

Waves in a dusty plasma over the Moon

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The upcoming lunar missions assume often the investigation of the lunar dust. The NASA's LADEE (Lunar Atmosphere and Dust Environment Explorer) mission was launched in 2013. LADEE is a robotic mission that will orbit the Moon to gather detailed information about the lunar exosphere, conditions near the surface and environmental influences on lunar dust. The Russian (Roscosmos) missions Luna-25 and Luna-27 have been designed for studying the lunar polar regions. These missions will, in particular, include investigations of dust near the surface of the Moon [1-5]. Measurements are planned in the daytime to ensure the power supply of instruments at lunar stations owing to solar energy.

The present paper deals with the waves in a dusty plasma over the lunar dayside. Dusty plasma of the lunar exosphere is an unstable system which admits the excitation of waves, because of the relative motion of solar wind with respect to the photoelectrons and charged dust particles. By turn, the waves in a dusty plasma over the Moon can influence the results of measurements performed within the future lunar missions.

Plasmas over the lunar dayside contain electrons, ions, neutrals, and fine dust particles [6]. Dusts located on or near the surface of the Moon absorb photons of solar radiation, electrons and ions. All these processes lead to the charging of dust particles, their interaction with the charged surface of the Moon, rise and levitation of dust [1, 2, 7]. Typical distributions of charged dust particles over the sunlit lunar surface are given in [2].

Despite the existence of neutrals in the lunar atmosphere on the lunar dayside ($\sim 10^5 \text{ cm}^{-3}$), the long photo-ionization time-scales ($\sim 10 - 100$ days) combined with rapid ion pick-up by the solar wind (~ 1 s) should limit the associated electron and ion number densities to only $\sim 1 \text{ cm}^{-3}$. However, there are some indications on larger electron number densities in the lunar ionosphere. In particular, the Soviet Luna-19 and Luna-22 spacecrafts conducted a series of radio occultation measurements to determine the line-of-sight electron column number density, or total electron content, above the limb of the Moon as a function of tangent height [8]. From these measurements they inferred the presence of a "lunar ionosphere" above the sunlit lunar surface with electron number densities reaching 1000 cm^{-3} .

Electrons over the lunar dayside appear [2] due to the photoemission from the lunar surface

as well as from the surfaces of dust particles levitating over the Moon, while the photoelectron emission is due to the solar vacuum ultraviolet (VUV) radiation. The electron distributions can be represented in the first approximation as a superposition of two Maxwellian those characterized by different electron temperatures. The photoelectron distribution function is determined by the integral (over the relevant photon energy range) containing the Solar radiation flux I and photoelectric yield Y as multipliers [9]. The largest contributions to the distribution function are due to photon energies in the vicinity of the work function W (in our case of 5 to 6 eV) and in the photon energy range corresponding to H Lyman-alpha line of the solar radiation spectrum (10.2 eV). The existence of these ranges results in an appearance of two groups of the photoelectrons. The first one (corresponding to the photon energies close to the work function) is characterized by large photoelectron number density and small electron temperature, while the second one (corresponding to the photon energies close to 10.2 eV) – by small photoelectron number density and large electron temperature. The contributions N_{01} , N_{02} to the photoelectron number density N_0 and the electron temperatures T_{e1} and T_{e2} are given in Table 1. The columns I, II, III, and IV in Table 1 correspond to the conditions of the X28 class solar flare, solar maximum, solar minimum [7, 10], and those based on the data [11, 12], respectively. Here and below, the subscripts 1 and 2 fit the contributions due to photon energies close to the work function W and H Lyman-alpha line.

Table 1. Parameters of the near-surface photoelectron environment for different solar activity conditions

	I	II	III	IV		I	II	III	IV
N_{01} , cm ⁻³	$2.2 \cdot 10^5$	$2.1 \cdot 10^5$	$1.9 \cdot 10^5$	$2.0 \cdot 10^5$	N_{02} , cm ⁻³	$6.0 \cdot 10^3$	$1.3 \cdot 10^3$	$4.6 \cdot 10^2$	$8.6 \cdot 10^2$
T_{e1} , eV	0.2	0.1	0.1	0.1	T_{e2} , eV	1.2	1.3	1.2	1.3

At the daytime the surface of the Moon is subjected to the action of the solar wind. The typical solar wind parameters are: the electron and ion (proton) number densities $n_{eS} \approx n_{iS} = 8.7 \text{ cm}^{-3}$, the electron temperature $T_{eS} = 12 \text{ eV}$, the ion temperature $T_{iS} = 6 \text{ eV}$, the solar wind velocity $u_S = 400 \cdot 10^5 \text{ cm/s}$. The relative motion of the solar wind with respect to the ambient dusty plasma results in the excitation of waves over the lunar surface.

An instability due to the relative motion of the solar wind with respect to the photoelectrons develops for the case of high-frequency oscillations, when $kv_{TiS} \ll kv_{Te1} \ll \omega \ll kv_{Te2} \ll kv_{TeS}$. Here, \mathbf{k} is the wave number, $k = |\mathbf{k}|$, ω is the wave frequency. In this case (with taking into account the characteristic parameters of the dusty plasma constituents) the linear dispersion relation is

$$1 - \frac{\omega_{pe1}^2}{\omega^2} + \frac{1}{k^2 \lambda_{De2}^2} - \frac{\omega_{piS}^2}{(\omega - k u_S)^2} = 0, \quad (1)$$

where $\omega_{pe(i)}$ is the electron (ion) plasma frequency, λ_{De} is the electron Debye length, the subscript S characterizes a physical value determined by the solar wind parameters.

For instability the dispersion relation (1) must have at least two complex roots; the condition for this is $ku_S < \omega_{pe1}$. The unstable solution of (1) is

$$\omega = ku_S \left(1 + i\omega_{piS} / \sqrt{\omega_{pe1}^2 - k^2 u_S^2} \right). \quad (2)$$

The wave number and the growth rate of the most unstable mode are equal approximately to $k_{\max} \approx \omega_{pe1}/u_S$ and $\gamma_{\max} \approx \omega_{pe1}v_{Te2}/u_S$, respectively. Thus the relative motion of the solar wind with respect to the photoelectrons results in the excitation of high-frequency oscillations with frequencies in the range of Langmuir and electromagnetic waves in a dusty plasma near the lunar surface.

Another situation when oscillations can propagate in a lunar dusty plasma corresponds to the case $kv_{Td} \ll \omega \ll kv_{TiS}$. In this case (with taking into account the characteristic parameters of the dusty plasma constituents) the dispersion equation takes the form

$$1 + (1/k^2 \lambda_{De1}^2) - \left(\omega_{pd}^2 / \omega^2 \right) = 0, \quad (3)$$

which corresponds to the well-known dust acoustic waves [13]. Here, v_{Td} is the thermal dust speed, ω_{pd} is the dust plasma frequency. The dispersion equation (3) does not have unstable solutions. The excitation of the dust acoustic waves can take place in the vicinity of the lunar terminator. The terminator's speed (several hundred cm/s) 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 [14], 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 $M > 1$.

Thus the dusty plasma system over the lunar dayside contains photoelectrons, electrons and ions of the solar wind, neutrals, and fine dust particles. The photoelectron distribution function in the first approximation can be represented as a superposition of two Maxwellian distribution functions which are characterized by different electron temperatures and number densities. The first one is formed due to photons with energies in the vicinity of the work function of the lunar regolith while the second one is due to photons corresponding to the H Lyman-alpha line of the solar radiation spectrum. The relative motion of the solar wind with respect to the photoelectrons results in the excitation in a dusty plasma near the lunar surface of high-frequency oscillations

with frequencies in the range of Langmuir and electromagnetic waves. The excitation of the dust acoustic waves is possible in the vicinity of the lunar terminator.

This work was supported by the Alexander von Humboldt Foundation, by the Presidium of the Russian Academy of Sciences (basic research program no. 22), by the Russian Foundation for Basic Research (project no. 12-02-00270-a), and by the International Space Science Institute (project “Dusty Plasma Effects in the System Earth-Moon”).

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