SCIENTIFIC PUBLICATIONS OF THE STATE UNIVERSITY OF NOVI PAZAR
SER. A: APPL. MATH. INFORM. AND MECH. vol. 17, 1, 2025, 27–33

Modeling the dynamics of lunar dust, taking into account the actual optical properties of minerals

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Abstract: This work presents the development of a two-dimensional model of lunar regolith dust particle motion that accounts for the actual optical properties of the main lunar minerals—olivine and pyroxene. Radiation pressure coefficients for particles of various sizes were calculated using the Mie algorithm, which made it possible to refine the conditions for their levitation and horizontal transport. The modeling revealed the existence of a new stable mode of motion: the formation of a "hovering" dust layer at altitudes on the order of several tenths of a meter, exhibiting horizontal drift of up to several meters per minute. The results obtained refine our understanding of the mechanisms of electrostatic dust transport and may be used to improve predictions of dust-related processes near the surfaces of the Moon and other airless celestial bodies.

Keywords: lunar dust, electrostatic levitation, radiation pressure, optical properties of minerals, modeling

1 Introduction

In recent years, there has been a significant increase in scientific interest in lunar exploration, which contrasts with the decline in activity following the end of the Apollo program. The renewed attention to lunar missions from the scientific community and private companies is driven by a combination of factors, including technological advancements, reduced costs of space launches, the emergence of commercial operators, and the development of international partnerships. A special role is played by the discovery of water ice reserves in the polar regions, which creates practical prerequisites for the deployment of long-term lunar stations and the use of local resources for future missions to Mars and other objects in the Solar System. Modern research programs are focused not only on studying the geology and origin of the Moon, but also on developing infrastructure to ensure a sustainable human presence in the lunar environment.

Manuscript received November 22, 2025; accepted December 18, 2025

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https://doi.org/10.46793/SPSUNP2501.27Y

However, one of the main unresolved problems remains lunar dust, which is a fine and sharp regolith particle that can damage equipment and astronauts' spacesuits [2]. Additionally, lunar dust poses a significant health risk, as evidenced by historical observations from the Apollo missions and modern laboratory studies. Sharp and abrasive dust particles cause mechanical irritation of the skin and eyes, and their small size (less than 10 μm)) allows them to easily penetrate the respiratory system [16]. Combating their effects is a key focus of modern lunar programs.

2 Historical review

The first studies of the motion of lunar dust microparticles were related to attempts to explain the unusual scattering of sunlight near the lunar terminator, which was observed by the astronauts of the Apollo 17 mission, resulting in the appearance of "horizon glow" and "light streams" above the lunar surface. These observations led to the formulation of the key hypothesis, which is the hypothesis of electrostatic levitation of dust. According to this theory, regolith particles that are charged by solar ultraviolet radiation and solar wind plasma experience electrostatic forces that can overcome lunar gravity and lift particles ranging from fractions of a micron to several micrometers in size. The primary mechanism of charging is believed to be photoelectron emission, where the lunar surface gains a positive charge during the day and a negative charge during the night due to the capture of electrons from the solar wind. This results in the formation of complex, non-stationary electrical fields in the near-surface layer. Observations by orbiting spacecraft such as Lunar Prospector and LADEE subsequently confirmed the presence of dust particles at altitudes of up to several kilometers. These data reinforced the notion that electrostatic processes are capable of sustaining a persistent dust exosphere [4, 5, 17].

In the next stage of research, attention was focused on one-dimensional models of particle dynamics. Early theoretical works considered the vertical motion of a dust particle under the assumption of a uniform electric field. In such models, the equation of motion included two main forces: electrostatic and gravitational. This allowed for the estimation of the threshold conditions for levitation, which is the dependence of the maximum size of the rising particles on the field strength. Calculations showed that submicron-scale particles could rise to altitudes of several kilometers, which was in good agreement with observations of "twilight glow." However, one-dimensional models were insufficient because they did not account for the inhomogeneity of the field caused by topographical features, differences in regolith conductivity, shadow zones, and horizontal components of motion [4, 5, 13].

The transition to two-dimensional modeling was a natural development of the research. This approach allowed for the consideration of more complex effects, such as the horizontal transport of dust, its redistribution, and the formation of local accumulations. These models take into account the actual configuration of the electric field, which is particularly complex in the terminator region, the boundary between the day and night sides of the Moon. Here, phenomena such as the drift of particles from charged zones to neutral zones, their focusing in topographical depressions, and the formation of "dust clouds" above the surface occur

[11]. More details about the dynamics of lunar dust can be read in the review [14].

The studies of dust dynamics initiated by the example of the Moon have received a convincing development in the study of small bodies of the Solar System, primarily asteroids. One of the most striking manifestations of electrostatic processes is the formation of the so-called ”dust ponds” on the asteroid 433 Eros [3].

Numerical simulations performed as part of lunar dust dynamics studies have shown that fine particles less than one micron in size can not only levitate on the Sun-lit surface, but also move in a directional manner. In the photoelectron layer above the surface, the dust acquires a significant electric charge and is transported horizontally by the inhomogeneous electric fields, which ultimately leads to its accumulation in topographical depressions such as craters and permanently shaded areas. [3].

This redistribution leads to the formation of characteristic flat deposits that contrast sharply with the surrounding uneven terrain. Therefore, dust airless celestial bodies is not a passive coating: it is capable, through purely electrostatic interactions, of changing the microrelief and forming specific landscape structures, observed, in particular, on Eros. This fact indicates that dust dynamics is a fundamental process that determines the development and appearance of the surfaces of airless celestial bodies throughout the Solar System [3].

3 A mathematical model of the motion of lunar regolith particles

In the study [11], a model of two-dimensional dynamics of dust particles of lunar regolith in the photoelectron layer was developed, based on the following key assumptions: particles are considered to be ideally spherical and conductive with a radius R; the surface of the Moon and particles is covered with a monolayer of hydrogen compounds, which determines the photoemission properties; the lunar surface in the vicinity of a particle is considered to be flat; the photoelectron layer is assumed to be locally one-dimensional; the adhesion forces are assumed to be negligible.

The motion of a particle is described by the following system of equations:

$$\frac{d^2x}{dt^2} = \frac{3F_r}{4\pi R^3 \rho} \sin\theta_0(t) \tag{1}$$

$$\frac{d^2z}{dt^2} = -\frac{3\beta_1}{4\pi R^3 \rho}\left[\frac{G\sqrt{\cos\theta_0(t)}\,\xi \ln(4\cos\theta_0(t))}{1+G\sqrt{\cos\theta_0(t)}\,z}\right] - g_{moon} - \frac{3F_r}{4\pi R^3 \rho}\cos\theta_0(t) \tag{2}$$

$$\begin{gathered}\frac{d\xi}{dt} = -\frac{\beta_2[1-\xi\ln(4\cos\theta_0(t))]}{\ln(4\cos\theta_0(t))} \\ \times\left[\frac{\exp\left(\xi\ln(4\cos\theta_0(t))\right)}{4} - \cos\theta_0(t)\exp\left(\frac{e\Phi(z)}{kT}\right)\right],\end{gathered} \tag{3}$$

where equation (1) describes the horizontal motion under the influence of radiation pressure; equation (2) — vertical motion taking into account electrostatic, gravitational and radiation forces; equation (3) — evolution of the dimensionless charge of a particle $\xi = -Q/Q_0 \ln(4\cos\theta_0(t))$.

In the system of equations (1)-(3) the value g_{moon} represents the acceleration of gravity near the lunar surface. The constants in the model have the following values:

$$\beta_1 = 8\pi\varepsilon_0 \left(\frac{kT}{e}\right)^2, \beta_2 = \frac{\pi R^2 ne}{Q_0}\sqrt{\frac{8kT}{\pi m}}, F_r = \frac{SA}{c}Q_{pr}$$

The potential in the photoelectron layer is given by the expression:

$$\Phi(z) = -\frac{2kT}{e}\ln(1 + G\sqrt{\cos\theta_0}z),$$

where $G = \sqrt{2\pi/kT\varepsilon_0}$, Q_{pr} — radiation pressure coefficients [10].

The main results of the original [11] model include: the levitation condition for particles $R = 0.1$ μm at $\theta_0 > 76.14°$; three modes of vertical oscillations—oscillations near the surface ($R = 0.23$ μm), damped vibrations reaching a stationary height ($0.01 < R < 0.1$ microns) and undamped periodic oscillations ($R < 0.01$ microns); as well as horizontal transport over distances up to 440 km at $\varphi = 0°$ and up to 220 km at $\varphi = 60°$.

4 Method for calculating the radiation pressure coefficient

In contrast to the original model [11], which used model data for basalt, in this work the calculation of the radiation pressure coefficient Q_{pr} was carried out for specific lunar minerals: olivine and pyroxene. The calculation of Q_{pr} was carried out using the classical BHMIE algorithm [1], solving the Mie scattering problem for spherical particles. The computational procedure included: calculation of the diffraction parameter $x = 2\pi R/\lambda$; determination of the number of required expansion terms $n_{\text{stop}} = x + 4x^{1/3} + 2$; recursive calculation of the a_n and b_n Mie scattering coefficients; accounting for the angular distribution of scattered radiation; averaging over the solar spectrum with weighting coefficients.

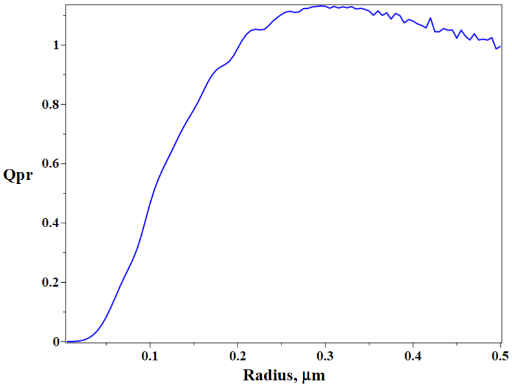
Our study utilizes the optical constants of 13 silicate samples from the Jena University database [8] with the original data in [6, 9, 7, 15].

Table 1. Radiation pressure coefficients Q_{pr} for representative samples at characteristic radii

No.	Sample	$Q_{pr}(0.007\ \mu m)$	$Q_{pr}(0.1\ \mu m)$	$Q_{pr}(0.23\ \mu m)$
1.	$Mg_1Fe_0SiO_3$ (pyroxene)	0.000081	0.41	0.87
2.	$Mg_{0.8}Fe_{0.2}SiO_3$ (pyroxene)	0.0033	0.51	1.0022
3.	$Mg_{1.72}Fe_{0.21}SiO_4$ (olivine)	0.000045	0.47	1.053

The choice of radii 0.007, 0.1, and 0.23 μm is based on their correspondence to the three regimes of vertical oscillations identified in the original model [11]. As follows from the data in Table 1, significant variation in Q_{pr} is observed depending on both the mineral composition and the particle size, which confirms the need to take into account the actual mineralogical composition when modeling the dynamics of dust particles.

5 Simulation results of dust particle dynamics



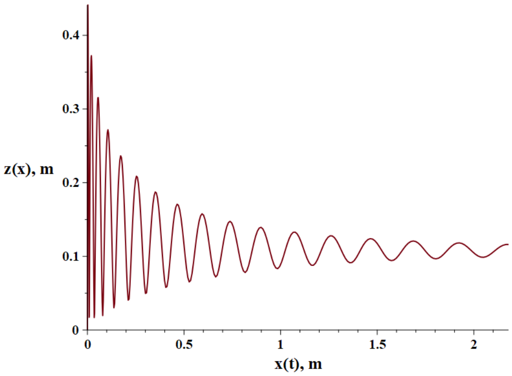


Fig. 1. Dependence of Q_{pr} on the radius for sample 3.

Fig. 2. Trajectory of a particle with a radius of $0.1\ \mu m$ for sample 3. The particle reaches a stationary levitation height of $z \approx 0.1\ m$ with a horizontal displacement of $x \approx 2\ m$ over a simulation time of $t = 30\ s$.

The calculated coefficients Q_{pr} for various minerals were substituted into the original system of equations of the model [11]. Figure 1 shows the dependence of $Q_{pr}(R)$ for sample 3, which was later used in modeling particle dynamics. In the equation of horizontal motion (1), the radiation pressure force F_r was calculated using the obtained values of Q_{pr}.

Particle dynamics simulations revealed qualitatively new behavior compared to the original model. For particles with an average radius of $R = 0.1\ \mu m$, a stationary levitation with significant horizontal displacement is observed, as shown in Figure 2. The particle reaches a stationary levitation height of $z \approx 0.1\ m$ with a horizontal displacement of $x \approx 2\ m$ over a simulation time of $t = 30\ s$.

The analysis shows that in this mode, the vertical component of the force is balanced by gravity and electric forces, while the horizontal component of the radiation pressure causes the particle to drift. This phenomenon is interpreted as the formation of a ”floating” layer of dust above the lunar surface.

Thus, taking into account the actual optical properties of lunar minerals makes it possible to identify new modes of movement of dust particles, in particular, the formation of a stable levitating layer with horizontal transport.

6 Conclusion

In the present work, the model of two-dimensional dynamics of lunar regolith dust particles proposed in [11] has been further developed. The key improvement was the replacement of the model optical parameters of basalt with the actual optical constants of specific lunar minerals, such as olivine and pyroxene. We used the Mie algorithm to calculate the radiation pressure coefficient Q_{pr} for particles of different sizes, which allowed us to account for the specific interaction of solar radiation with the actual mineralogical composition of the lunar surface.

The conducted modeling revealed qualitatively new modes of dust particle motion compared to the original model. The most significant result is the establishment of the stationary levitation regime for medium-radius particles ($R \approx 0.1\ \mu m$), in which the vertical forces are balanced, and the horizontal component of the radiation pressure causes a steady drift of the particles at altitudes of about 0.1 m with a significant horizontal displacement (up to 2 m over 30 s). This phenomenon is interpreted as the possibility of a ”floating” dust layer above the lunar surface in the terminator regions.

The results obtained are important for understanding the physics of the near-surface plasma-dust environment of the Moon and other airless celestial bodies. Accounting for the actual mineralogical composition is a necessary condition for accurate prediction of dust dynamics, which is critical for planning future long-term lunar missions, as electrostatic dust transport poses a serious threat to the operation of space technology, life support systems, and human health.

Further research directions include expanding the model to include a wider variety of lunar minerals, as well as considering the three-dimensional nature of the problem and the inhomogeneities of the surface.

In addition, further development of the model, it is planned to account for the influence of the horizontal component of the electric field on the motion of dust particles, which will allow for a more accurate description of their spatial distribution and transport under the complex geometry of the lunar surface.

Acknowledgments

The study was carried out with the financial support of St. Petersburg State University. (project No. 116636233)

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