J. Plasma Physics (2013), *vol.* 79, *part* 4, *pp.* 405–411. © Cambridge University Press 2013
doi:10.1017/S0022377813000214

Future lunar missions and investigation of dusty plasma processes on the Moon

SERGEY I. POPEL[1] and LEV M. ZELENYI[2]

[1]Institute for Dynamics of Geospheres of RAS, Moscow 119334, Russia
(popel@idg.chph.ras.ru)

[2]Space Research Institute of RAS, Moscow 117997, Russia

(Received 14 December 2012; revised 14 December 2012; accepted 23 January 2013; first published online 27 February 2013)

Abstract. From the Apollo era of exploration, it was discovered that sunlight was scattered at the terminators giving rise to "horizon glow" and "streamers" above the lunar surface. Subsequent investigations have shown that the sunlight was most likely scattered by electrostatically charged dust grains originating from the surface. A renaissance is being observed currently in investigations of the Moon. The Luna-Glob and Luna-Resource missions (the latter jointly with India) are being prepared in Russia. Some of these missions will include investigations of lunar dust. Here we discuss the future experimental investigations of lunar dust within the missions of Luna-Glob and Luna-Resource. We consider the dusty plasma system over the lunar surface and determine the maximum height of dust rise. We describe mechanisms of formation of the dusty plasma system over the Moon and its main properties, determine distributions of electrons and dust over the lunar surface, and show a possibility of rising dust particles over the surface of the illuminated part of the Moon in the entire range of lunar latitudes. Finally, we discuss the effect of condensation of micrometeoriod substance during the expansion of the impact plume and show that this effect is important from the viewpoint of explanation of dust particle rise to high altitudes in addition to the dusty plasma effects.

1. Introduction

The field of dusty plasmas is intrinsically interdisciplinary and encompasses astrophysics, planetary science, atmospheric science, fusion science, and various applied technologies. Dusty plasmas (also known as complex plasmas) are ordinary plasmas with embedded solid or liquid particles. The particles can be made of either dielectric or conducting materials and can have different size and shape. The typical size ranges from dozens of nanometers to say hundred micrometers. Henceforth, a dusty plasma is a multi-component plasma consisting of ions, electrons, and charged solid or liquid particles in the micron or nanometer size.

Understanding of the processes taking place in dusty plasmas has significantly improved due to laboratory experiments conducted since the mid-1990s (Shukla and Mamun 2002; Tsytovich et al. 2005; Vladimirov et al. 2005), the significant part in these investigations having played by the activities onboard the "Mir" Space Station and the International Space Station. This motivates the application of methods developed in studies of dusty plasmas to natural dusty plasma systems (Popel et al. 2011) and, in particular, to a plasma system over the Moon.

A renaissance is currently being observed in investigations of the Moon, which are planned in the People's Republic of China, the European Union, India, Russia, and the United States. The upcoming NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission will be launched in 2013. LADEE is a robotic mission that will orbit the Moon to gather detailed information about the lunar atmosphere, conditions near the surface, and environmental influences on lunar dust. It will carry an *in-situ* and a remote sensing instruments dedicated to the mapping of the lunar dust environment from orbit.

The Russian (Roscosmos) missions Luna-Glob and Luna-Resource (the latter jointly with India) have been designed for studying the lunar polar regions. These missions will, in particular, include investigations of dust near the surface of the Moon. It is planned to equip the Luna-Glob and Luna-Resource stations with instruments both for direct detection of dust particles over the surface of the Moon and for optical measurements. Figure 1 shows the scheme of the location of instruments (at heights of 20 and 90 cm over the surface of the Moon) detecting dust particles at the Luna-Glob and Luna-Resource stations. Optical observations of dust will be performed at heights that do not exceed several meters. Measurements are planned during the daytime to ensure the power supply of instruments at lunar stations because of solar energy.

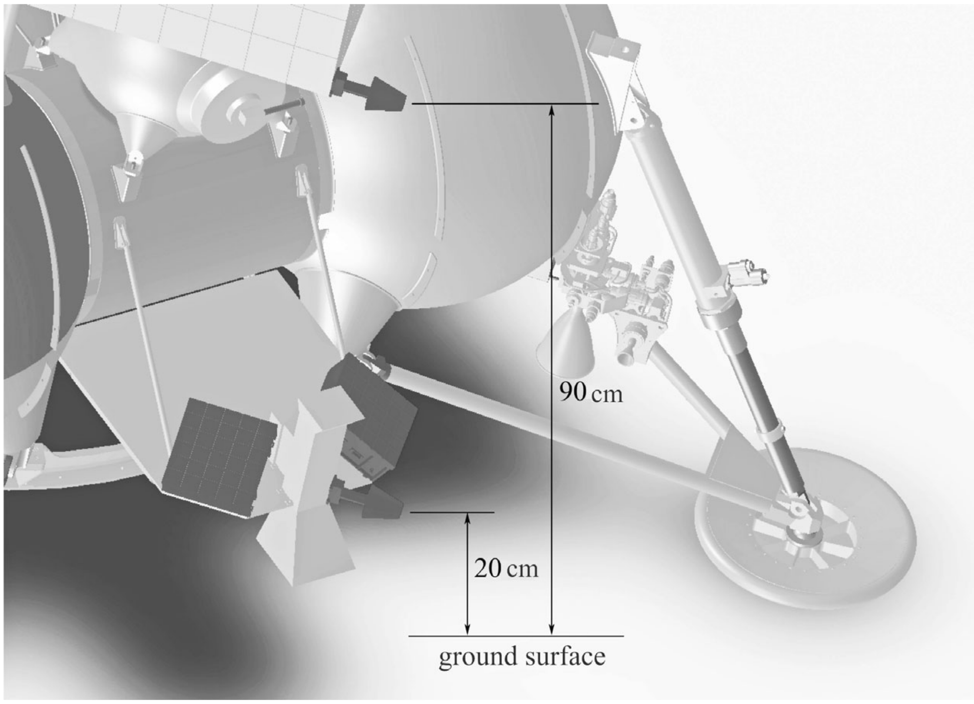

Figure 1. Scheme of the location of instruments (at heights of 20 and 90 cm over the surface of the Moon) detecting dust particles at the Luna-Glob and Luna-Resource stations.

The present paper deals with the origin and manifestations of a dusty plasma over the Moon. From the Apollo era of exploration, it was discovered that sunlight was scattered 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). The Surveyor landers observed dust grains levitating about 10 cm above the surface. During the Apollo missions, 0.1-μm scale dust in the lunar exosphere was observed up to about 100-km altitude.

Since the Moon is in the solar wind plasma flow for most of its orbit, lunar dust constitutes a part of a dusty plasma system. This also takes place for the situation when the Moon is not in the solar wind. For about one-quarter of its orbit, the Moon is either in the tenuous plasma of the Earth's magnetospheric tail lobes, or the turbulent and energetic plasmas encountered in the magnetosheath and the plasma sheet. At the orbit of the Moon, the plasma conditions in the magnetosheath are not significantly different from those in the solar wind. However, inside the magnetosphere, the plasma environments are typically much more tenuous and significantly hotter than in the solar wind. The plasma sheet is much hotter than the tail lobes. This is an important factor for lunar surface and dust grain charging.

The surface of the Moon is charged under the action of the electromagnetic radiation of the Sun, solar-wind plasma, and plasma of the Earth's magnetotail. The surface of the Moon and dusts levitating over the lunar surface interact with solar radiation. They emit electrons due to photoelectric effect, which leads to the formation of a photoelectron layer over the surface. Dusts located on or near the surface of the Moon absorb photoelectrons, photons of solar radiation, electrons and ions of the solar wind, and, if the Moon is in the Earth's magnetotail, electrons and ions of the magnetospheric plasma. All these processes lead to the charging of dust particles, their interaction with the charged surface of the Moon, and rise and motion of dust.

Usually, conclusions about the dusty plasma system over the Moon are made on the basis of consideration of the motion of single charged dust particles (Colwell et al. 2009). Furthermore, data on the near-surface density of dust on the Moon are almost non-existent. The existing works describe the dust density using either the model disregarding photoelectrons (Stubbs et al. 2007) that is certainly inapplicable for the surface dusty plasma layer or analysis of the scattering of light by dust on Apollo 15 (Glenar et al. 2011). The dust density was estimated by Glenar et al. (2011) at altitudes of several kilometers. An attempt to describe the dusty plasma system in the surface layer of the Moon using the consideration of the motion of single charged dust particles was made by Golub' et al. (2012), where the charging of dust particles over the surface of the Moon is calculated taking into account the effect of photoelectrons from the lunar surface, electrons and ions of the solar wind, and solar radiation. The consideration of single charged dust particles does not allow us to take into account the photoelectrons from the dust particle surfaces which modify the results (distributions of dust particles and electrons over the lunar surface) strongly and require a self-consistent investigation, because the photoelectrons influence dust particle distributions, while the dust particle distributions determine the number of photoelectrons.

The Moon landing of the Luna-Glob and Luna-Resource missions will be performed near the polar regions of the Moon. Recent detections by Mitrofanov et al. (2010) of neutron fluxes passing through regions of the surface of the Moon in the Southern Hemisphere of the Moon on the Lunar Reconnaissance Orbiter show the existence of hydrogen-enriched regions in the surface layer of the Moon at lunar latitudes exceeding 70°. The investigation reported by Mitrofanov et al. (2010) possibly indicates the existence of ice in surface regions of the Moon, and the existence of surface regions of hydrogen is possibly due to electrons and protons of the solar wind, which collide with the Moon and are absorbed by its surface, where they form neutral hydrogen atoms. This hydrogen can rise on the surface of the Moon in the form of atomic or molecular hydrogen or water vapor (Kolesnikov and Manuilov 1982). In this case the sensitivity of hydrogen-enriched regions of the surface of the Moon to photoemission is much higher than that of surrounding regions; this finally affects the charging of dust particles and their dynamics. Measurements on the Luna-Glob and Luna-Resource are planned in the daytime to ensure the power supply of instruments at lunar stations because of solar energy. All of this shows an importance of the analysis of the situations where dust particles levitate over lunar regolith regions and hydrogen-enriched regions in the daytime when the surface of the Moon is illuminated by solar radiation.

In this paper the dusty plasma system near the surface layer of the Moon is considered (Sec. 2) for the lunar regolith and hydrogen-enriched regions. We also discuss the importance of micrometeoroid impacts and condensation during the expansion of the impact plume from the viewpoint of explanation of dust particle rise to high altitudes. A summary of our findings is given in Sec. 4.

2. Dusty plasma system in the surface layer of the Moon

To describe the dusty plasma system in the surface layer of the Moon, we use a modified model (Golub' et al. 2012) in which the charging of dust particles over the surface of the Moon is calculated taking into account the effect of photoelectrons, electrons and ions of the solar wind, and solar radiation. The interaction of dust particles with the plasma of the Earth's magnetotail is neglected because this interaction is significant only for the dark side of the Moon. The modification of the model (Golub' et al. 2012) is that here we take into account the photoelectrons from both the lunar surface and the surfaces of dust particles whereas in Golub' et al. (2012) only the photoelectrons from the lunar surface are taken into account. The consideration of photoelectrons from the dust particle surfaces modifies the model strongly and requires a self-consistent investigation because the photoelectrons influence dust particle distributions whereas the dust particle distributions determine the number of photoelectrons.

The angle between the Moon's axis and the ecliptic plane is only 1.5424°, which determines the small difference of the lunar latitude from angle θ between the local normal and the direction to the Sun. For this reason, calculations are performed in terms of angle θ. Furthermore, we use two photoemission working functions: $W = W_R = 6\,\text{eV}$ for regolith regions, and $W = W_H = 4\,\text{eV}$ for hydrogen-enriched regions of the surface of the Moon.

Here we present photoelectrons and dust distributions obtained as a result of our calculations. The photoelectron density $n_{e,\text{ph}}$ as a function of the height h within the range of angle θ from 0° to 89° is described with a good accuracy by the formula

$$n_{e,\text{ph}} \approx N_0 \frac{\cos\theta}{[1+\sqrt{\cos\theta/2}(h/\lambda_D)]^2} + N_e\left(h/h_1\right)^{\alpha}, \quad (2.1)$$

where $N_0 \approx 2\times 10^5\,\text{cm}^{-3}$ for regolith regions and $N_0 \approx 2\times 10^8\,\text{cm}^{-3}$ for hydrogen-enriched regions, λ_D is the Debye length for photoelectrons with the temperature $T_{e,\text{ph}} \approx 0.1\,\text{eV}$ and the number density N_0, $h_1 = 1\,\text{cm}$, and the constants α and N_e are given in Fig. 2 for regolith and hydrogen-enriched regions of the surface of the Moon.

Data characterizing the dust distributions under the conditions corresponding to the lunar regolith region are plotted in Figs. 3 and 4. Histograms given in Figs. 3(a)–(c) present the results of calculations of the number densities n_d of dust particles over the surface of the Moon for $\theta = 77°$, 82°, and 87°. The length of the single-color horizontal segment in each of the plots shown in Fig. 3 characterizes the density of particles (in cm^{-3}) with sizes in the corresponding interval (indicated on the right scale) at the corresponding heights. The total length of the horizontal segment in the plot corresponds to the total density of the particles with the sizes presented in this plot. Figures 3(d) and 4 show, respectively, maximum possible rise heights of dust particles of various sizes and the height distributions of dust charge numbers Z_d for different θ.

For hydrogen-enriched lunar regions, the height distributions of electrons and dusts are qualitatively the same as in the case of regolith surface. The calculated maximum possible rise height of dust particles of various sizes (from 10 to 250 nm) over hydrogen-enriched regions is shown in Fig. 5 as a function of angle θ. The solid lines in Fig. 5 are the exact solutions that are obtained under the assumption of the smooth spherical surface of the Moon. It can be seen that for each size of dust particles there is a certain critical angle θ (larger than 74° for the sizes of the particles under consideration) such that the rise of particles under the indicated assumption is impossible for angles smaller

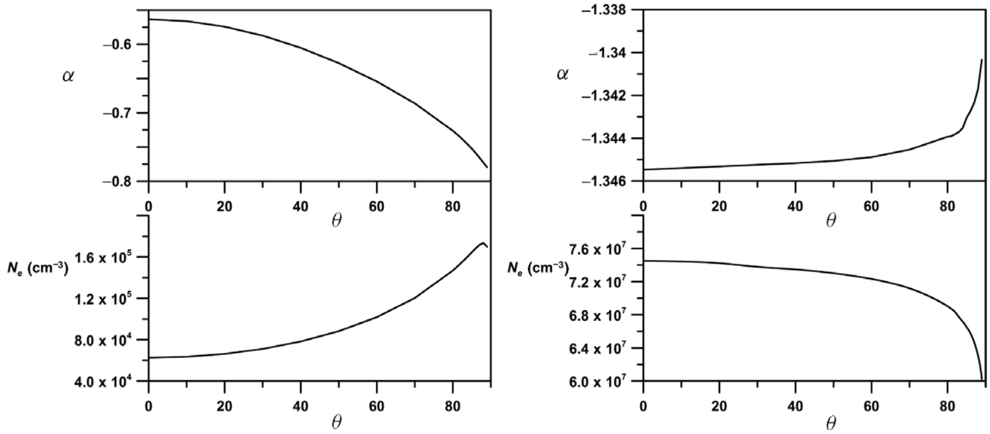

Figure 2. The constants α and N_e vs. θ for regolith regions (left panel) and hydrogen-enriched regions (right panel) of the surface of the Moon.

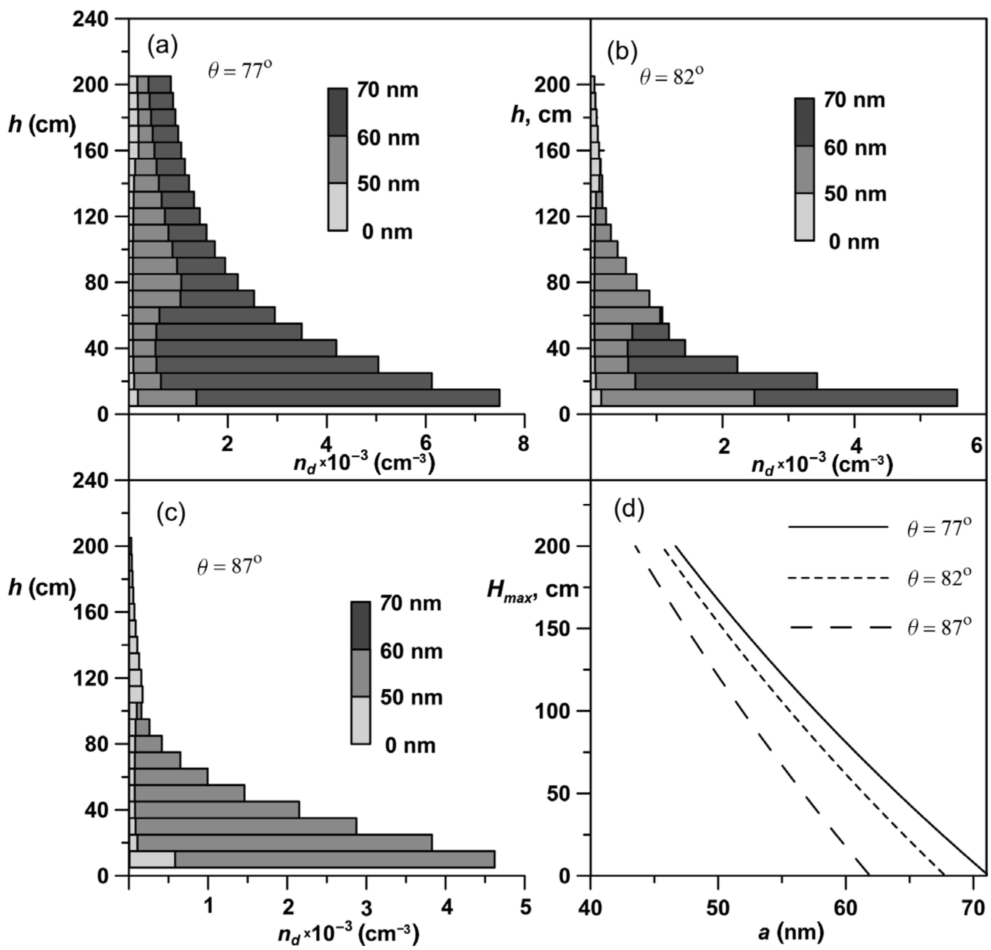

Figure 3. Distributions of dust particles over the surface of the Moon for (a) $\theta = 77°$, (b) 82°, and (c) 87° as well as (d) dependencies of maximum possible rise heights $H_{\max}$ of dust particles on their sizes a under the conditions corresponding to lunar regolith regions.

than this critical value (cf. Kolesnikov and Yakovlev 1997). The reason for the indicated constraint is the fact that the electrostatic and gravitational forces act on dust particle in different directions. The condition for the separation of a positively charged dust particle from the positively charged surface of the Moon is the dominance of the electrostatic force over the attractive gravitational force. The electrostatic force depends on the charge of the particle, which in turn strongly depends on the density of photoelectrons. At θ smaller than the critical value, photoelectrons that are incident on the dust particle and reduce its (positive) charge prevent the dominance of the electrostatic force over the attractive gravitational force. However, owing to the

https://doi.org/10.1017/S0022377813000214 Published online by Cambridge University Press

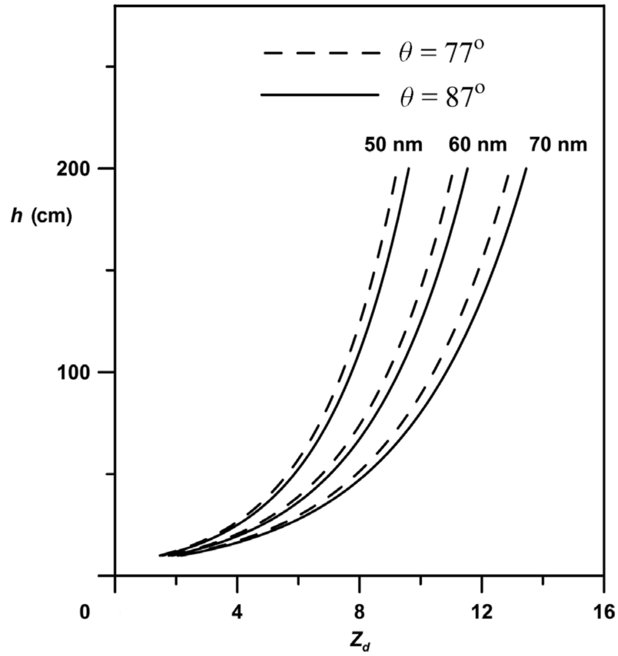

Figure 4. Height distributions of dust particle charge numbers Z_d over regolith regions of the surface of the Moon for (a) $\theta = 77^o$, (b) 82^o, and (c) 87^o and dust particle sizes of 50 nm, 60 nm, and 70 nm.

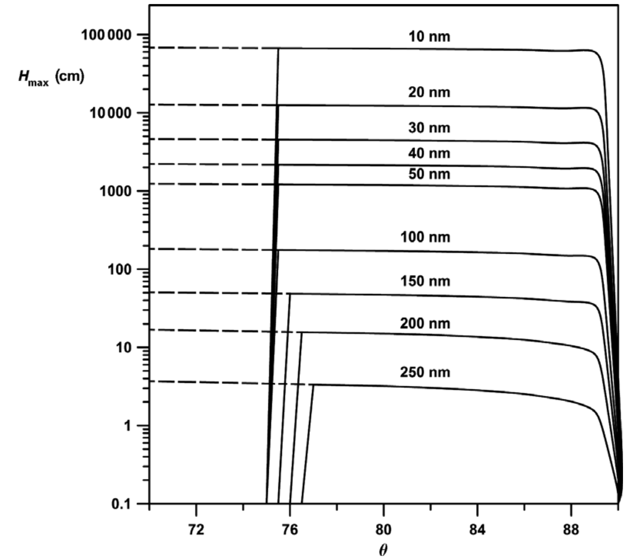

Figure 5. Maximum possible rise heights of dust particles of various sizes over hydrogen-enriched regions of the surface of the Moon versus angle θ.

sharp decrease in the density of photoelectrons with an increase in height, even at angles θ smaller than the critical value, the dust particle rising at a height of about 1 mm because of some processes acquires a positive charge sufficient for the dominance of electrostatic force over gravitational force. As a result, the particle continues to rise and reaches significantly larger heights. This fact is marked in Fig. 5 by dashed lines. The reasons for the separation of dust particles from the surface of the Moon are, in particular, their heating by solar radiation and cooling. The linear sizes of dust particles in the surface layer and, correspondingly, their pressures on each other change. As a result, at a certain arrangement of particles, forces ejecting them upward appear. This process depends on the linear expansion coefficient, the heat conductivity of rock in the upper layer, and the time of thermal action, and can be enhanced in the presence of a volatile adsorbed component in the surface layer. In addition, at angles θ smaller than the critical value, inhomogeneities of the surface of the Moon ensure the rise of particles to heights of about the characteristic size of inhomogeneities because of electrostatic effects. Thus, the possibility of rising dust particles over the surface of the Moon in the entire range of angles θ is demonstrated. We emphasize that the characteristics of dust rising over the lunar regolith and hydrogen-enriched regions of the lunar surface are different. The difference is that the dust levitating over hydrogen-enriched regions has larger sizes (up to $\approx$ 250 nm), larger charges, rises to larger heights, etc. than in the case when the dust levitates over the lunar regolith region.

Thus, the dusty plasma system in the surface layer of the illuminated part of the Moon includes positively charged dust, photoelectrons, and electrons and ions of the solar wind. There are no significant constraints (Golub' et al. 2012) on the Moon landing sites for future lunar missions that will study dust in the surface layer of the Moon.

3. Dust at high altitudes

Figures 3 and 5 show that dusty plasma effects do not result in the rise of 100-nm dust particles up to the altitudes of about 100 km over the lunar surface. To explain the presence of 100-nm 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 larger (10–100-nm) negatively charged grains around the terminator region. However, it appears that submicron dust grains could contaminate astronomical observations of infrared, 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 the many ways in which dust could interfere with the science and exploration activities on the Moon.

Another phenomenon which can be responsible for the appearance of dust particles at the altitudes of about 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). In Fig. 6, the portions of the impact processes are presented schematically. Among them are optical photons appeared due to the impact, plume formation and evolution, formation of

https://doi.org/10.1017/S0022377813000214 Published online by Cambridge University Press

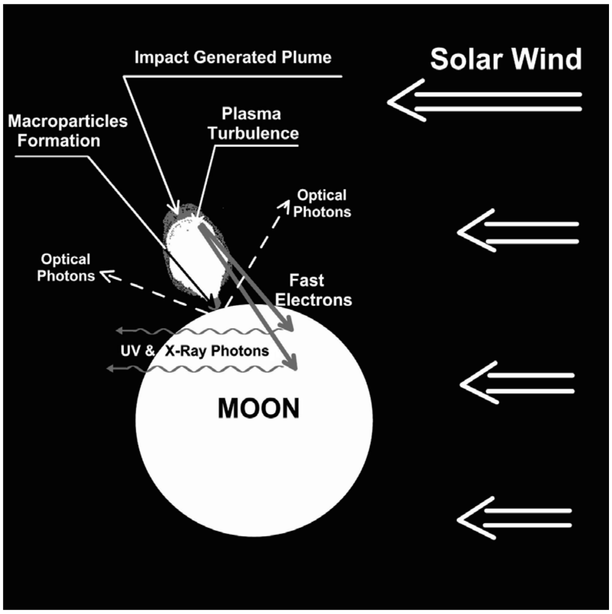

Figure 6. The portions of impact processes: optical photons appeared due to meteoroid impact onto the Moon, plume formation and evolution, formation of dusts (droplets) in the plume, zone of plasma turbulence in the region of the solar wind interaction with the plume, generation of fast electrons as well as the UV and x-ray photons (Nemtchinov et al. 2002; Popel and Gisko 2006).

dust particles (droplets), zone of plasma turbulence in the region of solar wind interaction with plume, generation of fast electrons as well as the UV and x-ray photons.

The evolution of the impact plume can lead to the formation of charged particles. One type of 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 centers of condensation is very short and all droplets have approximately the same size. The degree of condensation is usually between 0.1 and 0.5. The droplets move together with the substance of the plume. Their speed often exceeds the first astronautical velocity of 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 km/s and 2.38 km/s, perform finite movement around the Moon. The estimates based on the methods by Zeldovich and Raizer (1967) for 1-μm iron meteoroid and the droplet speed of 2.38 km/s give the value of the order of 100-nm for droplet size. The impact flux for such (1-μm size) micrometeoroids in space is of the order of 10^{-4} impacts/m^2/s (Drolshagen et al. 2008). Thus, one can expect an appearance of $\sim 3.6 \times 10^9$ particles (with the sizes of about 100 nm) per second from the lunar surface, the particles rising to 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 in addition to dusty plasma effects.

4. Summary

Thus, we have discussed the future experimental investigations of lunar dust within the missions of Luna-Resource and Luna-Glob and presented some results of theoretical investigations of dusty plasma over the lunar surface. We have described mechanisms of formation of the dusty plasma system over the Moon and its main properties, determined maximum heights of lunar dust rise due to dusty plasma effects, found height distributions of electrons and the dust as well as size-distributions of the dust, and shown the importance of the effect of condensation of micrometeoriod substance during the expansion of the impact plume from the viewpoint of explanation of dust particle rise to high altitudes. We have demonstrated that the dusty plasma system in the surface layer of the illuminated part of the Moon includes positively charged dust, photoelectrons, and electrons and ions of the solar wind. The characteristics of dust rising over the lunar regolith and hydrogen-enriched regions of the surface of the Moon are different. This is indicated, in particular, by the size and height distributions of dust particles. In view of the absence of the dead zone near a lunar latitude of $\theta = 80^{\circ}$, where, as was assumed by Stubbs et al. (2006), dust particles cannot rise over the surface of the Moon, there are no significant constraints on the Moon landing sites for future lunar missions that will study dust in the surface layer of the Moon.

Acknowledgements

This work was supported by the Presidium of the Russian Academy of Sciences (basic research program No. 22 'Fundamental Problems of Research and Exploration of the Solar System'), the Russian Foundation for Basic Research (project No. 12-02-00270-a), and the International Space Science Institute (project "Dusty Plasma Effects in the System Earth-Moon").

References

Colwell, J. E., Robertson, S., Horányi, M., Wang, X., Poppe, A. and Wheeler, P. 2009 Lunar dust levitation. *J. Aerosp. Eng.* **22**, 2–9.

Drolshagen, G., Dikarev, V., Landgraf, M., Krag, H. and Kuiper, W. 2008 Comparison of meteoroid flux models for near Earth space. *Earth Moon Planets* **102**, 191–197.

Glenar, D. A., Stubbs, T. J., McCoy, J. E. and Vondrak, R. R. 2011 A reanalysis of the Apollo light scattering observations, and implications for lunar exospheric dust. *Planet. Space Sci.* **59**, 1695–1707.

Golub', A. P., Dol'nikov, G. G., Zakharov, A. V., Zelenyi, L. M., Izvekova, Yu. N., Kopnin, S. I. and Popel, S. I. 2012 Dusty plasma system in the surface layer of the illuminated part of the Moon. *JETP Lett.* **95**, 182–187.

Kolesnikov, E. K. and Manuilov, A. S. 1982 Calculation of the electrostatic field intensity over the lunar surface covered by hydrogen monolayer. *Sov. Astron.* **26**, 502–506.

Kolesnikov, E. K. and Yakovlev, A. B. 1997 Condition for the electrostatic levitation of lunar-regolith microparticles. *Solar Syst. Res.* **31**, 62–64.

Mitrofanov, I. G., Sanin, A. B., Boynton, W. V., Chin, G., Garvin, J. B., Golovin, D., Evans, L. G., Harshman, K., Kozyrev, A. S., Litvak, M. L., et al. 2010 Hydrogen mapping of the lunar South Pole using the LRO neutron detector experiment LEND. *Science* **330**, 483–486.

Nemtchinov, I. V., Shuvalov, V. V., Artemieva, N. A., Kosarev, I. B. and Popel, S. I. 2002 Transient atmosphere generated by large meteoroid impacts onto an atmosphereless cosmic body: gasdynamic and physical processes. *Int. J. Impact Eng.* **27**, 521–534.

Popel, S. I. and Gisko, A. A. 2006 Charged dust and shock phenomena in the solar system. *Nonlin. Proc. Geophys.* **13**, 223–229.

Popel, S. I., Kopnin, S. I., Yu, M. Y., Ma, J. X. and Huang, F. 2011 The effect of microscopic charged particulates in space weather. *J. Phys. D: Appl. Phys.* **44**, 174036, 7 p.

Rennilson, J. J. and Criswell, D. R. 1974 Surveyor observations of lunar horizon-glow. *The Moon* **10**, 121–142.

Shukla, C. J. and Mamun, A. A. 2002 *Introduction to Dusty Plasmas Physics*. Bristol, UK: Institute of Physics.

Stubbs, T. J., Vondrak, R. R. and Farrell, W. M. 2006 A dynamic fountain model for lunar dust. *Adv. Space Res.* **37**, 59–66.

Stubbs, T. J., Vondrak, R. R., Farrell, W. M. and Collier, M. R. 2007 Predictions of dust concentrations in the lunar exosphere. *J. Astronaut.* **28**, 166–167.

Tsytovich, V. N., Morfill, G. E., Vladimirov, S. V. and Thomas, H. 2008 *Elementary Physics of Complex Plasmas*. Bristol, UK: Institute of Physics.

Vladimirov, S. V., Ostrikov, K. and Samarian, A. A. 2005 *Physics and Applications of Complex Plasmas*. London: Imperial College Press.

Zeldovich, Ya. B. and Raizer, Yu. P. 1967 *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, Vol. 2. Waltham, MA: Academic Press.

Zook, H. A. and McCoy, J. E. 1991 Large scale lunar horizon glow and a high altitude lunar dust exosphere. *Geophys. Res. Lett.* **18**, 2117–2120.