Non-Gaussian distribution of regolith particles deposited on tantalum and molybdenum surfaces under gyrotron pulsed radiation

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Abstract. The distribution of regolith simulant particles deposited on the surface of tantalum and molybdenum in microwave discharges induced by gyrotron pulsed radiation is studied. To analyze the deposited particles, an image processing algorithm is developed. It is shown that the particle size distributions are non-Gaussian with heavy power-law tails and flat tops. These properties are also characteristics of the lunar regolith.

1. Introduction

As the Moon does not possess a dense atmosphere and a permanent magnetic field, it is repeatedly bombarded by cosmic rays, electromagnetic radiation and meteoroids. These aggressive factors lead to a unique exosphere which consists of plasma and levitating dust particles – a plasma-dust system. The source of the levitating dust is lunar regolith, and the particles may levitate at heights of more than 100 km. The authors of [1] consider micrometeoroids (submicron- and micron-sized meteoroids) one of the main factors that contribute to dust elevation. Furthermore, the authors of [2] demonstrate the importance of chemical processes accompanying meteoroid bombadments in the creation of the lunar plasma-dust system.

As shown during the lunar missions, the regolith poses problems to space equipment due to its high abrasivity and adhesion [3]. Since the experiments on the lunar surface are still not economically feasible, it is crucial to study how the regolith interacts with various materials in the laboratory.

In this work, we present the size distribution of laboratory regolith (i.e., synthesized in the laboratory [4]) particles deposited on tantalum and molybdenum. These metals have been chosen for our simulation material tests because they find use in space engineering due to their high performance at elevated temperatures. In the simulation material tests, we recreate the conditions accompanying micrometeoroid bombadments on the Moon and use a laboratory
regolith sample, which is analogous to the lunar regolith in chemical composition and size distribution.

Our microwave method for reproducing lunar conditions is a novel approach to simulation experiments in Earth laboratory conditions.

2. Methods

2.1. Creation of plasma-dust clouds

The simulation material tests are conducted in the plasma physics department of the Prokhorov General Physics Institute of the Russian Academy of Sciences. The schematic diagram of the experiment is shown in Figure 1(a).

Gyrotron pulses (with the power of up to 400 kW and the duration of up to 10 ms) irradiate a lunar regolith simulant [2], which is analogous to the lunar regolith in chemical composition and particle size distribution (from now on, we will also refer to the regolith simulant as ‘regolith’ or ‘simulant’). The simulant is a mixture of metal oxides. After the energy threshold for the dielectric breakdown is achieved, microwave energy is effectively absorbed by the plasma phase inside the powder mixture and above the mixture surface. Simultaneously, the superficial particles are charged by contact with the plasma. It leads to strong Coulomb repulsion between the particles and subsequently to an explosive process. As a result, regolith particles arise in the reactor and levitate above the powder mixture. The plasma temperature may reach 7000 K, which suffices to initiate exothermic chain reactions above the powder surface. They include oxide decomposition and synthesis of new micro- and nanomaterials, which are regolith derivatives. The levitating dust particles become crystallization centers for such materials.

After the chain reactions terminate, the levitating dust particles deposit on all the surfaces in the reactor including the metal plates (Ta and Mo), which are placed 3-4 cm above the regolith simulant (Figure 1(b)).
2.2. Particle size distribution
The metal plates with deposited regolith particles are studied with a scanning electron microscope JEOL JSM-6390LA. The obtained microphotographs are then processed in ImageJ and the data are visualized in MATLAB. The schematic diagram of the algorithm is shown in Figure 2.

To identify regolith particles in the microphotographs, we use the thresholding segmentation technique [5]. Despite its simplicity, the thresholding method requires highly contrast pictures with a correctly selected exposition time which is sometimes difficult to obtain with an electron microscope. Therefore, the images are preliminarily processed, and their histograms are corrected in ImageJ. Image processing tools used for microphotograph analysis include Fourier Transformation, Anisotropic Diffusion, and morphological filters (e.g., Watershed).

After the preliminary image correction, the deposited regolith spherules (because particles melt at high temperatures) are approximated with ellipses, their areas are calculated (Figure 3), and the data are exported as tables to MATLAB. In MATLAB, the linear particle sizes are calculated, and normalized size distribution histograms are plotted.

The algorithm is based on the ethical guidelines summarized in [6].

3. Results
The tantalum and molybdenum surfaces with deposited regolith particles are shown in Figures 4(a) and 5(a). As one can notice, the deposited particles are of two types – spheroids of different sizes and amorphous particles. The latter prevails on molybdenum. The particle layer is not dense and does not entirely cover the metal surface of both tantalum and molybdenum.

The chemical composition of the deposited structures is analogous to the lunar regolith and will be presented in our future works.

The particle size distribution histograms are shown in Figures 4(b) and 5(b). For tantalum, 2-4 micron particles prevail, bigger particles are less frequent, and their maximum linear size...
is 40–42 microns. For molybdenum, the contribution of smaller particles (1–4 microns) has increased, and there are no particles with linear sizes of more than 26 microns.

Both size distributions are non-Gaussian with heavy power-law tails and flat tops. Thus, the contribution of bigger particles cannot be neglected. It should be noted that non-Gaussianity is also characteristic of the actual lunar regolith samples [7].

As shown in [8, 9], nonlinear processes which lead to non-Gaussian distributions are splitting and baking of regolith grains. These processes may be examined within the Reed-Jorgensen, Sorensen, and Barndorff-Nielsen distribution models [10].
4. Conclusion
The analysis of the laboratory regolith particles deposited on tantalum and molybdenum surfaces under gyrotron pulsed radiation has revealed a non-Gaussian distribution with a heavy power-law tail and a flat top. The same distribution characterizes the lunar regolith.

Particle size distribution is one of the four fundamental properties of the lunar regolith, which are considered when devising simulation experiments with regolith analogs in Earth laboratory conditions [11]. The fact that the particle size distribution of the plasma-dust clouds created under gyrotron pulsed radiation mimics the size distribution of the actual lunar samples demonstrates the feasibility of recreating lunar conditions with the microwave method and the practicality of the microwave method in material testing for lunar missions. However, further studies are due.

In our future works, we will examine the microwave method for creating plasma-dust clouds with regard to the other fundamental properties of the lunar regolith (particle composition, shape distribution, and bulk density) as well as the limitations of the method.

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