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The influence of the surface conductivity on the local electric fields and the motion of charged dust grains on the Moon

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ABSTRACT

It is investigated how finite regolith conductivity influences the magnitude of strong electric fields required for lofting dust grains above the surface. It is shown that even very weak conductivity typical for the lunar regolith restricts the maximum values of the local electric fields formed near mini-craters or mini-hills on the dark side of the Moon. As a result the lofting of dust grains from the surface of the Moon is suppressed significantly. The effect depends on the regolith conductivity, parameters of the solar wind plasma, and the steepness of the slopes of the mini-crater or mini-hill.

1. Introduction

The surfaces of airless cosmic bodies are covered with a particular dust layer known as regolith (Carrier et al., 1991; Colwell et al., 2005, 2007). The regolith is formed by combined action of the solar UV radiation, solar and cosmic particles, and continuous bombardment of the surface by micrometeorites for billions of years. The physical properties of the lunar regolith were investigated many years ago during the era of Apollo and Luna missions. It was found out that the regolith is extremely dry and due to this its electric conductivity is very small (Carrier et al., 1991). At the dark side of the Moon the variations of the electric conductivity from $\sigma \sim 10^{-13}$–10^{-14} S/m (Carrier et al., 1991) up to $\sigma \sim 10^{-17}$ S/m (Stubbs et al., 2014) are confirmed in the laboratory experiments. At the sunlit side the electric conductivity is somewhat higher still remaining very small. Due to this in the theoretical computations usually it is assumed that the surface conductivity is equal to zero (see, e.g. Halekas et al., 2011).

The motion of dust grains above the surface near the terminator and on the dark side of the Moon was registered in the LEAM (Lunar Ejecta and Meteoroids) experiment carried out by the Apollo 17 team (Berg et al., 1975). It was found that dust grains move near the surface in the vicinity of the terminator and at the dark side of the Moon. Also it was speculated that such moving grains should have large electric charges. Recently it was argued that some of the electric signals in the circuits of LEAM near the terminator were caused by interference rather than dust grains hitting the sensors (O'Brien, 2011). Due to this scientists reanalyzed available data related to the LEAM experiment and confirmed the motion of dust grains close to the surface of the Moon (Grün and Horányi, 2013).

To explain the results of the LEAM experiment and the so-called “horizon glow” (Rennilson and Criswell, 1973) it was suggested that the transport of dust is caused by the interaction between charged dust particles and the electric fields. As the typical nondisturbed fluxes of the solar wind electrons and ions towards the surface of the Moon are not equal to each other the electric potential appears on the surface (positive on the sunlit side or negative at the terminator and at the dark side). Simultaneously close to the surface the layer known as a double layer (Debye sheath) is formed where the quasineutrality of plasma is violated (Goldstein, 1974; Borisov and Mall, 2002). Despite that the negative potential on the dark side of the Moon can be very large, the electric field in the double layer is weak enough (see, e.g. Borisov and Mall, 2002). At the same time estimates show that to overcome the gravity on the Moon and also cohesive and adhesive forces the electric fields should be much stronger than those expected in the double layer. Cohesive (adhesive) forces describe the property of the molecules of the same substance (different substance) to stick to each other, (see, e.g. Walton, 2007). As the electric field in the Debye sheath is not sufficient for lofting of dust grains from the surface the idea of strong local electric fields was introduced. There are two versions of this idea. Long ago it was

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suggested that strong local electric field can be formed exactly on the terminator (De and Criswell, 1977). Later this idea was slightly modified to include surface irregularities (small crater or a hill) at the terminator (Farrell et al., 2008). It should be mentioned that according to the LEAM experiment the motion of dust grains was registered not only very close to the terminator but rather far from it at the dark side of the Moon. Therefore another mechanism of formation of strong local electric fields was suggested to explain qualitatively experimental data (Borisov and Mall, 2006). It was argued that at the dark side the fluxes of ions that hit the slope in the direction of the solar wind flow and the opposite slope are quite different. Due to this significant potential variation on two slopes and hence strong electric fields appear. Note, that the energy of the solar wind protons is the main source of potential variations on the opposite slopes of mini-craters (mini-hills).

In the stationary conditions the electric potential and the electric charge on the surface do not vary with time. If the surface conductivity is equal to zero there is no electric current in the regolith. In such case the total electric current to the surface carried by the charged solar wind particles (protons and electrons) should be equal to zero. In reality despite that the surface conductivity is very weak strong local electric fields can produce not too small currents in the regolith (because the current is a product of the electric field and the electric conductivity). In the stationary conditions the continuity of electric currents should exist. This means that the electric current to each small square $d\sigma$ on the surface caused by the bombardment by the solar wind particles should be equal to the current flowing from it into the regolith. As the fluxes of the solar wind particles at the dark side after the propagation through the Debye sheath become very weak (see, e.g. Borisov and Mall, 2006) they are not able to provide the continuity of electric currents if strong enough currents exist in the regolith. In such case the potential difference between two opposite slopes of a mini-crater (mini-hill) tends to decrease which in turn causes the decrease of the current in the regolith. Thus small but finite electric conductivity of the regolith restricts the magnitude of local electric fields. The aim of the present paper is to discuss theoretically the role of finite conductivity of the regolith in the suppression of strong local electric fields on the dark side of the Moon.

2. Assumptions and basic equations

The distribution in space of the electric potential at the dark side of the Moon depends on several factors: the solar wind speed, the velocity distributions of the solar wind protons and electrons, the direction and the magnitude of the magnetic field, and the physical properties of the surface. At the same time yet unknown electric potential influences the motion the solar wind electrons and protons in the shadow. To solve nonlinear system of coupled equations for electrons, protons and the electric potential in general case is a very difficult task. That is why our analysis is an approximate one based on some assumptions that help to make the consideration of the problem easy enough. Our aim is to demonstrate the formation of strong local electric fields and the influence of finite regolith conductivity on these fields in a rather simple way. Due to this the following assumptions are introduced:

1. The velocity distribution of the solar wind electrons and protons depend only on the particles energy.
2. We consider the bombardment of the lunar surface in the shadow by the solar wind particles not too far from the terminator (approximately ≲30°–45° from the nearest terminator.)
3. The influence of the secondary electrons emission and protons reflected from the lunar surface on the electric fields in the shadow is neglected.
4. The thickness of the Debye sheath ΔR is assumed to be small enough (much smaller than the radius of the Moon R_m) and the variations of the potential along the radius is much stronger than in the azimuthal direction.

The first assumption makes it possible to present the velocity distribution in the potential electric field (in the shadow) in an explicit form (because the total energy is conserved). We assume that the velocity distribution far away from the shadow is known. In reality the distribution functions of electrons and protons in the solar wind are rather variable. Usually they consist of the thermal core and the suprathermal tails that can be modeled by two temperature distribution functions (see, e.g. Lie-Swendsen and Leer, 2000). In our calculations we use such distributions and show that in the shadow the suprathermal tails are of prime importance (because thermal particles are not able to penetrate deep into the shadow close to the surface). The second assumption means that we do not consider the charging of the surface in the central part of the shadow. According to the data obtained by Kaguya (Nishino et al., 2013) solar wind protons directly penetrating into the shadow are registered close to the surface at the angles ~30°–45° from the terminator (Type-I entry), see Figure 1b in Nishino et al. (2013). Our conclusion is that thermal protons can be registered only close to the terminator while deeper into the shadow penetrate only suprathermal protons. Such protons have very large Larmour radius (hundreds of kilometers). That is why for our approximate analysis it is possible to consider these protons as nonmagnetized. As for the third assumption, the secondary electron emission from the surface should influence the magnitude and the variation of the electric potential on the Moon. But the dependance of such emission on the surface properties, electric potentials, solar wind parameters is not well known. That is why it looks reasonable to consider as a first step the problem (the influence of the regolith conductivity on electric fields) without taking into account such emissions as well as the existence of protons reflected from the surface. (We assume that the solar wind particles which collide with the surface disappear.) The fourth assumption means that only protons with significant component of the initial velocity orthogonal to the solar wind speed can reach a given point on the surface in the shadow. It will be shown that approximately this component is influenced by the angle between the solar wind speed and the normal to the surface at a given point.

We introduce the system of coordinates $\{x, y, z\}$ where the x and the y axes lie in the ecliptic plane and the direction of the solar wind speed U_{sw} coincides with the x-axis. The z-axis is directed downwards. We would like to discuss the formation of the Debye sheath in the shadow in the meridional plane parallel to the vector of the solar wind speed U_{sw}. Similarly can be considered parameters of the Debye sheath in the equatorial plane. Suppose that outside the Debye sheath the electric field is weak enough and can be neglected. Indeed, the electric field $[\mathbf{U}_{sw} \times \mathbf{B}]$ associated with the frozen magnetic field $\mathbf{B}$ of the solar wind is orders of magnitude smaller than the typical electric field in the double layer at the dark side of the Moon (see, Borisov and Mall, 2002). In such approximation the distribution function at the upper boundary of the double layer can be easily found. For this purpose we introduce an additional system of coordinates $\{x_1, y_1, z_1\}$ in which the z_1-axis is directed along the local normal into the surface and lies in the x,z plane. The link between two systems of coordinates is the following:

$$x = x_1 \cos\theta - z_1 \sin\theta \tag{1}$$

$$z = z_1 \cos\theta + x_1 \sin\theta \tag{2}$$