Dusty plasma environment near lunar surface

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Abstract. The dusty plasmas on the Moon are investigating through the direct detection of the dust particle fluxes on the lunar surface and through the measurements of the parameters of ambient plasma. The PmL instrument is the first device developed both to detect dust particles and to determine the characteristics of the plasma environment. The PmL instrument mounted on future Russian lunar missions Luna-25 and Luna-27 is described in the article. The suggested landing sites of the stations are situated nearby the Boguslavsky crater (nearby 70° south latitude of Moon). The values of the lunar surface potential, Debye length and electric field at a latitude of 70° were obtained in this paper. The distribution of the dust particles near the selected latitudes was also determined. A brief description of the methods for detecting the dusty plasma parameters near the lunar surface was suggested.

1. Introduction
Dusty plasma is the plasma that contains sets of the electrons, the ions, the neutrals, and the dust microscopic particles consisting of either solid or liquid materials. The results of the different investigations of dusty plasmas are interdisciplinary and considered with the astrophysics, the planetary science, the atmospheric science, the fusion science, and used in the development of the various technological process [1-5].

The lunar exosphere is an important example of dusty plasma system in nature. The Moon is immersed in the solar wind plasma where ions and electrons have a variable speed. Due to the faster speed of the thermal electrons, the lunar surface would collect electrons and negative charge in the absence of other currents. At the same time the surface of the Moon is directly exposed to the full solar spectrum influence with including high-energy photons that can eject electrons from the surface. On the lit lunar surface the photoemission is the dominant current and the surface becomes positively charged to a surface potential approximately equal to the energy of the photoelectrons [6]. The value of the potential developed between the lunar surface and ambient plasma was determined in [7] with the help of the collisionless electrostatic probe theory and took the value of 10 V. The measurements of the lunar surface potential were made firstly by Apollo Suprathermal Ion Detector Experiment [8]. This instrument found the energy of ions at the lunar surface and determined the dayside potential as about +10 V. Next measurements of surface potential and electron fluxes were made by Lunar Prospector [9]. The plasma parameters measured by Lunar Prospector allowed calculating the distribution of the lunar surface potential in dependence on solar zenith angle (SZA) for different solar wind conditions [10].
The levitating dust particles are also a component of the lunar exosphere. The discovery of rising lunar dust was made in the post-sunset Surveyor lunar lander television camera images under the lunar horizon [11]. During the Apollo missions 0.1 µm scale dust was observed up to about 100 km altitude [12]. Similar conclusions were made from observations of the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, which have demonstrated the existence of dust grains at heights from 30 to 110 km [13]. The distributions of the dust and electrons in the near surface layers due to the irradiance of the Moon were calculated in [14]. The results were obtained using the theoretical model in which the charging of dust grains over the lunar surface is determined within the orbit-limited probe model. The [15] shows that the ranges of the stable levitation levels and the maximum allowable sizes of levitating dust particles depended on both the cyclic changes in the uv part of the solar spectrum and on the variation of the parameters of the solar wind (SW).

The lunar exosphere is one of the objects of interest for the future Russian lunar missions: Luna-25 and Luna-27. The landing sites of the stations are situated nearby the Boguslavsky crater (nearby 70° south latitude of Moon). The PmL instrument created both for registration of the dust particles and for measuring the characteristics of the ambient plasma is mounted on the board of the stations for the first time. In the paper the parameters of the dusty plasma environment were investigated close to the landing site of the future lunar missions. The lunar surface potential is calculated for different values of the solar zenith angle using the collisionless electrostatic probe theory. The distributions of the Debye length and the electric field in dependence on SZA are obtained. Dust particle distribution depending on the height above the lunar surface is considered. A brief description of the functional features of the PmL device is presented.

2. Dusty plasma environment near the surface of the Moon

2.1. Lunar surface potential

In order to better understanding the plasma process near the landing sites of the future lunar missions we calculate the distributions of a potential, Debye length and an electric field in dependence of the solar zenith angle \( \chi \). SZA is related to the latitude \( \theta \) by the following expression \( \chi = \theta + \delta \), where \( 90° - \delta \) is the angle between the axis of rotation of the Moon and the plane of the ecliptic. Under the lunar condition we assume that \( \chi \approx \theta \). Considering the operating mode of the lander we investigate the surface charging processes of the dayside of the Moon.

First, under the conditions of stationary plasma, we calculate the surface potential \( \phi_S \) with the help of the basic probe equations assuming spherical symmetry first derived in [16] and summarized in [17]. The plasma sheath can be assumed to be the thin skin in comparison to the lunar radius for most of the cases considered. In addition, the dc conductivity at the lunar surface can be assumed to be very small so that the potential of the local lunar surface can be calculated as if the equilibrium condition at that point existed over the entire surface. The local lunar surface reaches a potential \( \phi_S \) when the net current to it is zero,

\[
I_{ph} + I_e + I_i + I_s = 0, \tag{1}
\]

where \( I_{ph} \) is the photoelectron current density induced by uv radiation, \( I_e \) is the electron current density of solar wind, \( I_i \) is the ion current density of solar wind, and \( I_s \) is the secondary electron current density.

Let us determine equations for the current densities mentioned in equation (1). We calculate the current densities under the assumptions that the photoelectron and plasma populations involved have a non-relativistic, isotropic Maxwellian velocity distribution function. The sign of the expressions for current densities depends on whether the species is repelled (plus) or attracted.
Figure 1. The plasma parameters near the lunar surface in dependence on SZA: (a) electrostatic potential; (b) Debye length; (c) electric field calculated in dependence on solar zenith angle. Solid lines represent the distributions calculated under the conditions of the slow stream; dotted lines indicate the distributions obtained under the conditions of the slow stream. Dash-dotted line shows the SZA value of $\chi = 70^\circ$.

(minus). The photoelectron current density is determined using the following equation suggested in [10]

$$I_{ph} = I_{P0} \cos \chi \exp \left( \frac{-e \varphi_S}{k_B T_{ph}} \right), \quad (2)$$

where $I_{P0}$ is the photoelectron current density produced by sunlight at normal incidence to the surface at 1 AU depends on the solar spectrum and the photoemissive properties of the regolith [10], $k_B$ is the Boltzmann constant, $T_{ph}$ is the photoelectron temperature. The current density of the electrons of the solar wind we calculate using the formula [7]

$$I_e = -en_0 \left( \frac{k_B T_e}{2\pi m_e} \right)^{0.5}, \quad (3)$$

where $n_0$ is the electron density, $T_e$ is the electron temperature, $m_e$ is the electron mass. On the dayside the photoemission current charges the lunar surface positively and the lunar surface
Table 1. Typical fast and slow stream conditions suggested in [10, 21].

| Parameter                              | Slow stream | Fast stream |
|----------------------------------------|-------------|-------------|
| Concentration $n_0$ (cm$^{-3}$)        | 10.0        | 5.0         |
| Electron temperature $T_e$ (K)         | $1.4 \times 10^5$ | $1.4 \times 10^5$ |
| Ion temperature $T_i$ (K)              | $1.0 \times 10^5$ | $1.5 \times 10^5$ |
| Photoemission current density $I_{P0}$ (µA m$^{-2}$) | 4.5         | 4.5         |
| Photoelectron temperature $T_{ph}$ (K) | $1.7 \times 10^5$ | $1.7 \times 10^5$ |
| Photoelectron concentration $n_{p0}$ (cm$^{-3}$) | 139         | 139         |

repels the ions. In the following calculations we consider that all the ions are the protons. The expression for ion current density is given on the following way [7]

$$I_i = en_0 \left( \frac{k_B T_i}{2\pi m_i} \right)^{0.5} \exp \left( -\frac{e \varphi_S}{k_B T_i} \right),$$  \hspace{1cm} (4)

where $T_i$ is the ion temperature, $m_i$ is the proton mass. In our calculations we also neglect that 10–20% of solar wind ions reflect from the surface with 0.1–1% of them remaining charged and the remainder gaining an electron to become energetic neutral atoms [18]. We assume that the plasma particles incident on the surface are absorbed with no secondary emission of electrons, so $I_s = 0$.

Second, we suggest the way to calculate the dependence of the Debye length $\lambda_D$ on the SZA. On the dayside the positively charged surface is shielded by the photoelectrons and plasma electrons, and $\lambda_D$ is obtained by the following expression [10]

$$\lambda_D = \left[ \frac{\varepsilon_0 k_B T_{ph}}{e^2 (n_{p0} + n_0 (T_p/T_e))} \right]^{1/2},$$  \hspace{1cm} (5)

where $n_{p0}$ is the photoelectron density at the surface. The equation (5) is derived using the following relation $\lambda_D^{-2} = \lambda_{DP}^{-2} + \lambda_{DE}^{-2}$, where $\lambda_{DP}$ and $\lambda_{DE}$ are the Debye lengths for the photoelectron and plasma electron components respectively [19].

The third parameter characterized the plasma environment near the landing site of Luna-25 and Luna-27 is the electric field, $E$. Under the assumption of the approximately exponential drop in potential

$$\varphi = \varphi_S \exp \left( -\frac{x}{\lambda_D} \right),$$  \hspace{1cm} (6)

where $x$ is the distance from the lunar surface [20], the electric field is determined using the following expression

$$E \propto \frac{\varphi_S}{\lambda_D}.$$

Figure 1 shows the dependences of the equilibrium potential $\phi_S$, the Debye length $\lambda_D$ and the electric field $E$ on the solar zenith angle $\chi$. Due to the fact that the solar wind flow is broadly divided into two main types: fast and slow streams [21], the plasma parameters are calculated using the values suggested table 1 for two types of the solar wind.

Figure 1(a) shows that the equilibrium potential decreases nonlinearly with increasing of SZA under conditions of a slow solar wind. At the $\chi = 70^\circ$ the surface potential is equal to $\phi_S = 0.8$ V. The decrease of the surface potential is due to the drop in solar illumination and photoelectric
current density $J_{\text{ph}}$. Under the fast solar wind conditions the character of the dependence of $\phi_S$ on $\chi$ does not change, however, the potential increases in magnitude and reaches the value of $\phi_S = 1.8 \text{ V}$ at $\chi = 70^\circ$. As well as being faster, the fast streams usually have lower $n_0$ and hotter $T_i$ than slow streams, see table 1. These differences arise from the fact that the slow streams originate from the equatorial regions of the Sun, while the fast streams originate from the polar regions [21]. The $\phi_S$ values on the dayside are higher during fast streams due to the drop in $n_0$, as well as the relative increase in $J_i$ driven by increased velocity of solar wind (and to a lesser extent increased $T_i$). At the same time, a drop in the electron concentration does not make a significant contribution to the change in the Debye length, see figure 1(a), which in both cases takes the value of $\lambda_D = 1.3 \text{ m}$ at $\chi = 70^\circ$. The rise of the $\lambda_D$ values with an increase in SZA is due to the decrease in the current density of photoelectrons. In figure 1(c) one can see that the dependence of the electric field profile on the SZA mainly characterized by the values of the surface potential, see equation (7). At $\chi = 70^\circ$ the electric field takes the values of $E = 0.6 \text{ V/m}$ under the conditions of the slow stream of SW and $E = 1.4 \text{ V/m}$ under the conditions of the fast stream of SW.

2.2. Dust particles above the lunar surface

One of the goals of future lunar missions is to measure the characteristics of charged microdust particles near the lunar surface, for example, the Luna-25 landing station, designed to study dusty plasma near the lunar polar region. Let us consider the distributions of dust grains above the lunar surface for latitude of $\theta = 77^\circ$. The calculation of the dust grain distribution was conducted by the method developed in [14] for the values of photoelectron densities $n_{\text{ph}} = 1.3 \times 10^5 \text{ cm}^{-3}$ and of photoelectron temperature $T_{\text{ph}} = 1.3 \text{ eV}$. Figure 2 is shown the histograms of the computed dust grain number densities over the lunar surface. The length of the single color of the horizontal segment in each of the plots, as is shown in figure 2, characterizes the density of particles $n_d$ (in cm$^{-3}$) with sizes in the corresponding interval (indicated on the
Figure 3. (a) Front and (b) top views of the electrostatic field sensor (right) and impact sensor (left). Numbers indicate the PmL detectors: 1—charge-sensitive shaped electrode; 2—charge-sensitive grid; 3—impact piezoelectric sensor; 4—planar LP; 5—additional electrode.

The dust particle charge previously obtained by the Lunar Ejecta and Meteorites (LEAM) takes the value of the order of $10^7e$ [12]. This value is consistent with the sunrise and sunset-triggered levitation and transport of slow moving highly charged lunar dust particles.

3. PmL instrument for diagnostic lunar dusty plasma

The Russian mission Luna-25 is scheduled to be launched in 2021. The PmL instrument intended both for the direct detection of the dust particle fluxes above the surface of the Moon and for the electric field measurements at the lunar exosphere is mounted onboard the space Russian missions for the first time. The PmL device described in detail in [22] consists of 3 units: two remote electrostatic field sensors (EFSs) presented in figure 3 on the left and one impact sensor (IS) shown in figure 3 on the right. EFSs will be located at the height of 20 and 90 cm above the lunar surface. The IS will be located at the angle of $45^\circ$ to the surface and at the distance of about 20 cm.

3.1. Measurements of plasma parameters

Electrostatic field sensor consists of the charge-sensitive shaped electrode cone, see figure 3(a), and Langmuir probe (LP) located on the top of the sensor, see figure 3(b). The cone detects a charge of a dust particle greater than $10^3e$, when a dust grain has collided with it. The LP consists of the flat disk with a diameter of 3 cm and the additional electrode with a diameter of 0.3 cm. The planar LP was chosen for measuring the current–voltage characteristic in the region of ion saturation current [23]. The Langmuir probes of the PmL detect the current of charged particles to the disk surface sequentially changing the voltage from $-88$ to $+88$ V during $4.7$ s. At each moment of time, the voltage at the additional electrode, see figure 3(b), is shifted with respect to the disk voltage by 0.2 V. Such delay prevents the exit of photoelectrons and secondary electrons from the surface of the disk.

A typical current–voltage characteristic measured by the LP is shown in figure 4(a). The measurements were carried out in a vacuum chamber at a pressure of 0.001 Torr. The source of electrons with temperature $T_e = 8$ eV was a tungsten filament, the ionization of the residual
Figure 4. Typical signals detected by the PmL instrument: (a) The typical $I$–$V$ characteristic measured by the LP; arrow indicates the floating potential $V_f$. (b) The typical electrical signal detected by the impact sensor; $A_1$ is the first maximum significantly exceeding the noise level, $t_1$ is the rise time of this maximum.

gas was provided by a uv lamp with a wavelength of 120 nm. The measured $I$–$V$ curve made it possible to obtain the values of the ion saturation current 4 nA and the floating potential
$V_f = 4.2$ V. The lack of the electron saturation current on the measured curve is due to the fact that under our experimental conditions, the Debye length took the value of 0.01 cm, which is smaller than the size of the LP disk. At the latitude of $70^\circ$ of the South Hemisphere of the Moon the measurements of the plasma potential will possible due to the Debye length there takes the value of $\lambda_D = 1.3$ m, see figure 3. The electron saturation current makes possible the determine the important plasma parameters such as concentration of electrons and electron temperature, and to evaluate the electron energy distribution function (EEDF) and plasma potential [24]. The availability of two sensors located at the distance of 40 and 90 cm from the lunar surface allows us to estimate the variation of the electric field.

3.2. The detection of the dust particles
Impact sensor consists of twenty four impact piezoelectric sensors and one charge-sensitive grid, see figure 3. Due to the hit of the grain in the piezoelectric sensor, an electrical signal with an amplitude proportional to the momentum of the arriving dust particle is generated. Figure 4(b), shows the typical electrical signal generated by the piezoelectric sensor. The first maximum $A_1$ significantly exceeding the noise level and the rise time of this maximum $t_1$ make it possible to measure the momentum the dust particle. The grid detects a charge of a dust particle greater than $10^3 e$, when a dust grain has passed through it. The delay between the signal from the piezoelectric sensors and that from the charge-sensitive grid makes it possible to measure the velocity of the dust particle, and to calculate its mass under the known value of the dust particle momentum. Moreover in [25] it was shown that the shape of the electrical signal allows us to estimate the degree of porosity of dust particles.

Near the lunar surface, the average value of the dust particle velocity is equal to $v = 1$ m/s and the largest diameter of the dust particles levitating at a height of 20 cm is 400 nm, see figure 2. At the same time the ultimate sensitivity of the IS of PmL instrument allows detecting dust grain at least with diameter $> 5$ µm. So, the impact sensor could detect such a small particle size only if the grain obtained the velocity above the order of 20 m/s. It is possible under the influence of micrometeorites or with the possible occurrence of strong electric fields during the terminator [6].

4. Conclusion
In this paper, the parameters of the lunar exosphere are calculated for conditions related to the PmL instrument operation, which is part of the Luna-25 Lander. The instrument makes possible to measure both the parameters of lunar dusty plasma environment and the characteristics of the dust particles which is included in the lunar mission for the first time.

Langmuir probes, which are part of the PmL, allow measuring the parameters of the fluxes of the charged particles at height lunar latitude in the South Hemisphere. At the latitude of $70^\circ$ of the South Hemisphere of the Moon the surface potential, Debye length, and electric field calculated under the conditions of the slow solar wind takes the values $\phi_S = 0.8$ V, $\lambda_D = 1.3$ m and $E = 0.6$ V/m correspondingly. It was shown that under the conditions of fast solar wind, the values of surface potential and electric field increased by an order of 2.3 and were equal to $\phi_S = 1.8$ V and $E = 1.4$ V/m.

The calculation of the distribution of dust particles in dependence on the height above the lunar surface showed that the characteristic diameter of dust particles at latitude of was 200 nm. The sensitivity of the piezoelectric element, which is part of the device, currently does not allow measuring the parameters of dust particles of such a small diameter, but makes it possible to study the effect of micrometeorites on the formation of lunar regolith.

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