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Waves in a dusty plasma over the illuminated part of the Moon

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Abstract. 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.

1. Introduction

Dusty plasmas are multi-component plasmas consisting of ions, electrons, neutrals and charged solid or liquid particles in the micron or nanometre size (Shukla and Mamun 2002; Tsytovich et al. 2005). 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. 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 approximately 100 km altitude.

The upcoming lunar missions assume often the investigation of the lunar dust. The NASA's LADEE (Lunar Atmosphere and Dust Environment Explorer) mission is supposed to be 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-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 (Golub′ et al. 2012; Popel and Zelenyi 2013). 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.

Here, we describe the dusty plasma system over the illuminated part of the Moon (Sec. 2). In Sec. 3, we discuss a possibility of wave excitation in dusty plasmas over the lunar dayside. A summary of our findings is given in Sec. 4.

2. Dusty plasma over the lunar dayside

Plasmas over the lunar dayside contain electrons, ions, neutrals, and fine dust particles (Stern 1999). 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 (Sternovsky et al. 2008; Golub′ et al. 2012; Popel and Zelenyi 2013). Typical distributions of charged dust particles over the sunlit lunar surface are given in Popel and Zelenyi (2013).

Despite the existence of neutrals in the lunar atmosphere on the lunar dayside ($\sim 10^5$ cm^{-3}), the long photo-ionization time-scales ($\sim$ 10–100 days) combined with rapid ion pick-up by the solar wind ($\sim$ 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 22 spacecraft conducted a series of radio occultation measurements to determine the line-of-sight electron column number

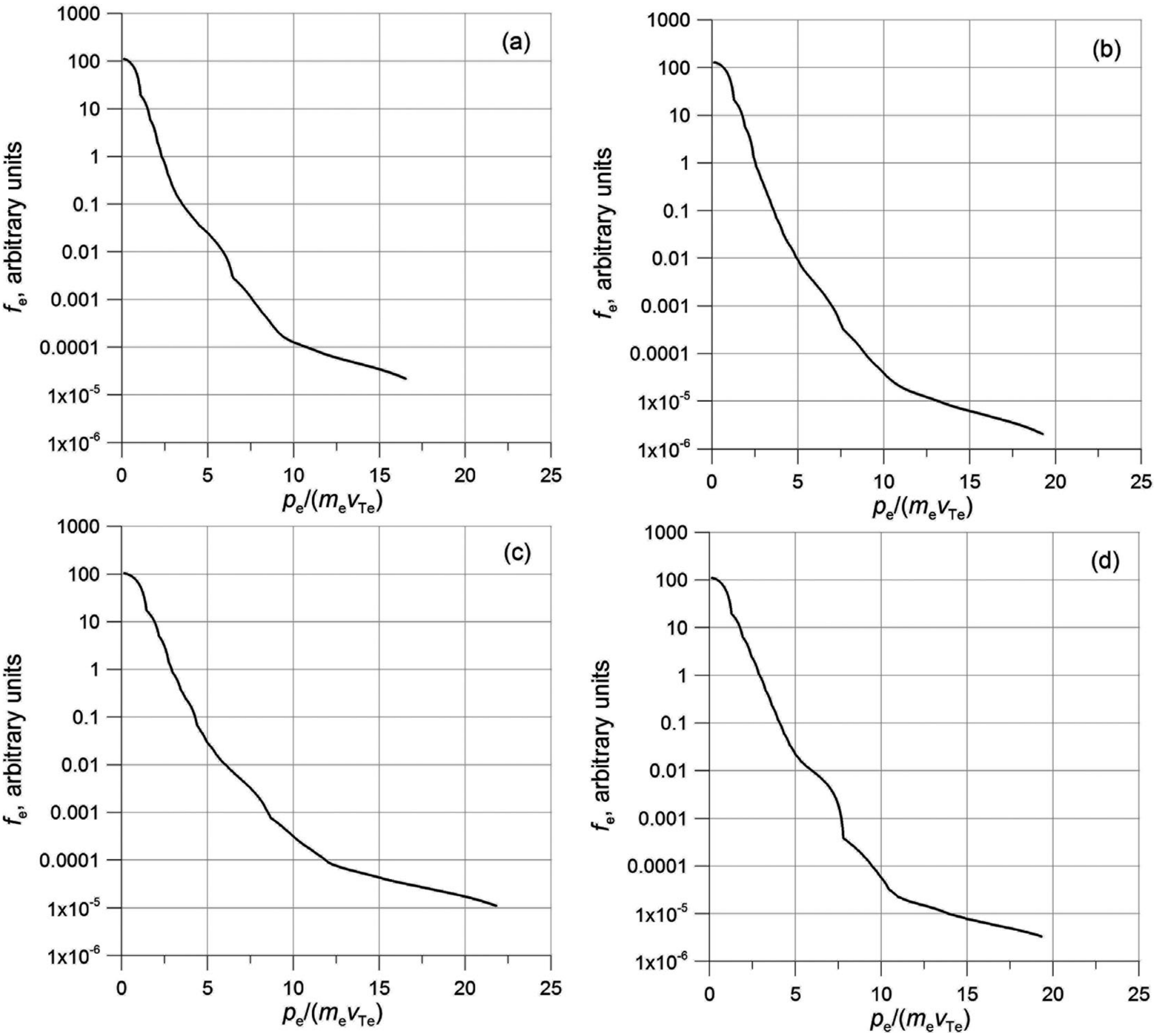

Figure 1. The photoelectron distribution functions near the lunar surface for an X28 class solar flare event (a), solar maximum (b), solar minimum (c), and under the conditions described by Hinteregger (1965), Ivanov-Kholodnyi and Firsov (1974) close to the solar maximum (d).

density, or total electron content, above the limb of the Moon as a function of tangent height (Stubbs et al. 2011). 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 (Popel and Zelenyi 2013) 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. During the 11-year solar cycle the amount of radiated VUV energy changes significantly, that results in a significant variation in the photoelectron current. Here, we present the results of our calculations for four different solar activity conditions. These are the solar minimum, solar maximum, an X28 class solar flare event (Chamberlin et al. 2008; Sternovsky et al. 2008), as well as the conditions described by Hinteregger (1965), Ivanov-Kholodnyi and Firsov (1974) which are close to the solar maximum.

The photoelectron distribution functions $f_e(p_e)$ calculated for the above solar activity conditions, the photoelectric yield Y of the lunar regolith given by Walbridge (1973), and the work function $W = 6$ eV of the lunar regolith are presented in Fig. 1. Here, p_e is the absolute value of the electron momentum, m_e is the electron mass, and v_{Te} is the electron thermal speed (determined in terms of the averaged electron kinetic energy).

The distributions shown in Fig. 1 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 (Walbridge 1973).

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}	2.2×10^5	2.1×10^5	1.9×10^5	2.0×10^5	N_{02}, cm^{-3}	6.0×10^3	1.3×10^3	4.6×10^2	8.6×10^2
T_{e1}, eV	0.2	0.1	0.1	0.1	T_{e2}, eV	1.2	1.3	1.2	1.3

The largest contributions to the distribution function are due to photon energies in the vicinity of the work function W (in our case 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 6 eV) 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} calculated under the same conditions as the distribution functions presented in Fig. 1 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 (Chamberlin et al. 2008; Sternovsky et al. 2008), and those based on the data (Hinteregger 1965; Ivanov-Kholodnyi and Firsov 1974), 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.

The distribution functions shown in Fig. 1 are isotropic in the momentum-space. Thus, they are stable. However, 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 $n_{eS} \approx n_{iS} = 8.7$ cm^{-3}, the electron temperature $T_{eS} = 12$ eV, the ion temperature $T_{iS} = 6$ eV, the solar wind velocity $u_S = 400 \times 10^5$ cm s^{-1}. The relative motion of the solar wind with respect to the ambient dusty plasma results in the excitation of waves over the lunar surface.

3. Dispersion relations and waves

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

$$1 - \frac{\omega_{pe1}^2}{\omega^2} + \frac{1}{k^2\lambda_{De2}^2} - \frac{\omega_{piS}^2}{(\omega - ku_S)^2} = 0, \qquad (3.1)$$

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 (3.1) must have at least two complex roots; the condition for this is $ku_S < \omega_{pe1}$. The unstable solution of (3.1) is

$$\omega = ku_S\left(1 + i\omega_{piS}/\sqrt{\omega_{pe1}^2 - k^2u_S^2}\right). \qquad (3.2)$$

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

$$1 + \left(1/k^2\lambda_{De1}^2\right) - \left(\omega_{pd}^2/\omega^2\right) = 0, \qquad (3.3)$$

which corresponds to the well-known dust acoustic waves (Rao et al. 1990). Here, v_{Td} is the thermal dust speed, ω_{pd} is the dust plasma frequency. The dispersion equation (3.3) 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^{-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 $M > 1$.

4. Summary

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.

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References

Amyx, K., Sternovsky, Z., Knappmiller, S., Robertson, S., Horanyi, M. and Gumbel, J. 2008 In-situ measurement of smoke particles in the wintertime polar mesosphere between 80 and 85 km altitude. *J. Atmos. Sol-Terr. Phys.* **70**, 61–70.

Chamberlin, P. C., Woods, T. N. and Eparvier, F. G. 2008 Flare Irradiance Spectral Model (FISM): flare component algorithms and results. *Space Weather* **6**, S05001(1–5).

de Angelis, U. 2006 Dusty plasmas in fusion devices. *Phys. Plasmas* **13**, 012514(1–10).

Dubinskii, A. Yu. and Popel, S. I. 2012 Formation and evolution of dusty plasma structures in the ionosphere. *JETP Lett.* **96**, 21–26.

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.

Hinteregger, H. E. 1965 Absolute intensity measurements in the extreme ultraviolet spectrum of solar radiation. *Space Sci. Rev.* **4**, 461–497.

Horányi, M., Hartquist, T. W., Havnes, O., Mendis, D. A. and Morfill, G. E. 2004 Dusty plasma effects in Saturn's magnetosphere. *Rev. Geophys.* **42**, RG4002(1–20).

Ivanov-Kholodnyi, G. S. and Firsov, V. V. 1974 Spectrum of short-wavelength solar radiation for different activity levels. *Geomagn. Aeron.* **14**, 392–398.

Norton, R. H., Guinn, J. E., Livingston, W. C., Newkirk, G. A. and Zirin, H. 1967 Surveyor 1 observations of the solar corona. *J. Geophys. Res.* **72**, 815–817.

Ostrikov, K., Neyts, E. C. and Meyyappan, M. 2013 Plasma nanoscience: from nano-solids in plasmas to nano-plasmas in solids. *Adv. Phys.* **62**, 113–224.

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: Applied Phys.* **44**, 174036(1–7).

Popel, S. I. and Tsytovich, V. N. 1999 Shocks in space dusty plasmas. *Astrophys. Space Sci.* **264**, 219–226.

Popel, S. I. and Zelenyi, L. M. 2013 Future lunar missions and investigation of dusty plasma processes on the Moon. *J. Plasma Phys.* **79**, 405–411.

Rao, N. N., Shukla, P. K. and Yu, M. Y. 1990 Dust-acoustic waves in dusty plasmas. *Planet. Space Sci.* **38**, 543–546.

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

Shukla, P. K. and Mamun, A. A. 2002 *Introduction to Dusty Plasmas Physics*. London, UK: Institute of Physics Publishing.

Stern, S. A. 1999 The lunar atmosphere: history, status, current problems, and context. *Rev. Geophys.* **37**, 453–491.

Sternovsky, Z., Chamberlin, P., Horanyi, M., Robertson, S. and Wang, X. 2008 Variability of the lunar photoelectron sheath and dust mobility due to solar activity. *J. Geophys. Res.* **113**, A10104(1–4).

Stubbs, T. J., Glenar, D. A., Farrell, W. M., Vondrak, R. R., Collier, M. R., Halekas, J. S. and Delory, G. T. 2011 On the role of dust in the lunar ionosphere. *Planet. Space Sci.* **59**, 1659–1664.

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

Walbridge, E. 1973 Lunar photoelectron layer. *J. Geophys. Res.* **78**, 3668–3687.

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.