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Dusty plasmas over the Moon

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The results on dusty plasmas over the Moon are reviewed. The problems concerning the dusty plasma over the lunar surface are formulated.

1. Introduction

Dusty plasmas are multi-component plasmas consisting of ions, electrons, neutrals and charged solid or liquid particles in the micron or nanometer size (Shukla and Mamun 2002). The field of dusty plasmas is interdisciplinary and encompasses astrophysics and planetary science (Horányi et al. 2004; Popel et al. 2011), atmospheric science (Amyx et al. 2008; Dubinskii and Popel 2012), fusion science (de Angelis 2006), and various applied technologies (Ostrikov et al. 2013).

An important example of a dusty plasma system in nature is the lunar exosphere which consists mainly of gases that arrive as the solar wind. The solar wind is a continuous flow of gases from the Sun – mostly hydrogen and helium, along with some neon and argon. The lunar surface gas concentration is less than 10^6 cm^{-3} – compared with 10^{19} cm^{-3} at Earth and 10^{17} cm^{-3} at Mars. The remainder of the gases in the exosphere form on the Moon. A continual 'rain' of micrometeoroids heats lunar rocks, melting and vaporizing their surface. The most common atoms in the vapor are atoms of sodium and potassium. Those elements are present in tiny amounts – only a few hundred atoms of each per cubic centimeter of exosphere. In addition to vapors produced by impacts, the Moon also releases some gases from its interior. Most gases of the exosphere concentrate about halfway between the equator and the poles, and they are most plentiful just before sunrise. The solar wind continuously sweeps vapor into space, but the vapor is continuously replaced.

A powdery dust that levitates over the Moon is also a constituent of the lunar exosphere. The discovery of the lunar dust 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 (Norton et al. 1967). This effect was related to sunlight scattering at the terminators giving rise to 'horizon glow' and 'streamers' above the lunar surface (Rennilson and Criswell 1974). Subsequent investigations have shown that the sunlight was most likely scattered by electrostatically charged dust grains originating from the surface (Zook and McCoy 1991). During the Apollo missions 0.1 μm–scale dust was observed up to about 100 km altitude.

A renaissance is currently being observed in investigations of the Moon, which are planned in the People's Republic of China, United States, Russia, India, and European Union. The Luna-25, Luna-26, Luna-27, Luna Sample Return, *etc.*, missions are under

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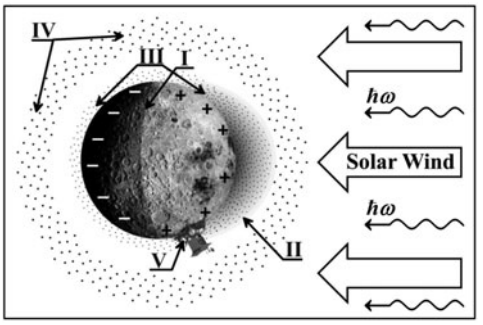


FIGURE 1. The main elements characterizing the dusty plasma system over the Moon (the terminator (I), the photoelectrons (II), the near-surface dust particles (III), dust particles at high altitudes (IV), photons of solar radiation ($\hbar\omega$), and the solar wind) as well as the lunar lander at a high lunar latitude in the South Hemisphere (V).

preparation in Russia. The landing modules of the Luna-25 and Luna-27 spacecrafts are planned to be equipped with instruments for studying the properties of the dusty plasma over the surface of the Moon. The dusty plasma is studied by means of observations from the orbit of the US LADEE (Lunar Atmosphere and Dust Environment Explorer) launched in 2013. In this connection, studies on lunar dust and dusty plasmas over the Moon are of significant importance. Here, we present a brief review of the corresponding results.

2. Dusty environment over the Moon

It is now almost universally accepted [see, *e.g.* (Stubbs et al. 2006; Colwell et al. 2009)] that the dust over the lunar surface is a component of a dusty plasma system. Fig. 1 presents schematically the main elements characterizing the dusty environment over the Moon. The lunar surface is charged under the influence of the solar electromagnetic radiation, the solar wind plasma, and the plasma of the terrestrial magnetosphere tail. Upon interacting with the solar radiation, the lunar surface emits photoelectrons due to the photoelectric effect. This leads to the emergence of a layer of photoelectrons above the surface. Additional photoelectrons are emitted by the dust particles levitating above the lunar surface when these particles interact with the solar electromagnetic radiation. The analysis (carried out by analogy with (Popel et al. 2013a)) shows that photoelectrons from the surfaces of the levitating dust particles prevail over photoelectrons from the lunar surface already at heights of several centimeters above the surface of the Moon and at greater heights for the case characterized by the quantum yield from (Walbridge 1973) and altitudes higher than several meters for the case when the quantum yield is determined by the dependence from (Willis et al. 1973). The dust particles located on the lunar surface or in the near-surface layer absorb photoelectrons, photons of the solar radiation, electrons and ions of the solar wind, and (if the Moon is located in the terrestrial magnetosphere tail) electrons and ions of the magnetosphere plasma. All these processes promote charging of the dust particles, their interaction with the charged lunar surface, and the dust levitation and motion.

To explain the presence of 0.1 μm–scale grains at altitudes of about 100 km the so-called dynamic fountain model for lunar dust has been proposed by (Stubbs et al. 2006). Within this model it is possible to predict that a lunar orbiting spacecraft with a charged dust detector would observe very small (10 nm) positively charged grains and

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larger (10 to 100 nm) negatively charged those around the terminator region. However it appears that submicron dust grains could contaminate astronomical observations of infra-red, visible and UV light over the majority of the lunar surface, and not just at the terminator. Thus the dynamic fountain model for lunar dust is one of many ways in which dust could interfere with science and exploration activities on the Moon. Furthermore, the dynamic fountain model can predict only the maximum heights reached by dust grains. It does not give the values of a number for the dust particles above the Moon. To obtain the corresponding number one has to consider physical processes which are not taken into account in the dynamic fountain model.

Another phenomenon which can be responsible for an appearance of dust particles at high altitudes (of the order of 100 km) is related to impacts of meteoroids or man-made projectiles with the surface of the Moon (Nemtchinov et al. 2002; Popel and Gisko 2006). The evolution of the impact plume can lead to the formation of charged particles. One type of the particles (small droplets) is created as a result of the process of condensation which takes place during the expansion of the vapor plume. The period of the formation of the centers of condensation is very short and all droplets have approximately the same size. The droplets move together with the substance of the plume. Their speed exceeds often the first astronautical velocity for the Moon, 1.68 km/s, and the droplets will not fall down the surface of the Moon. Moreover, the droplets with the speeds between the first and second astronautical velocities, *i.e.* between 1.68 and 2.38 km/s, perform finite movement around the Moon. One can expect (Popel and Zelenyi 2013) an appearance of $\sim 3.6 \cdot 10^9$ particles (with the sizes of about 100 nm) per second from the lunar surface, the particles rising rather high altitudes (*e.g.* about 100 km) over the lunar surface. This shows that the effect of condensation of micrometeoriod substance after impact can be important from the viewpoint of explanation of dust particle rise to high altitudes. The implicit confirmation of this effect is given by the observations performed by the US LADEE (Elphic et al. 2014) where it was shown that the velocities of dusts at the altitudes of 30 to 110 km over the lunar surface are of about the first astronautical velocity for the Moon.

3. Recent lunar dusty plasma studies in Russia

The Luna-25 and Luna-27 spacecrafts will detect dust particles and carry out optical observations of dust with the aid of piezoelectric shock sensors, electric field sensors, as well as stereo and surveillance cameras (Popel et al. 2014). Location of the piezoelectric shock sensors and electric field sensors is supposed to be at the altitudes of 20 and 90 cm, while the cameras for optical observations will be placed on the top of the spacecrafts (approximately 2 m over the lunar surface). The measurements are planned to be carried out in the daytime so as to use solar power to supply the lunar station equipment. The plans are to land the Luna-25 and Luna-27 stations on the Moon at high lunar latitudes exceeding 70° (see Fig. 1). All these facts have determined the character of studies of dusty plasmas over the Moon performed recently in Russia. They are devoted mainly to the description of the plasma-dust system, photoelectron and dust particle distributions in the near-surface layer of the illuminated part of the lunar surface at sufficiently high lunar latitudes. These studies present considerable interest (even from the purely technological standpoint), as their results may help to choose the landing site, to prepare the instrumentation of the lunar stations, to determine the range of dusty plasma parameters to be measured, and so on.

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As for the photoelectrons, an important parameter used in the calculations is the quantum yield determining the number of electrons knocked out from the surface by one photon (Popel et al. 2014). The dependencies (Walbridge 1973; Willis et al. 1973) of the quantum yield are usually used in studies of the plasma-dust system and/or photoelectrons near the surface of the Moon. The most probable quantum yield of the material of the surface of the Moon presented in (Walbridge 1973) (Fig. 11) can be approximated as

$$\begin{aligned} &Y(E_{ph}) = 0 \text{ if } E_{ph} < 6, \\ &Y(E_{ph}) \approx 0.02 + 0.06(E_{ph} - 6) \text{ if } 6 \leqslant E_{ph} \leqslant 9, \\ &Y(E_{ph}) \approx 0.2 \text{ if } E_{ph} \geqslant 9, \end{aligned} \tag{3.1}$$

where the energy of photoelectrons (E_{ph}) is measured in electronvolts and the value $W = 6$ eV is taken for the work function. Another value of the quantum yield was obtained in (Willis et al. 1973) from the experimental study of lunar dust samples delivered to the Earth by the Apollo 14 and Apollo 15 missions. The dependence of the quantum yield in (Willis et al. 1973) differs significantly from theoretical (semiempirical) dependence (3.1). First, the maximum value of $Y(E_{ph})$ in (Willis et al. 1973), which is approximately 0.09 ± 0.003, is reached at an electromagnetic wavelength of about 900 Å, which corresponds to $E_{ph} \approx 13.7$ eV. The quantum yield at E_{ph} values differing from 13.7 eV is much (several orders of magnitude) smaller. In particular, the quantum yield decreases to about 10^{-6} at $E_{ph} \approx 7$ eV and decreases additionally by one or two orders of magnitude when E_{ph} approaches the work function.

The difference between the quantum yields presented in Walbridge (1973) and (Willis et al. 1973) affects the calculation much more strongly than the variation of the work function which typically (for lunar regolith) is within the range of 5 to 6 eV. Indeed, the number density N_0 (near the lunar surface) and the temperature T_e of photoelectrons corresponding to the quantum yield from Walbridge (1973) are of the order of 10^5 cm^{-3} and 0.1 eV, while those values calculated for the quantum yield from Willis et al. (1973) are $\sim 10^2 - 10^3$ cm^{-3} and ~ 1 eV (Popel et al. 2014). The above data are calculated for $\cos\theta = 1$, where θ is the subsolar angle. The N_0 values for $\cos\theta \neq 1$ are obtained by multiplying the values calculated for $\cos\theta = 1$ by $\cos\theta$. The electron temperature T_e is independent of $\cos\theta$. Thus the quantum yield is a very important parameter requiring further refinement (Popel et al. 2014).

The calculation with the quantum yield from Walbridge (1973) differs from the calculation with the quantum yield from Willis et al. (1973) because photons with energies close to the work function make a significant contribution in the former case. These photons, whose number is large, are responsible for the emission of the main fraction of photoelectrons. In the latter case, the quantum yield at energies quite close to the work function is rather low. In this case, the significant generation of photoelectrons is due to photons corresponding to the 10.2 eV peak in the solar radiation spectra, which is attributed to the H Lyman-alpha line. Correspondingly, the number of photoelectrons in the latter case is much smaller than that in the former case, whereas the temperature is significantly higher. Furthermore, in both the cases the total photoelectron distribution function is the superposition of the distribution function of photoelectrons knocked out by photons that have energies close to the work function and a temperature of about 0.1–0.2 eV and the distribution function of photoelectrons that are associated with the H Lyman-alpha line and have a temperature of about 1 eV (Popel et al. 2014). Although, the number of electrons

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with energies of about 1 eV is (even in the latter case) smaller than the number of photoelectrons with lower energies, photoelectrons with energies of about 1 eV should be observed in the corresponding measurements. We note that the number density of photoelectrons near the sunlit lunar surface is larger than that of the solar wind electrons. In this connection, here we do not consider distribution of the solar wind electrons. However, in some cases this distribution should be taken into account because the relative motion of the solar wind with respect to the photoelectrons leads to the excitation of plasma oscillations over the lunar surface (Popel et al. 2013b).

Here, we have discussed the distribution functions and the number densities of photoelectrons in the vicinity of the lunar surface. The height-dependencies of the photoelectron number densities as well as the size- and height-distributions of the charged dust particles located over the illuminated part of the lunar surface were calculated self-consistently (Popel et al. 2013a; Popel and Zelenyi 2013) for different subsolar angles in the near-surface layer (with the altitudes less than several meters) of the Moon. For this purpose the probability of the presence of a particle at a certain height (which is inversely proportional to the time of presence of a particle at this height) was calculated. This probability was multiplied by a normalization factor, which was calculated to ensure an adequate description of the size distribution of surface lunar dust. To determine the normalization factor, we used the data from Colwell et al. (2007) that made it possible to plot the distribution of dust particles of the surface of the Moon in the size range from 20 to 500 μm. This distribution is in good agreement with the Kolmogorov distribution (Adushkin et al. 2007), which is the size distribution of particles in the case of multiple crushing. This fact is in agreement with the conclusions (Colwell et al. 2007) that the surface of the Moon is regolith evolving because of multiple crushing under meteorite impacts. Adushkin et al. (2007) showed that the Kolmogorov distribution for the case of multiple crushing is valid at least for particles with sizes $\sim$100 nm. Therefore, the distribution of dust particles of the surface of the Moon that was obtained using the data from (Colwell et al. 2007) can be extended down to a size of 100 nm.

A possibility of rising charged dust particles with the sizes of the order of 100 nm over the surface of the Moon in the entire range of the subsolar angles was demonstrated (Popel et al. 2013a; Popel and Zelenyi 2013). This explains the lack of the so-called 'dead zone" [where dust particles, as it was previously believed (Stubbs et al. 2006), do not rise off the surface] at lunar latitudes of about 80° was demonstrated. Thus, it was shown that no substantial restrictions are imposed on the choice of the landing site for future lunar spacecraft missions aimed at studying the near-surface dust on the Moon.

We emphasize that the considerations (Popel et al. 2013a; Popel and Zelenyi 2013) showed the difference in the parameters of the dusty plasma system over the Moon for the work functions and the quantum yields inherent in typical and hydrogen-rich lunar regolith areas. This indicates the variability of the dusty plasma properties together with those of the lunar regolith depending on location.

4. Unsolved problems

The description we have given make clear some features of dusty plasma system over the Moon. However, there are unsolved problems concerning its parameters and manifestations. Here we outline some of the problems which can be important for detailed study of the dusty plasma over the lunar surface.

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4.1. *The quantum photoemission yield and work function of lunar regolith*

Unfortunately, quantum yields presented in Walbridge (1973) and Willis et al. (1973) are insufficiently justified. For example, as was mentioned in Willis et al. (1973), where the quantum yield was experimentally measured for lunar regolith particles delivered by the Apollo 14 and Apollo 15 missions, it was impossible to deal with samples occurring before that in high vacuum. Manipulations with particles were performed in an inert atmosphere containing impurities. Thus, the surface of lunar regolith samples was subjected to the action of foreign substances and its electrophysical properties (including the quantum yield and work function) could have changed significantly. Moreover, the authors of Willis et al. (1973) studied quite small particles. This also could have affected the resulting quantum yield. All these circumstances indicate the necessity of the determination of the quantum yield (and the work function) for lunar regolith by independent methods implying the absence of the interaction of samples with air. It is very difficult to deliver lunar soil so as to avoid its interaction with the Earth's atmosphere. For this reason, studies of the quantum yield and work function of lunar regolith from landers directly on the Moon is of significant interest. This possibility will be provided within the future Luna-27 mission (Popel et al. 2014). A possible layout of an experiment on the measurement of the quantum yield and work function of lunar regolith is shown in Fig. 2. Electromagnetic radiation comes from the Sun. An optical channel consisting of a mirror and/or an optical cable is used to create the redirected photon beam. On one hand, the mirror modifies the radiation spectrum, which should be taken into account when analyzing the final results. On the other hand, this mirror can be used to enhance (by several times) the radiation interacting with the surface of the Moon. This will provide more reliable experimental results. Laser light-emitting diodes, a mercury-vapor lamp, *etc*., can also be used as radiation sources. However, in this case, it is necessary to select the energy spectrum of a source according to the solar spectrum by, *e.g*. using maxima in the solar radiation spectrum. The Langmuir probe can detect the photoelectron flux with a step of about 0.05 V in the range from −100 to 100 V both in the presence of a light source illuminating the surface of the Moon and in the absence of such a source, detecting the energy spectrum of electrons. The energy spectrum of electrons correlates in turn with the current-voltage characteristic of the Langmuir probe. Comparison of the current-voltage characteristics obtained in the presence and absence of illumination of the surface of the Moon makes it possible to determine the quantum yield and work function of lunar regolith. Equipment for the measurements of the quantum yield and work function of lunar regolith will be mounted on a support pole, which can be pushed to a certain distance from a lander in order to reduce the effect of photoelectrons from the lander on the measurement results. To this end, it is also proposed to color parts of the lander near the support pole with a special dye in order to avoid the generation of photoelectrons from these parts. The support pole can be displaced in space, allowing measurements at various altitudes (from 0 to about 2 m) from the surface of the Moon.

4.2. *Influence of implanted hydrogen on photoemission properties of lunar regolith*

Recent data from the Lunar Reconnaissance Orbiter (Mitrofanov et al. 2010) show the existence of hydrogen-enriched regions in the surface layer of the Moon at lunar latitudes exceeding 70° in the Southern Hemisphere. The existence of surface regions of hydrogen is possibly due to electrons and protons of the solar wind and/or the Earth magnetotail, which collide with the Moon and are absorbed by its surface, where they form neutral hydrogen atoms. This implanted hydrogen can rise on the surface of the

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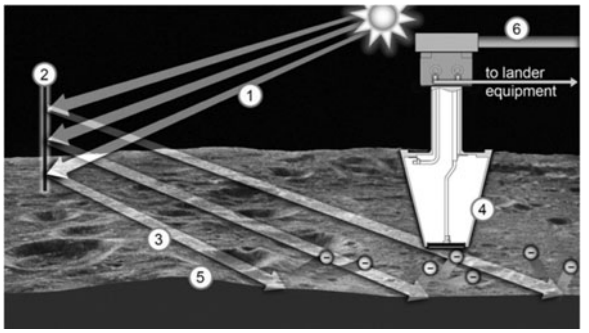


FIGURE 2. Layout of the experiment on the measurements of the quantum yield and work function of lunar regolith: (1) light flux from a source of radiation, (2) mirror, (3) light flux transformed by the mirror, (4) Langmuir probe, (5) surface of the Moon, and (6) support pole for equipment for measurements.

Moon in the form of atomic or molecular hydrogen. In this case, the sensitivity of the hydrogen-enriched regions of the surface of the Moon to photoemission can be much higher than that of surrounding regions (Popel et al. 2013a); this finally affects the charging of dust particles, their dynamics, and properties of the dusty plasma system over the lunar surface. The implanted hydrogen can be trapped in the interstitials or in radiation defects, in particular, in OH-groups formed at broken chemical bonds of oxygen. Inward diffusion from the implanted layer may dominate over the diffusion to the surface; then the implanted hydrogen atoms bound in OH-groups are captured within the regolith particles. A model should be developed which will allow us to calculate migration of free protons in regolith and describe physical-chemical activity of protons in lunar soil in the dependence of the system parameters.

4.3. *Adhesion of rough particles of lunar regolith and release of dust particles from the lunar surface*

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 in future attempts to understand particle launching methods (Hartzell and Scheeres 2011). The effect of surface roughness (Meine et al. 2004) results in significant attenuation of the effect of adhesion in comparison with the results given by Hartzell and Scheeres (2011). However, 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 if the dust particles rise at a height of about dozens of nanometers owing to some processes [*e.g.* dust particle heating by solar radiation and cooling which result in an appearance of forces ejecting the particles upward (Golub' et al. 2012)]. This is enough for the particles to acquire charges sufficient for the dominance of the electrostatic force over the gravitational and adhesive forces. The mechanisms of dust particle release from the lunar surface require further investigations.

4.4. *Plasma waves over the lunar surface*

The relative motion of the solar wind with respect to the photoelectrons over the lunar dayside results in the excitation of high-frequency oscillations with frequencies in the range of Langmuir and electromagnetic waves (Popel et al. 2013b). Possibilities of the existence of plasma waves in the vicinity of the lunar terminator are not

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yet studied. The excitation of the dust acoustic waves can take place in the region of the lunar terminator. The terminator's speed (several hundred cm s^{-1}) is several times larger than the dust acoustic velocity. Correspondingly, the instability resulting in the excitation of the dust acoustic oscillations can develop. By analogy with the active space experiments which involve the release of some gaseous substance in Earth's ionosphere (Popel and Tsytovich 1999), the motion of the terminator can be associated with the propagation of dust acoustic shock: the terminator treated as the shock front distinguishes sharply the dusty plasma parameters before and behind it and moves with the Mach number $M > 1$.

5. Summary

Thus dusty plasma system over the Moon includes charged dust, photoelectrons, and electrons and ions of the solar wind and Earth's magnetosphere. In spite of rather long history of investigations of the lunar dusty plasma, there are unsolved problems concerning its parameters and manifestations. Here, we have presented the results and stated the problems related to the dusty plasma over the lunar surface.

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