+ \) is the time of positive phase (\( u_r > 0 \)) in the shock wave, \( u_r \) is the horizontal component of velocity in the shock wave. We use the linear interpolation for the description of the spallation layer depth within zones I to IV

\[ w(r) = W_0 + \frac{w_c - W_0}{r_{IV}}r, \quad \text{if } r \leq r_{IV}, \]  

(5)

where

\[ W_0 = \frac{2a_i\rho_0\cos\theta}{\rho_0} \]  

(6)

is the depth of the impact epicenter, \( \theta \) is the angle of meteoroid incidence (between the meteoroid speed and vertical directions).
We note that, in addition to the shock compression wave, the rarefaction wave is formed. The interaction of the compression and rarefaction waves results in an appearance of vertical component of velocity \( u_z \) in the shock wave. In our calculations, we assume \( u_r \sim u_z \). In particular, for \( r > r_{IV} \) we have \( u_r = (1-1.5)u_z \) [28]. 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.

The general conclusions of the calculations are as follows:

(i) the mass of dust particles originated from zone V of linear elastic deformations rising over the surface of the Moon owing to the impacts of meteoroids to the altitudes higher than 10 m (1 km) is 80 times (6 times) larger than from the other zones (I-IV);

(ii) the mass of dust particles originated from zones IV and V of elastic deformations rising over the surface of the Moon owing to the impacts of meteoroids to the altitudes higher than 10 km is 4 times larger than from zones I–III;

(iii) only the material from the zones of evaporation of the substance (I), its melting (II), and destruction of particles constituting lunar regolith and their irreversible deformations (III) is released to the altitudes of 100 km and higher;

(iv) the altitude of 700 km is attained only by the material pushed by the shock wave from the zones of evaporation of the substance (I) and its melting (II).

Furthermore, the most important zone from the viewpoint of the formation of dust cloud at high altitudes over the Moon is that of melting of the substance (II). Indeed, at the border between zones II and III the speed of the substance release is \( u_{nt} = \sqrt{2E_{cm}} \approx 1.5 \text{ km/s} \), while at the border between zones I and II the speed of the substance release is \( u_v = \sqrt{2E_{cv}} \approx 6 \text{ km/s} \). Here, \( E_{cm} \approx 1.1 \text{ MJ/kg} \) is the specific threshold internal energy of complete melting of anorthosite and \( E_{cv} \approx 18 \text{ MJ/kg} \) is the specific threshold internal energy of complete evaporation (under fast adiabatic mechanical unloading). Thus only the droplets originated from the zone of melting of the substance (II) have the speeds between the first and second astronautical velocities (for the Moon), i.e. between 1.68 and 2.38 km/s. Only such droplets can perform finite movement around the Moon. Below we estimate the sizes of such melt droplets.

3. Melt droplets

In accordance with a theory for estimating the sizes of the melt droplets as a function of impactor size and velocity [29], the ultimate droplet radius (as \( t \to \infty \)) is

\[
r_{\infty} = a_d = \left( \frac{15}{4} \frac{\sigma C_D}{\rho_d a} \right)^{1/2},
\]

where \( \sigma \) is the surface tension of the liquid droplet (for silicate liquids, \( \sigma \) is typically \( \approx 0.3 \text{ N m}^{-1} \), \( C_D \) is the drag coefficient (assumed to be constant, which implies that velocities are high enough to be in the turbulent flow regime), \( \rho_d \) is the droplet density, \( a \) is the overall acceleration,

\[
a = -\frac{1}{\rho} \frac{dP}{dr},
\]

\( \rho \) is the overall density, and \( dP/dr \) is the pressure gradient.

Calculating the pressure gradient for the parameters of the shock formed as a result of a high-speed meteoroid impact, supposing \( C_D = 1 \) (see [29]), \( \rho_d = 3 \text{ g/cm}^3 \), and \( \sigma = 0.3 \text{ N m}^{-1} \), and taking into account that the most of melt droplets are originated from the part of zone II close to the outer boundary of this zone, we find the characteristic droplet radius

\[
a_d \approx 1.5 \times 10^{-4} a_{i}^{1/2},
\]

where \( a_d \) and \( a_i \) are calculated in units of cm.
Table 1. Contributions $F_d(a_{d_{\text{min}}}, a_{d_{\text{max}}})$ to the flux $F_d$ for different size ranges $a_{d_{\text{min}}} \leq a_{d} \leq a_{d_{\text{max}}}$ of the droplets.

| $a_{d_{\text{min}}}$ (nm) | $a_{d_{\text{max}}}$ (nm) | $F_d(a_{d_{\text{min}}}, a_{d_{\text{max}}})$ (cm$^{-2}$s$^{-1}$) |
|--------------------------|--------------------------|-------------------------------------------------|
| 30                       | 100                      | 0.27                                            |
| 100                      | 300                      | 0.06                                            |
| 300                      | 1000                     | 0.002                                           |

The mass of the substance released from zone II is determined by the relationship

$$M_{II} = 2\pi \rho_0 \int_{r_i}^{r_{\text{II}}} w(r) r \, dr \approx 0.05 E_i,$$

(10)

where $E_i$ is the kinetic energy of the impactor calculated in units of kJ, while $M_{II}$ is calculated in units of g. Thus the number of the droplets formed from the melted substance which is released from the lunar surface by the shock wave of a meteoroid explosion is

$$N_{II} = \frac{M_{II}}{m_{dr}} \approx 0.56 \times 10^9 \frac{E_i}{a_i^{3/2}}.$$

(11)

Here, $m_{dr} = (4\pi/3)a_i^3 \rho_0$ is the mass of a droplet, $E_i$ and $a_i$ are calculated in units of kJ and cm, respectively.

Let us introduce the value of $N(h)$ characterizing the number of the droplets formed as a result of the individual impact and reaching the altitude $h$ ($N(h) \sim N_{II}$ at high altitudes, say, of the order of 100 km). We see that this value depends on $E_i$ and $a_i$. Averaging this value over the impact events per unit of area of the lunar surface and unit of time (with the use of the distribution functions $f_m(m_i)$ and $f_u(u_i)$ [26] characterizing impactors) we determine the flux $F_d$ of the droplets at high altitudes. Table 1 presents the results of the calculation of the contributions to the flux $F_d$ made by the droplets of different sizes.

Using the data of table 1 and the characteristic value of the speed of the droplets $v_d \geq u_{\text{mat}} = \sqrt{2E_{\text{cm}}} \approx 1.5$ km/s, we estimate the number density of the droplets with the sizes $300$ nm $\leq a_{d} \leq 1$ $\mu$m at high altitudes over the lunar surface: $n_d \leq 10^{-8}$ cm$^{-3} = 10^{-2}$ m$^{-3}$. This estimate corresponds to the data of the LDEX measurements revealing the presence of small dust grains, from $<0.3$ $\mu$m to $>0.7$ $\mu$m in radius with the number densities ranging between $(0.4–4) \times 10^{-3}$ m$^{-3}$.

4. Conclusions

Thus we have studied a possibility of the formation of dust cloud at high altitudes ($\approx 10–100$ km) over the Moon due to meteoroid impacts onto the lunar surface. The most important zone from the viewpoint of the formation of dust cloud at high altitudes over the Moon is that of melting of the substance. Only the droplets originated from this zone have the speeds between the first and second astronautical velocities (for the Moon), i.e. between 1.68 and 2.38 km/s. Only such droplets can perform finite movement around the Moon. The material from the zones of melting of the substance is released due to the meteoroid impacts in the form of melt droplets to the altitudes of 100 km and higher. Because the flux of impactors with the lunar surface has always existed and will exist forever, we observe permanently present dust cloud engulfing the Moon. Because the dust cloud is created by the substance released due to the meteoroid impacts, we observe intermittent density enhancements during several of the annual meteoroid streams, in particular, during the Geminids. The liquid droplets harden when rising over the
lunar surface. Furthermore, they acquire electric charges due to the action, in particular, of the solar wind electrons and ions, as well as of the solar radiation. For example, over the dark side of the Moon, the droplet charge can be estimated with the aid of the Orbit Motion Limited approach \( q_d \sim a_d T_e/e \), where \( T_e \) is the temperature of solar wind electrons. For \( a_d = 5 \, \mu m \) and \( T_e = 1.4 \times 10^5 \, K \), we have \( q_d \approx 5 \, fC \). Thus dusty plasmas exist in the lunar exosphere with the characteristic number density \( n_d \lesssim 10^{-2} \, m^{-3} \) of dust particles with the sizes \( 300 \, nm \leq a_d \leq 1 \, \mu m \) which is in accordance with the results of measurements performed by LADEE.

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