LINEAR AND NONLINEAR WAVES IN THE LUNAR EXOSPHERE

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Abstract. Linear and nonlinear waves in a dusty plasma over the lunar dayside are considered. It is shown that the relative motion of the solar wind with respect to the photoelectrons over the lunar surface leads to the excitation of high-frequency oscillations with frequencies in the range of Langmuir and electromagnetic waves. The dust acoustic wave excitation is possible in the vicinity of the lunar terminator. The parameters of the dust acoustic solitons in the dependence on the height over the lunar surface are determined.

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.

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 Fig. 1.

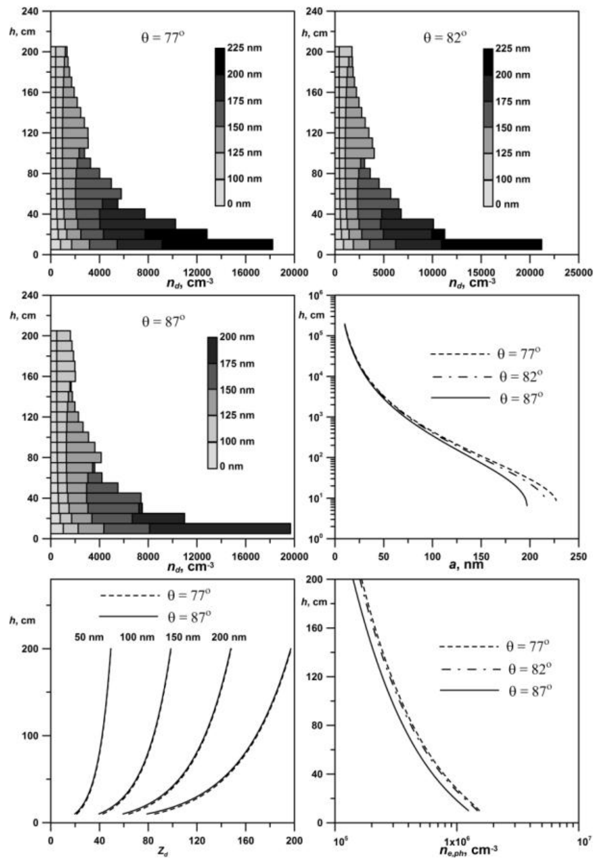

Fig. 1. Distributions of dust particles over the lunar surface calculated for the subsolar angles θ =(a) 77°, (b) 82°, and (c) 87°, the maximum heights (d) that may be attained by dust particles of the size a, height distributions of charge numbers Z_d of dust particles (e) over the lunar regolith areas calculated for different subsolar angles and the dust particle sizes of 50, 100, 150, and 200 nm, and photoelectron distributions over the lunar surface (f); h is the height over the lunar surface.

Despite the existence of neutrals in the lunar atmosphere on the lunar dayside (~10^5cm^{-3}), the long photo-ionization time-scales (~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 ~1 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].

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 $n_{eS} \approx n_{iS} = 8.7\ \mathrm{cm}^{-3}$, the electron temperature $T_{eS}=12$ eV, the ion temperature $T_{iS}=6$ eV, the solar wind velocity $u_S=400 \cdot 10^5$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 [10]. In this case (with taking into account the characteristic parameters of the dusty plasma constituents) the linear dispersion relation is

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

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, the subscript 1 fits the photoelectrons produced by photons with the energies close to the work function of lunar regolith [10].

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

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

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

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

which corresponds to the well-known dust acoustic waves [11]. 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.

Growth of the dust acoustic waves, which occurs in the terminator region, can lead to the formation of dust acoustic nonlinear structures. Solitons play an important role among them. Description of dust acoustic solitons is given below.

The behavior of the dust acoustic solitons is governed by the conservation equations, Boltzmann distributions, and the Poisson equations

$$\partial_t n_d + \partial_x\left(n_d v_d\right) = 0, \quad \partial_t v_d + v_d \partial_x v_d = \frac{Z_d e}{m_d}\,\partial_x \varphi,$$

$$n_e = n_{e0}\exp\left(\frac{e\varphi}{T_e}\right), \quad n_i = n_{i0}\exp\left(-\frac{e\varphi}{T_i}\right), \quad \partial_x^2 \varphi = 4\pi e\left(n_e + Z_d n_d - n_i\right), \tag{4}$$

where φ is the electrostatic potential; x and t are the space and time variables; n_α and $n_{\alpha 0}$ ($\alpha = e,i,d$) are the density and the unperturbed density of the electrons, ions and dust particles; m_d, v_d, and Z_d are the mass, velocity, and charge number of a dust particle, $-e$ is the electron charge; and $T_{e(i)}$ is the electron (ion) temperature. The equations are valid if the characteristic velocity of the process is larger than the dust thermal speed and much less than the ion thermal speed.

The main contributions to the terms of the above equations containing the electron parameters are made by photoelectrons, while to those containing the ion parameters are made by solar wind ions. The role of ions in the formation of the dust acoustic structures in dusty plasmas over the illuminated part of the Moon is negligibly small. Thus below the ion contribution is omitted. Furthermore, we neglect dust charge variations within the soliton.

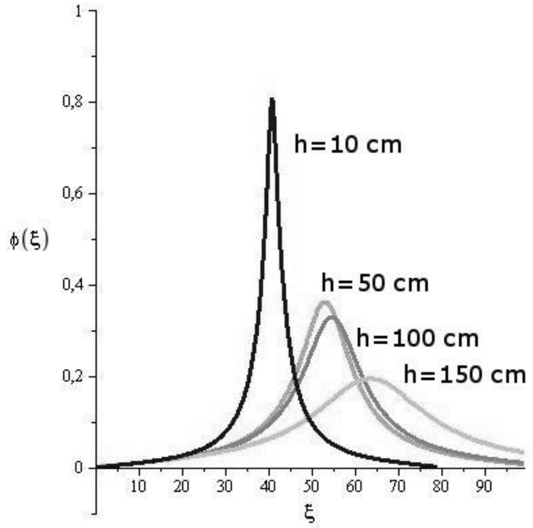

Fig. 2. The $\varphi(\xi)$ profiles for the dust acoustic solitons for different heights (h).

We now look for solutions of (1) in the form of localized wave structures propagating with constant velocities *M* in the *x*-direction. Thus, all the parameters involved depend on *x* and *t* only through the variable $\xi = x - Mt$. We shall assume that all perturbations vanish for $\xi \rightarrow \pm\infty$. We use the standard Sagdeev potential approach and reduce the problem to the analysis of the effective energy integral

$$\frac{1}{2}(\varphi_\xi)^2 + V(\varphi) = 0, \tag{5}$$

where the normalizations $e\varphi/T_e \rightarrow \varphi$ and $M/c_d \rightarrow M$ have been used, and

$$V(\varphi) = 1 - \exp(\varphi) + |M| d \left(|M| - \sqrt{M^2 - 2Z_d \varphi} \right). \tag{6}$$

Here, $c_d = T_i/m_d$ and $d = n_{d0}/n_{e0}$.The data presented in Fig. 2 are calculated for the dusty plasma parameters presented in Fig. 1. The photoelectron temperature is assumed to be 0.15 eV. For the existence of the dust acoustic solitons, the Sagdeev potential $V(\varphi)$ must have a local maximum at $\varphi = 0$, and the equation $V(\varphi) = 0$ must have at least one more real solution $\varphi_0 \neq 0$. A local maximum of the Sagdeev potential $V(\varphi) = 0$ at the point $\varphi_0 \neq 0$ exists if

$$M^2 > Z_d^2 d / (1 - Z_d d). \tag{7}$$

In addition to the solitons dust acoustic shocks can exist. Indeed, by analogy with the active space experiments which involve the release of some gaseous substance in Earth's ionosphere [12], 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 $M > 1$.

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