Levitation of charged dust grains and its implications in lunar environment

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The surfaces of airless, non-magnetized bodies like the Moon are directly exposed to solar wind and ultraviolet radiation, causing surface dust grains to be electrically charged and levitated, whenever electric fields exceed the surface forces and gravity. For an improved understanding of the lunar dust environment, we study the surface charging processes using electrostatic modelling and present the results here. We apply Gauss's law to examine the dust levitation and compare the implications with those obtained using free-space capacitance of the particle. Calculating grain charge on surface by assuming its free-space capacitance is erroneous and is therefore inapplicable. The daytime surface potential during high solar activity is estimated to be ~20 V, while the nighttime potential can be as high as –3.8 kV. The maximum radius of levitating particles is greatly affected by the method used to model the dust levitation. Using Gauss's approach, it comes out to be in the picometre range near the terminator, in contrast to existing calculations which estimate it to be in the nanometre to micrometer range. The LDEX provided no indication of 0.1 μm-sized particles near the terminator, as suggested previously from Apollo observations. This result is not inconsistent with our predictions based on Gauss's law. Hence, it still remains an open question whether dust levitation occurs on the Moon or not, and experiments are necessary on future lunar lander mission which provide direct measurement of surface potential and near-surface charged dust particles to confirm the same.

Keywords: Dust, levitation, lunar environment, photoemission, plasma.

THE surfaces of airless, non-magnetized bodies in our solar system are directly exposed to the solar wind plasma and ultraviolet (UV) radiation, causing dust grains on their surfaces to be electrically charged. The lunar surface acquires electrostatic potential while being exposed to sunlight during lunar day, or due to plasma electron and ion currents at lunar night. Further, significant temporal and spatial variations of the lunar surface potential are known to occur due to charging from photoemission and plasma currents and can range from nearly +10 V to less than –500 V (refs 1–3). These electric fields can exceed surface forces (cohesion) and gravity for small dust particles, causing electrostatic dust levitation[4]. The sharp gradient in UV flux across the solar terminator can also generate pockets of electrostatically supported dust near the lunar surface region and set them into motion, as the terminator moves across the Moon, leading to electrostatic transport of dust. Dust levitation may occur within a few metres of the lunar surface, creating 'lunar horizon glow' (LHG), as captured by Surveyor lander camera during early lunar missions. The Surveyor lander observations estimated ~5 μm grains levitating 3–30 cm above the lunar surface[5]. The dust densities implied by the intensity of the feature were too high to be explained as secondary ejecta from the meteoritic influx[6]. The Lunar Ejecta and Meteorites (LEAM) experiment was deployed on the lunar surface during the Apollo 17 mission to monitor the cosmic dust influx. The signatures recorded by LEAM were unlikely to be caused by cosmic dust, but were consistent with the presence of high fluxes of slow-moving, highly charged lunar fines[7]. Stubbs *et al.*[8] have previously reported a dust fountain model up to about 100 km altitude. The examination of coronal photography indicates that if the dust is levitated to high altitudes, it rises to 100 km above the surface with a characteristic size of about 0.1 μm and scale height of ~10 km (refs 9, 10).

Recently, Lunar Prospector's electron reflectometer (ER) measured the magnetic reflection of electrons from surface crustal magnetic fields. Observations of electron distribution above shadowed lunar surface showed energy-dependent 'loss cones' (devoid of particles), which suggested that reflection occurred by both magnetic and electric fields, and were used to estimate the variation in electrostatic potential on the lunar surface for different plasma environments encountered on the Moon. Other evidence for a high-altitude component of lunar dust includes observations from the Lunokhod-2 photometer[11] and the star tracker camera of the Clementine mission[12]. The lunar dust environment has been studied by Grun *et al.*[13], who suggested that no theoretical model can explain the formation of a dust cloud above the lunar surface. The role of dust in the lunar ionosphere has been studied by Stubbs *et al.*[14]. They showed that electrons emitted from exospheric dust could be responsible for the Luna 19 measurements, and the process could dominate the formation and evolution of the lunar ionosphere. A reanalysis of the Apollo light scattering observations has been done by Glenar *et al.*[15], and lofted charged dust distribution above the Moon surface has been studied by Pines *et al.*[16]. Most of the above studies presumed that the LHG could be because of the lunar dust levitation, caused by the surface charging phenomena. Results from the lunar dust experiment on LADEE mission suggest the presence of a permanent, asymmetric dust cloud around the Moon, formed by impacts of high-speed cometary dust particles on eccentric orbits, in contrast to particles of asteroidal origin striking the Moon at lower speeds[17]. Horanyi *et al.*[18] have reported a permanent asymmetric

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*For correspondence. (e-mail: jayesh@prl.res.in) dust cloud around the Moon and have found that the density distribution exhibits a strong enhancement near the morning terminator. They reported that the observation suggests the spatial and velocity distributions of the interplanetary dust particles which generate the ejecta clouds. Also, Horanyi *et al.*[18] mentioned that the LDEX dust current measurements remained independent of altitude and hence gave no indication of the relatively dense cloud of 0.1 μm sized dust that was inferred from the Apollo observations over the lunar terminator. Thus, dust levitation has not been confirmed till date and this communication presents a study using electrostatic modelling of dust levitation and discusses its implications in lunar environment.

First, we describe the lunar surface charging phenomena and dust levitation. Then we present derivation of algebraic expressions for maximum radius of charged dust particles which may be levitated and give dependence of dust particle size on solar wind parameters. Finally we provide results as well as implications and summary.

All objects in space will be charged to an electric potential representing an equilibrium condition achieved by the combined effect of various charging currents[19]. In the absence of photocurrent during lunar night, the space plasma provides a source of current by fast-moving electrons and ions. At a given time, the number of electrons reaching the lunar surface is large and the surface becomes negatively charged, repelling electrons while attracting ions. In equilibrium condition, there would be net negative charge on the lunar surface because electrons travel about 40 times faster than the ions. This is true for shadowed regions as well. The surface potential on the dark side of the Moon is given as[6]

$$\phi_s = -\frac{kT}{e}\ln\left(\frac{J_{oe}}{J_{oi}}\right), \tag{1}$$

where k is the Boltzmann's constant, T the temperature, e the charge of an electron, J_{oe} the saturated thermal electron current density and J_{oi} is the saturated ion current density.

The photoemission process occurring in the sunlight leads to a net positive potential of a few volts on the surface; it is given by[6]

$$\phi_s = \frac{kT_p}{e}\ln\left(\frac{J_{op}}{J_{oe}}\right), \tag{2}$$

where T_p is the photoelectron temperature, J_{op} the photoelectron saturated current density and J_{oe} is the saturated electron current density in the solar wind given as[6]

$$J_{oe} = n_e e\left(\frac{kT_e}{2\pi m_e}\right)^{1/2}. \tag{3}$$

To obtain the photoelectron current density, we assume the photocurrent density from normally incident sunlight as 4×10^{-5} Am^{-2} (refs 3, 20). Typical photoelectric efficiency of dielectric surface is 10%, giving the value of J_{op} as 4×10^{-6} Am^{-2} (ref. 20). The value of photoelectron temperature T_p is 1.5 eV (refs 19, 20).

The definition of Debye length is[21]

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k/e^2}{n_e/T_e + \sum_{ij} j^2 n_{ij}/T_i}}. \tag{4}$$

Omitting the ion (heavier than electron) terms, one can get the Debye length[21] as

$$\lambda_D = \sqrt{\frac{\varepsilon_0 kT_e}{n_e e^2}}, \tag{5}$$

where ε_0 is the permittivity of free space, n_e the density of electrons, n_{ij} the density of atomic species i with positive ionic charge (je) and T_e and T_i are the temperatures of the electrons and ions respectively.

Near the terminator, the photoemission process is weakened and there is a plasma wake region. The lunar wake region is created on the night side due to the Moon being an obstacle to the solar wind. In this region, plasma densities are low and temperatures are high, implying large negative surface potential. The sharp gradient in UV flux across the solar terminator may generate clouds of electrostatically supported dust and set them into motion as the terminator moves across the Moon[22]. Significant temporal and spatial variations of the lunar surface potential are known to occur due to charging from photoemission and plasma currents, and range from about +10 V to –4.5 kV (refs 1–3). These variations in surface potential may cause the electrostatic transport of dust, as suggested for other airless bodies[23].

We have studied the maximum radius of charged and levitated dust particles using Gauss's method. The grains on the lunar surface will charge as if they were a small piece of the total surface area. The surface of the Moon will charge according to Gauss's law

$$\oint \boldsymbol{E}_s \cdot d\boldsymbol{A} = \frac{Q_s}{\varepsilon_0}, \tag{6}$$

where $\boldsymbol{E}_s$ is the electric field at the surface, Q_s the charge of a closed surface area and the integral is performed over the surface in question. Integrating this over an arbitrary surface area $\boldsymbol{A}$, the charge density of the insulating lunar surface σ is given by

$$\sigma = 2\varepsilon_0 E_s. \tag{7}$$

The charge of a grain (Q_d) with radius a on the surface, with this surface charge density is given by

$$Q_d = \sigma\pi r_d^2.$$

Therefore,

$$Q_d = 2\pi\varepsilon_0 E_s r_d^2, \tag{8}$$

where the dust particle is assumed to be in a spherical shape with radius r_d. The dust particles experience an upward electrostatic repulsive force ($\boldsymbol{F}_q$) against the gravitational force ($\boldsymbol{F}_g$) of the Moon due to its gravity (g_L) as well as the cohesive force among the grains. The cohesion of dust at the surface can be neglected for the smaller (micron-sized) dust particles on the lunar surface[24]. Therefore, the net force on the levitated particle is given as $\boldsymbol{F} = \boldsymbol{F}_q - \boldsymbol{F}_g$, acting upward. The magnitude of the upward electrostatic repulsive force (F_q) on the charged dust particle is given as

$$F_q = Q_d E_s. \tag{9}$$

Substituting charge of dust particle from eq. (8), we get

$$F_q = 2\pi\varepsilon_0 E_s^2 r_d^2. \tag{10}$$

The magnitude of gravitational force on the particle is given by

$$F_g = m g_L = \rho\left(\frac{4}{3}\pi r_d^3\right) g_L.$$

Therefore

$$F_g = \rho\left(\frac{4}{3}\pi r_d^3\right) g_L, \tag{11}$$

where m is the mass of the dust particle and ρ is the dust grain density.

In order for levitation to occur, the electrostatic force should be greater than the gravitational force. Hence, from eqs (10) and (11),

$$2\pi\varepsilon_0 E_s^2 r_d^2 > \rho\left(\frac{4}{3}\pi r_d^3\right) g_L.$$

Simplifying, we get the radius of the dust particle as

$$r_d < \frac{3\varepsilon_0 E_s^2}{2\rho g_L}. \tag{12}$$

The electrostatic dust levitation is based on the assumption of one-dimensional Debye shielding above a plane of the lunar surface, based on which the lunar surface electric field created due to the surface potential is given as

$$E_s = \frac{\phi_s}{\lambda_D}. \tag{13}$$

Substituting electric field in eq. (12), we get the radius of the levitated dust particle as

$$r_d < \frac{3\varepsilon_0 \phi_s^2}{2\rho g_L \lambda_D^2}, \tag{14}$$

and the maximum radius of charged, levitated dust particles is given by

$$r_{\max} = \frac{3\varepsilon_0 \phi_s^2}{2\rho g_L \lambda_D^2}. \tag{15}$$

The charged particle would travel vertically upwards within the plasma sheath; it will experience exit velocity at the boundary and reach maximum height in a given time called maximum time to follow the parabolic trajectories after the sheath[8].

Substituting eq. (5) into eq. (15) and simplifying, one can obtain the maximum radius of charged dust particle which is levitated as

$$r_{\max} = \frac{3e^2 n_e}{2\rho g_L k T_e}\cdot\phi_s^2. \tag{16}$$

Combining eqs (2), (3) and (16) and taking photoelectron parameters as mentioned earlier, we obtain the equation for the maximum radius of dust particles for the day side as

$$r_{\max} = 2.1 \times 10^{-16}\left(\frac{n_e}{T_e}\right)\left(\ln\left[\frac{149.48}{n_e\sqrt{T_e}}\right]\right)^2, \tag{17}$$

where the electron number density is per cubic centimetre and the electron temperature is in electronvolt. Equation (17) shows dependence of the maximum radius of charged dust particles on electron number density and electron temperature. A similar equation for the night side is found as

$$r_{\max} = 1.1 \times 10^{-18} T^2\left(\frac{2500 n_e}{29 T_e} + \frac{2500 n_i}{29 T_i}\right) \times \left(\ln\left[\frac{42.86 n_e\sqrt{T_e}}{n_i\sqrt{T_i}}\right]\right)^2, \tag{18}$$

where the temperatures are in electronvolt and number densities are per cubic centimetre.

Table 1. Lunar Prospector electron reflectometer data and effect on lunar surface charging

Parameter	Subsolar point	Intermediate region	Terminator
Angle[8] from subsolar point	0–6	42–48	90–96
LP[8] plasma electron density n_e (cm^{-3})	2.9	4.0	7.0
LP[8] plasma electron temperature, T_e (K)	1.4×10^5	1.5×10^5	1.1×10^5
Lunar surface potential (ϕ, V) at various photoelectric efficiencies	3 (5%) 4 (10%) 5 (20%)	2.5 (5%) 3.5 (10%) 4.6 (20%)	–35
Maximum radius of levitated particle ($r_{\max}$) at various photoelectric efficiencies	0.2 fm (5%) 0.4 fm (10%) 0.6 fm (20%)	0.2 fm (5%) 0.4 fm (10%) 0.6 fm (20%)	0.2 pm

Table 1 provides the range of plasma parameters from the Lunar Prospector electron reflectometer for three regions with different sunlight conditions[8]. We have studied the dependence of lunar surface potential and radius of charged dust particles on plasma parameters for these regions and the values are provided in Table 1. The effect of lunar surface photoelectric efficiency has also been indicated in Table 1. In the first region near the sub-solar point, the lunar surface potential is found to be less than 10 V and the maximum radius of charged dust particles is limited in the femtometre range. The intermediate region in Table 1 has almost similar ranges for the surface potential as well as the radius of the largest particles levitated above the lunar surface. However, near the terminator in the third region, the lunar surface gets negatively charged and the potential can be as high as –35 V. The radius of levitating dust particle is larger and is limited to about a picometre. During normal solar activity, the plasma electron temperature is 12.1 eV and ion temperature is 10.4 eV (ref. 25). The surface charge can create electrostatic repulsion on smaller sized dust particles and the grains may be levitating against the lunar gravity. Due to rapid change in surface potential from positive on dayside to negative on night side, there can be particle oscillations near the terminator. As the terminator moves, the dust cloud would lead to a net transport of charge from one place to the other, causing potential electrical failure of instruments. It should be noted that the above parameters are dependent on the prevailing plasma condition as well as sunlight at the time of measurement.

During the events such as transition of Moon through the Earth's magnetotail, the ion temperature can reach as high as 1000 eV and velocity is of the order of 100 km/s (ref. 26), whereas during coronal mass ejection the plasma electrons are cooler with temperature of about 1 eV and speed of about 1000 km/s (ref. 27). During SEP events, the electron density is between 0.001 and 0.1 cm^{-3}, and electron temperature is about 1 keV in the wake region[28]. We have studied variation of electron density from 0.001 to 100 cm^{-3} and electron temperature up to 1000 eV, and found that the daytime lunar surface potential remains up to about 20 V, while the particle radius remains within about 15 pm (Figure 1). The dependence of lunar surface potential as well as maximum radius of charged dust particles during lunar night is shown in Figure 2 *a* and *b* respectively. The largest surface potential has been found to be about –3.8 kV, while the particle radius can go as high as about 250 pm in extreme conditions. However, most of the time, the particle radius is limited to be in the picometre range. It is known that matter is usually found in the form of gas or molecule in picometre range, and it may be difficult to explain the dust levitation at these scales.

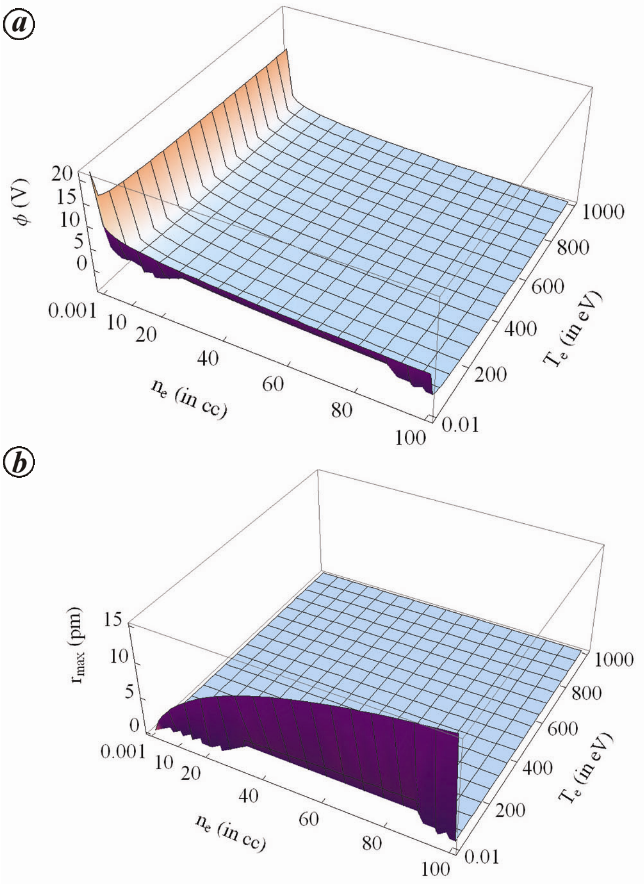

Figure 1. ***a***, Dependence of daytime lunar surface potential on plasma parameters for 10% photoelectric efficiency. ***b***, Dependence of daytime maximum radius of lifted particles on plasma parameters for 10% photoelectric efficiency.

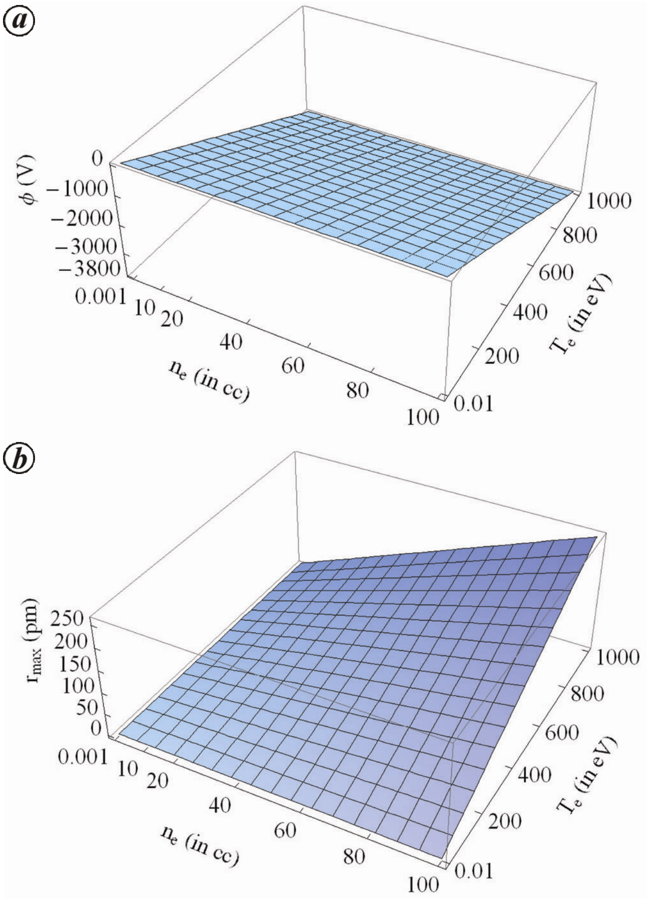

Figure 2. ***a***, Dependence of nighttime lunar surface potential on plasma parameters. ***b***, Dependence of nighttime maximum radius of lifted particles on plasma parameters.

The approach of finding charge on dust particle using its free-space capacitance ($Q_{\mathrm{d}} = C_{\mathrm{d}}\ \phi_{\mathrm{s}}$), as found in the literature (e.g. Stubbs *et al.*[8]), considers the grain capacitance[20] as $C_{\mathrm{d}} = 4\pi\varepsilon_0 r_{\mathrm{d}}$, with the assumption of the particle to be spherical in shape with radius r_{d} and $r_{\mathrm{d}} \ll \lambda_{\mathrm{D}}$. Calculating grain charge on surfaces by assuming its free-space capacitance is an incorrect approach. The lunar surface potentials are not affected by either of the above methods. However, the maximum radius of dust particles is greatly affected by the method used to explain dust levitation in the lunar environment. Assumption of free-space capacitance provides the maximum radius of dust particles in the nanometre to micrometre scale. These results are significantly different compared to those obtained above using Gauss's method. However, as there are no direct observations of levitated, charged dust particles near the lunar surface, an open question remains, as far as direct observations are concerned, whether dust levitation occurs on the Moon or not. Experiments by future lunar lander missions which measure the lunar surface potential as well as the charged dust particles can solve this problem[29]. These missions should comprise of a set of instruments near the lunar surface for confirmation of dust levitation as well as to understand the surface charging and dust dynamics in the lunar environment.

Theoretically over the lunar day and night, charged dust particles may be levitated initially, fall on the surface during the decreasing positive surface potential and are again levitated during lunar night. The particles travelling beyond the plasma sheath may follow parabolic trajectories after crossing the boundary and return within the sheath to experience the existing electric field once again. These phenomena can cause oscillations of charged dust particles after the plasma sheath, as long as the surface electric field remains unaltered. A lunar dust detector possibly on a future lunar lander (which is mostly within the plasma sheath) may not encounter more number of particles for detection. Towards the terminator, the charged dust particles are expected to be mostly near the surface, as the surface potential would be decreasing from a positive value. The lunar dust detector is now expected to receive more flux rate of charged particles. This phenomenon is repeated on night side beyond the lunar terminator, but in the opposite sense.

The daytime lunar surface potential in extreme conditions remains up to about 20 V, and the nighttime lunar surface potential can be as high as –3.8 kV. There is a sharp gradient in electric field near the terminator due to transition of surface potential from positive to negative, which may cause the dust particles to form a thin cloud. There is a possibility that the instruments on future lunar lander missions may be affected by floating electrostatic dust, sometime before and after the lunar terminator. Using the Gauss's method, the maximum radius of dust particles is found to be in the picometre range, where matter is usually found in the form of gas or molecule and it may be difficult to explain the dust levitation process. The assumption of free-space capacitance, as found in the literature, provides the maximum radius of dust particles in the nanometre to micrometre scale. Reports appearing in the literature based on theory or indirect observations explain the lunar dust levitation phenomenon and support the presence of levitated dust in the lunar environment. In the absence of direct observations of levitated, charged dust particles near the lunar surface, an open question remains whether the dust levitation occurs on the Moon. Further studies such as *in situ* experiments by future lunar lander missions are required to measure the lunar surface potential as well as the charged dust particles and also answer the above question.

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ACKNOWLEDGEMENTS. We thank the anonymous reviewer for constructive comments that helped improve the manuscript and Prof. A. K. Singal, Physical Research Laboratory, India for useful suggestions.

Received 22 June 2015; revised accepted 9 December 2015

doi: 10.18520/cs/v110/i10/1984-1989

Photonic crystal-based force sensor to measure sub-micro newton forces over a wide range

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A photonic crystal-based force sensor to measure forces in the wide range 100 nN–10 μN is proposed here. An optimized photonic crystal resonator integrated on top of a Si/SiO$_2$ bilayer cantilever, is used as the sensing device. A sensitivity of 0.1 nm for a force of 100 nN is obtained with a high-quality factor of 10,000. The sensor characteristics in the force ranges 0–1 μN and 0–10 μN are also presented here. Linear wavelength shift and constant quality factor are observed in the entire studied force range.

Keywords: Cantilever beam, force sensing, optical sensors, photonic crystal resonator.

PHOTONIC crystals (PhC) are artificial materials in which refractive index varies periodically. If these refractive indices are sufficiently different, it will give rise to photonic bandgap, which causes prevention of light propagation within a specified range of frequencies spanned by the bandgap. It is possible to manipulate the flow of light within PhCs[1], which makes them promising

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