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Electrostatic migration of lunar dust on sunlit surface: A primary theoretical result
月球光照区尘埃静电迁移规律:初步理论结果*

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Abstract　In space environment, dust grains exposed in solar wind plasma and ultraviolet radiation carry positive electrostatic charge since photoemission dominates. Charged dust grains on the sunlit lunar surface are driven by electrostatic field and/or micrometeorite impacts. According to our calculations, the grains with radius of 0.01μm lofted only by electrostatic force can reach the maximum height about 1km on lunar dayside, but the grains with radius of 0.1μm lofted by electrostatic force can reach the height about 50km on the nightside. The grains ejected by micrometeorite impacts or meteor showers could arrive the altitude of ~100km, but the dust number density is related to the meteor or micrometeorite impact events and varies with the height. These grains soon sink due to the gravity. Assuming that the local electric field and the Debye length are 5V/m and 1m respectively, charged dust grains with the radius <0.37μm move in "jumping mode", or else "bombing mode". Our results showed that the dust events on lunar nightside detected by Lunar Dust Experiment (LDEX) in the orbit altitude of 20 ~ 60km might be related to electrostatic field, but that on lunar dayside does not include the part of electrostatic migration.

Key words　Moon; Lunar dust; Electrostatic migration; Lunar Dust Experiment (LDEX)

摘　要　空间环境中,暴露在太阳风等离子体和紫外辐射中的尘埃颗粒由于光电发射等而带电。月球光照区带电的尘埃颗粒受静电场驱动或微陨石轰击发生迁移。本文计算结果表明,月球光照区粒径为0.01μm的尘埃颗粒静电迁移达到的最大高度约为1km,而在月球黑暗区亚微米级的尘埃颗粒静电迁移可以到达50km的高度。尽管微陨石轰击溅射的尘埃颗粒可到达~100km的高度,但是尘埃数密度与微陨石轰击事件直接相关,并随着高度变化。由于重力作用,溅射的尘埃快速沉降。溅射和沉降过程中,尘埃颗粒由于光电发射等继续充电。在局部电场强度和德拜鞘高度分别为5V/m和1m条件下,粒径<0.37μm的带电尘埃颗粒以"弹跳模式"运动,而粒径>0.37μm的带电尘埃颗粒返回月表,并再次轰击溅射尘埃。根据本文结果可以推断,月球尘埃实验(LDEX)在月球夜晚20~60km高度记录的尘埃事件可能与尘埃的静电迁移相关,但是月球白天记录的事件可能并不包括静电迁移的部分。

关键词　月球;月尘;静电迁移;月球尘埃实验
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1 Introduction

Migration of lunar dust is an important problem faced in manned and unmanned lunar surface exploration in the coming future. Usually, these lunar surface activities are implemented in sunlit area of the Moon. Lunar rovers will enter a hibernation state and astronauts will return to the chamber before the lunar dusk. During lunar daytime activities, electrostatic migration of charged dust is one of the main causes, which hazards the astronauts and damages the lunar rovers and other instruments. This harmfulness caused by lunar dust has been verified in Apollo era. For example, the lofting lunar dust could cause significant problems for spacecraft and astronauts on extravehicular activities, ranging from vision obscuration, false instrument reading, clogging of equipment, seal failures, coating and contamination of surface, and abrasion of space suits to inhalation and irritation problems for astronauts on the Moon (Gaier, 2005; Wagner, 2006; Gaier and Jaworske, 2007; Christoffersen *et al.*, 2009). It is worth noting that the phenomena of lunar dust electrostatic migration had been detected in previous explorations from Surveyor missions in 1960s to Apollo missions in 1970s, or even in the latest Lunar Atmosphere and Dust Environment Explorer (LADEE) probe launched in 2013.

In 1968, lunar horizon glow (LHG) along the western lunar horizon one hour after local sunset had been clearly imaged by the Surveyor 7 spacecraft. As an explanation for the LHG phenomenon, electrostatic migration of lunar grains at the terminator had been discussed by Criswell (1973). The origin of LHG is recognized to be the scattering of sun light by the lofting charged dust (Rennilson and Criswell, 1974). Actually, the earliest electrostatic transport of lunar surface material was suggested initially by Gold (1955). With theoretical analysis, however, these charged dust grains can at most rise only a few millimeters above the surface (Gold, 1962, 1965). Based on numerical estimation of Criswell (1973), the charged dust grains with radii of 5 ~ 6μm could be levitated 3 ~ 30cm above the surface in lunar terminator. And the rate of transport was estimated to be roughly 2×10^5 times greater than that of secondary micrometeoroids (Rennilson and Criswell, 1974). LHG was also identified by reanalyzing the images gathered by the surveyor 7, 6 and 5 spacecraft and possibly by Surveyor 1 (Rennilson and Criswell, 1974).

In Apollo 17 mission, the astronauts found the same phenomenon in the minutes before orbital sunrise (McCoy and Criswell, 1974). The above electrostatic migration theory cannot explain the LHG phenomenon caused by forward scattering of sunlight at several or even hundred kilometers. In 1973, the astrophotometer installed on Lunokhod-2 which was designed to measure the sky brightness in visible and ultraviolet range during lunar day and lunar night, detected an unexpected high value of brightness during the lunar day and twilight (Severny *et al.*, 1975). Strong excess brightness at the limb and LHG phenomenon found by Apollo 17 astronauts are interpreted as scattering by 'tenth micron' dust grains extending many kilometers above the surface (McCoy and Criswell, 1974; McCoy, 1976; Zook and McCoy, 1991). Coincidentally, a dim LHG was observed by the star-tracker camera on the Clementine spacecraft in 1994 (Zook, 1994; Zook *et al.*, 1995). To explain the very high altitude of dust grain migration, a dynamic fountain model (DFM) was proposed by Stubbs *et al.* (2006). Based on DFM, submicron charged dust grain driven by electrostatic force can reach the altitude up to ~100km above the lunar surface. This model pointed out that precious static dust levitation model is very applicable to the heavier micron-sized grains in close proximity to the surface, and DFM is most appropriate to explain the presence of extremely light grains at high altitudes.

Recently, the Lunar Dust Experiment (LDEX) onboard the LADEE, gathered the detailed information about the lunar atmosphere by in situ measurement of exospheric dust in a 20 ~ 60km orbit (Delory *et al.*, 2009). The LDEX instrument was turned off while the Sun is in its field-of view for it is sensitive to the ultraviolet (UV) light (Sternovsky *et al.*, 2014). However, LDEX had recorded about 65000 microchannel plate (MCP) signal and target waveform pairs until the end of 2013 (Horányi *et al.*, 2014) and approximately 140000 dust hits by the end of the mission (Horányi *et al.*, 2015b), which indicated an abundant potential dust events. Additionally, according to the occultation measurements of the Ultraviolet/Visible Spectrometer (UVS) onboard LADEE, the detected spectral color changes were also attributed to the presence of sub-micron dust grains in the lunar exosphere (Wooden *et al.*, 2014) and a sparse dust grains on the order of ~20nm in radius were found in the lunar tail (Cook *et al.*, 2015). New results of LDEX showed a close relationship between the lunar dust levitation and the impact of micrometeoroids shower (Elphic *et al.*, 2014; Stubbs *et al.*, 2014; Horányi *et al.*, 2014, 2015a). Although it is not clearly known whether the micrometeorid impact and/or the electrostatic force lofts lunar dust grains to tens of kilometers or even higher, electrostatic migration of lunar dust is still an important dust movement process close to the lunar surface.

LADEE results showed that the dust number density rapidly increased toward the surface (Horányi *et al.*, 2014), especially increased several-fold at 50km (Elphic *et al.*, 2014). The LDEX results and DFM are unified in terms of dust reached altitude. However, the number of recorded dust events was close related to impact process, such as meteor shower and explorer landing (Elphic *et al.*, 2014; Stubbs *et al.*, 2014), and no direct evidence is detected to support the charge dust grains levitated to a high altitude of 3 ~ 250km above the lunar terminator by electrostatic force (Szalay and Horányi, 2015). Is the electrostatic migration of lunar charged dust over estimated by the DFM? Were the dust events recorded by LDEX induced by meteor showers and/or electrostatic field? In order to discuss the migration altitude and lifetime, we reanalyzed the dynamic of dust electrostatic migration above the lunar surface in this study. Dynamic analysis of the charged dust grains in the near surface regions on the lunar dayside was described in Section 2 and Section 3 in detail. Dust transport above the lunar surface on the lunar nightside is just briefly introduced in Subsection 3.3.

2 Dynamic analysis

On lunar sunlit surface, dust grains are exposed to the UV, X-ray radiation and energetic electron, and charged positive by photoemission and second electron emission. With positive charged dust grains, a positive electric potential is formed at lunar surface, namely, a Debye sheath is formed in plasma environment near the lunar surface. Electrostatic migration process of the dust grain near the lunar surface is dominated by the Debye sheath. In the sheath, movement of a positive charged grain is mainly controlled by an upward electrostatic force and a downward gravity force. According to the law of energy conversation, the energy equation can be written as

$$\frac{1}{2}mv_{D-up}^2 - \frac{1}{2}mv_0^2 = qE\lambda_D - mg\lambda_D \qquad (1)$$

where m and q are the quality and charge of dust grain, respectively. λ_D and E are the Debye length and the electric field intensity in Debye sheath, and g is the acceleration of gravity on the Moon. When the charged grain leaves lunar surface with a zero initial velocity ($v_0 = 0$), the velocity of the dust grain passing the upper interface of Debye sheath ($v_{D\text{-}up}$) can be expressed as

$$v_{D-up} = \sqrt{2\left(E\frac{q}{m} - g\right)\lambda_D} \qquad (2)$$

For a charged dust grain, it can leave lunar surface when the electrostatic force is greater than the gravity force. From Eq. 2, it can be found that $v_{D\text{-}up}$ is related to the quality and charge of dust grain, the Debye length and the electric field intensity. These migrated charged dusts may result in two fates. First, it will escape to the deep space and never come back, if it charged much more electric quantity in a strong electric field that can accelerate the dust grain to a high velocity which is greater than the escape velocity (2.38km/s). Second, it will fall back to the lunar surface with a zero velocity if it charged a small electric quantity in a weak electric field. Both of the two cases are not be cared in this study because the short lifetime of these grains can be maintained. In fact, many uncharged or small charged dust grains that cannot leave lunar surface by electrostatic force are ejected by micrometeorite impact and other disturbance process. These dust grains can be also charged by photoemission and second electron emission when they move above the Debye sheath. If their upward velocity is smaller than the escape velocity, they will come back downward and pass through the Debye sheath again. The dynamic process of these grains in the Debye sheath would be discussed as follows.

On the dayside of the Moon, the downward grains entering the Debye sheath with neutral and negatively charges are accelerated by gravity and electrostatic force, and finally deposit to the lunar surface. However, the positively charged particles are inhibited by the electrostatic field. They may slow down and even be reversely accelerated by electrostatic force in Debye sheath if the dust charge increased or the velocity decreased, then leave the Debye sheath again following a near-parabolic trajectory. The charged grains fall down under the gravity effect and rebound due to the action of electric force. These charged dust grains move up and down just like jumping, so we call it "jumping mode". If there is no local electrostatic field above the lunar surface, all the dust grains finally return to the surface. The ubiquitous electrostatic field and the dust charging during the transport process make it possible to jump repeatedly. It does not jump until the grain charge and/or the electric field disappear. If the dust charge is neutralized partly or the velocity increased, the downward charged grains will hit the lunar surface and eject other dust grains to the space. This process just likes throwing a mini bomb to the lunar surface, so we call it "bombing mode". It enhances the jumping mode by ejecting much more dust grains into the space with a lower velocity. These two migration modes and the effects of charge quantity, Debye length and electric field intensity on dust movement would be discussed in the following section.

3 Discussion

3.1 Dust charge

Electrostatic migration of dust grain is close related to the charge-to-mass ratio q/m. On the sunlit side of the Moon, photoemission of dust grains induced by solar UV radiation and X-rays is an important charging mechanism. For example, we measured the work function of olivine (7.3 ~ 8.5eV) by Kelvin probe force microscopy (KPFM) based on the technique of an ultrahigh vacuum (UHV) non-contact atomic force microscope (NC-AFM). Results showed that olivine emits photoelectron and charges positive under the X-ray and solar UV irradiation with wavelength of < 171nm. We assume that the available energy of UV radiation and X-rays inducing the photoemission effect accounts for 0.01% of the total solar irradiation and that the photoemission yields of dust photoemission is 5%. Thus, exposed to solar irradiation for 10 minutes, an olivine grain with radius of 0.1μm obtains about 10^5 electrons which is much more than the theoretical saturation charge of a spherical grain. However, the charges on the area s of lunar surface can be integrated according to the Gauss' Law

$$\oint_s E \cdot dA = \frac{Q_{sur}}{\varepsilon_0} \qquad (3)$$

where Q_{sur} is the total charge enclosed in s and ε_0 is the vacuum permittivity. For an arbitrary surface area s in electric field with intensity E, the charge density (σ) of an insulating surface can be given by $\sigma = 2\varepsilon_0 E$. So, the charge ($q$) of a grain with radius r and surface charge density σ is

$$q = \sigma\pi r^2 = 2\varepsilon_0 E\pi r^2 \qquad (4)$$

Under the surface electric field of 10V/m, a dust grain with the radius of 0.1μm is charged approximately 10^{-5} electrons. That is, only one out of every tens of thousands grains with radius of 0.1μm obtains an electron. Consequently, a large-scale migration of dust grains driven by electrostatic force is difficult on lunar surface.

Once the dust grain leaves the lunar surface due to the other natural or anthropogenic processes, it can accumulate sufficient charge in the free plasma space. For example, LDEX recorded impact charges of 0.3fC (~ 10^3 electrons) and 4fC (~ 10^4 electrons) corresponding to dust grains with radii of 0.3μm and 0.7μm (Horányi *et al.*, 2015a, b), which means the submicron-sized grain can accumulate charges much more than 10^{-5} electrons. On the lunar sunlit side, the primary electric current sources are the photoemission of solar ultraviolet and X-ray radiation (J_p), the second electron emission (J_{se}), the collection of plasma electrons (J_e) and ions (J_i). Outside of the magnetotail, lunar surface typically charged positive (+5 ~ +10V) due to photoemission and second electron emission (Manka, 1973; Freeman and Ibrahim, 1975; Colwell *et al.*, 2007). The charge is continually accumulated until the increased potential results in the sum of the locally modified currents being zero, $J_p + J_e + J_i + J_{se} = 0$. For an isolated dust grain, equilibrium floating potential is $\phi_s = (hc / \lambda - W)/e$ (Sickafoose *et al.*, 2000), where W is work function of a dust grain and λ is the wavelength of illumination spectra. The charge of a grain immersed in the plasma environment can be calculated by $q = C\phi_s$, where C is the capacitance of the grain. For a spherical grain with radius $r \ll \lambda_D$, the grain capacitance is $C \approx 4\pi\varepsilon_0 r$ (Goertz, 1989) and the grain charge is

$$q \approx 4\pi\varepsilon_0 r\phi_s \qquad (5)$$

Generally, there is no charge transfer among dust particles because of the extremely low electrical conductivity and constantly recharging of the incident spectra. Here, surface potential on lunar dayside is adopted a conservative estimation of 5V, which is assumed to be equaled by equilibrium floating potential of dust grain. With an equilibrium potential of 5V, a submicron-sized grain is estimated to be charged about 10^2 electrons based on Eq. 5. In fact, the mature soils tend to carry more charges. Due to space weather, the crystal structure of many lunar soil grains was destroyed. One or more amorphous rinds coating on the soil grains was/were produced. Many grains were transformed to the amorphous silicate glass. Lunar soils reveal an abundance of nanophase-Fe^0 (np-Fe^0) globules in the rinds of soil grains and the silicate glass. The destroyed or amorphous soil grains have lower work function than the well-crystalline minerals. Especially, the existence of np-Fe^0 significantly reduces the work function of soil grains. Therefore, the charges collected by the lunar surface materials could be more than 10^2 electrons.

3.2 Dust movement

For a spherical grain with radius r, the mass can be derived by $m = \rho \cdot \frac{4}{3}\pi r^3$ where ρ is the dust density. According to the Eq. 5, the charge-to-mass ratio is given by

$$\frac{q}{m} = \frac{3\varepsilon_0\phi_s}{r^2\rho} \qquad (6)$$

The acceleration of gravity on the Moon is $1.622 m/s^2$, and the dust particle density is $3g/cm^3$. Regardless of the change of electrostatic field, dust grains transport in the "jumping mode" above the lunar surface if the charge and/or velocity changes. Velocity variation of dust grains caused by particles interaction is the event of small probability; however, the increase of dust grain charges is very common. Assumed that a dust grain enters the Debye sheath with the velocity $v_{D\text{-}down}$ and charges Q, it is just fast enough to reach the lunar surface with the zero velocity. Here, we consider the surface electric field intensity and the Debye length on the lunar dayside are 5V/m and 1m, respectively. Based on Eqs. 2 and 6, the critical velocity $v_{D\text{-}down}$ of dust grains passing through upper interface of a specific Debye sheath is related by r and it can be written as

$$v_{D\text{-}down} = \sqrt{2\left(E\frac{3\varepsilon_0\phi_s}{r^2\rho} - g\right)\lambda_D} = \sqrt{4.427 \times 10^{-13}\frac{1}{r^2} - 3.24} \qquad (7)$$

Based on the above equation, the trend of $v_{D\text{-}down}$ changes with r can be obtained. As shown in Fig. 1, the $v_{D\text{-}down}$ decreases with the increase of the grain radius. The $v_{D\text{-}down}$ curve separates different v_D vs. r into two parts. The charged grain with the radius r enters the Debye sheath at the velocity v_D. Above the curve, the grain has a velocity v_D larger than $v_{D\text{-}down}$ and migrates in "bombing mode". Below the curve, the charged grain has a velocity smaller than $v_{D\text{-}down}$ and migrates in "jumping mode". On the other hand, when r trends to 0.37μm, $v_{D\text{-}down}$ closes to zero. That is, only the grains with radius $r < 0.37$μm can migrate in "jumping mode" above the Debye sheath, which is 1m height and has a 5V/m electric field intensity. For such a Debye sheath, the $v_{D\text{-}down}$ is decided by the charge-to-mass ratio. Small charged grains with small charge quantity have large $v_{D\text{-}down}$ and migrate in "jumping mode". In this mode, these grains would keep jumping above the Debye sheath until the electric field changes. It indicates that these grains may keep moving before lunar night, when the electric field direction changes from upward to downward by charging lunar surface negative. Thus, the migration periods of these grains above lunar surface can last to lunar sunset since they leaved the lunar surface.

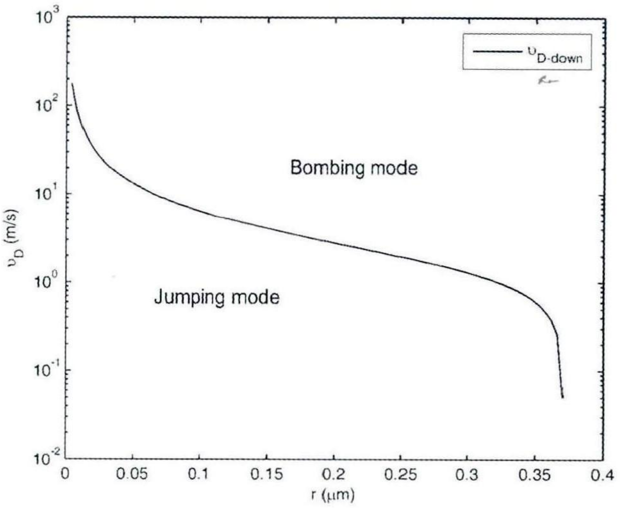

Fig. 1 The velocity ($v_{D\text{-}down}$) of dust grains entering the Debye sheath as a function of dust grain radius (r)

When $v_D = v_{D\text{-}down}$, the grains just fall to the lunar surface. Above the curve, the grains are in "bombing mode", otherwise in "jumping mode"

According to Eq. 4, the electrostatic force of the dust grains is difficult to overcome its gravity and other short-range forces such as van der Waals force and cohesion force. Therefore, it is almost impossible that the dust grains on lunar surface are lifted by electrostatic field. However, the distribution of dust charge on the lunar surface is not homogeneous. On the lunar surface, the levitation of the stationary dust grains by electrostatic field must meet that

$$Eq > \frac{4}{3}\pi r^3\rho g \qquad (8)$$

Where $q = ne$, and n is a round figure and denotes the number of the dust charge. Fig. 2 shows the maximum number of charge ($N_{\max}$, also known as the saturation charge) based on Eq. 5 and the minimum number of charge ($N_{\min}$) required by the lofting dust grain based on Eq. 8. In other words, the maximum radius of the charged dust grain leaving the surface by electrostatic field is the function of the number of dust charge. As shown in Fig. 2, the effect of electrostatic field force (F_{es}) on lunar fines provides one of the plausible explanations for the dust phenomenon photographed and observed by early lunar missions.

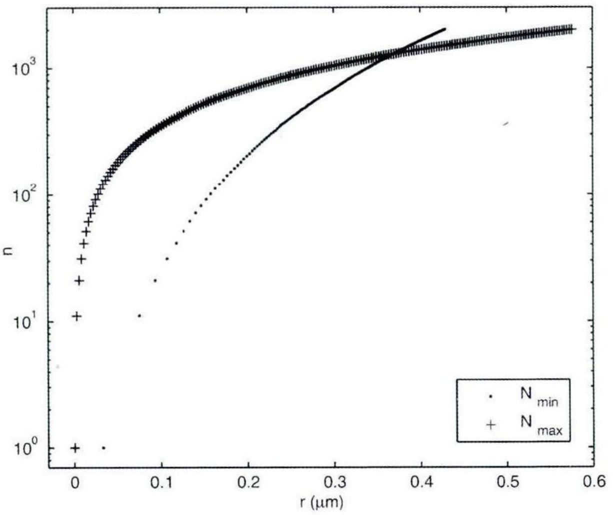

Fig. 2 The maximum number (N_{max}) and the minimum number (N_{min}) of charge required by the lofting dust grain as a function of dust grain radius (r)

N_{max} is the saturation charge of dust grain based on Eq. 5 and N_{min} is the minimum charge number required by the electrostatic levitation of dust grain based on Eq. 8

The charged dust grain leaves the lunar surface and is accelerated upwards across the plasma Debye sheath because the electrostatic force is larger than the gravity force. If $n = 1$, the dust grain with radii of $< 0.03\,\mu$m is lifted by electrostatic field; and if $n = 26$, the $< 0.1\,\mu$m grain can be levitated. However, dust grains with radii of $> 0.37\,\mu$m can not leave the lunar surface only by the action of electrostatic force for the saturation charge of the grains is smaller than the minimum charge required by dust migration.

On the lunar surface, the acceleration can be expressed as $a_1 = \frac{Eq}{m} - g$ inside Debye sheath and $a_2 = g$ beyond the electrostatic field, respectively. The maximum altitude reached by the charged grain is $H = h + \lambda_D$ where h is the height of the grain moving beyond the electrostatic field and $h = \frac{v_D^2}{2g}$. According to Eq. 2, the total height is given by

$$H = \frac{Eq}{mg}\lambda_D = 3.932 \times 10^{-23}\frac{n}{r^3} \qquad (9)$$

Based on the above equation, the maximum migrate altitude of dust grains is the function of grain size and the number of dust charge. As shown in Fig. 3, the maximum height of dust grains with the saturation charge is indicated by the black dashed-line. We can see that the highly charged grain with 0.01 micron-size radius can reach altitudes of up to 1km above the lunar surface. The heights (H) of dust grains reached with different charge number n are also shown in Fig. 3. The colored lines indicate the heights reached by dust grains accumulating 1 (blue line), 10 (green line), 100 (red line), 500 (cyan line) and 1000 (purple line) electrons, respectively.

3.3 Comparison

The DFM relaxes the static constraint of previous model and predicts the lofting altitude of submicron grains ranges from tens of centimeters to hundreds of kilometers above the lunar surface. In the model, after dust particle accumulates sufficient charges, it overcomes gravity and other short-range forces and leaves the lunar surface. Although LDEX did not detect the amount of potential dust grains in the altitude range of 3 ~ 250km above the lunar terminator, which is due to the electric field distortion above the lunar terminator and the large-scale horizontal migration of the grains. However, the electrostatically lofted grains migrate vertically on the dayside and the nightside of the Moon. Therefore, the DFM is still an effective mechanism of dust migration.

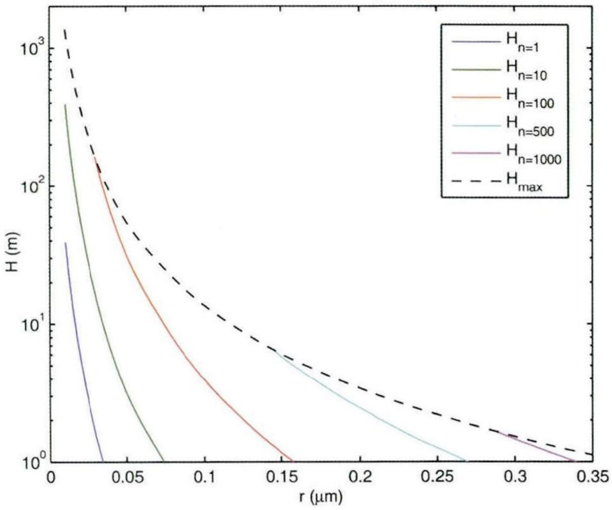

Fig. 3 Predictions of the maximum height of the dust grain with the saturation charge (black dashed-line) or a certain charge number n (colored lines) reached above the lunar surface by electrostatic field as a function of the dust radius

Based on DFM, electrostatic migration of lunar dust on sunlit surface, for example, was analyzed. We calculated the number of charge on the dust grain surface in different environments and the maximum height of dust grain with different charge reaching. In the free plasma environment, the number of charge on the dust grain surface is close to the saturation charge. However, dust grains cannot accumulate enough charge in the Debye sheath. Although the net charges of dust grain on the lunar surface is quite low, it cannot maintain standstill after receiving some charges. The grain with small radius can be lifted by electrostatic force even though it charged only one electron. However, the grains lifted by electrostatic force hardly reach the altitude of 1km. Therefore, dust events on the lunar daytime recorded by LDEX on 20 ~ 60km orbit may not include the part of electrostatic migration.

In addition, by considering the velocity and charge of dust grains, we can infer the dynamic mechanism inducing the movement of dust grains and predict its movement trends. As shown in Fig. 1, considering the local electric field 5V/m and the Debye length 1m on the dayside, the dust grains with radii of $> 0.37\,\mu$m will ultimately return the lunar surface. In addition, the movement of those with radii $< 0.37\,\mu$m is decided by the velocity. With $v_D < v_{D\text{-}down}$, charged dust grain will move in "jumping mode". Otherwise, it will hit back the lunar surface in "bombing mode". That is, the grains ejected by hypervelocity micrometeorite impacts or anthropogenic mechanism with radii

$>0.37\mu m$ sink finally, but those radius $<0.37\mu m$ repeatedly jump due to the saturation charge obtained during the moving process. The migration lifetime of dust grains with radius $>0.37\mu m$ ranges from 10s minutes to several hours depended on v_D. This result is consistent with the observation of LADEE. It is shown that the recorded number of dust impact events sharply increased with the impact of meteoroid streams during mission but it lasts a short time and diminishes before the next day of the meteor shower ends.

On the lunar dayside, the grain with "jumping mode" is driven by electrostatic field and mainly extends to the altitude of <1km. The number density of dust grains lofted to 50 ~ 100km above the lunar surface appears to be quite low, which appears a remarkable relation with the meteor showers. However, the number density of dust grains lofted below 1km is higher than that at the altitude of 50 ~ 100km. The density changes over time because the changes of solar wind plasma conditions and solar irradiation. On the lunar nightside, both uncharged and positive charged grains deposit to the lunar surface for the downward gravity and electrostatic force. However, the negative charged grains might be loft by the electrostatic force. LDEX can identify individual particles with radii $>0.3\mu m$ and the smaller grains ($0.1 \sim 0.3\mu m$) by measuring their collective signal. With an electrostatic field of −100V on the lunar nightside, the maximum migration altitude of dust grains with the radius of $0.1\mu m$ is about 50km based on the Eq. 3. It may be the reason why the rate of dust events suddenly increased several-fold at 50km (Elphic *et al.*, 2014). Although the dust events recorded by LADEE are most likely related to the meteor showers and the landing of Chang'e-3, the dust events increased with the lowered orbit of LADEE on Nov. 10 and Nov. 20, 2013, which might relate to electrostatic migration of dust grains except the meteor showers. LDEX did not find the expected number density enhancements of dust grains over the terminator (Horányi *et al.*, 2015a), as presented in DFM. Actually, the migration mechanism of lunar dust grains over the terminator is quite complicated because of the complex lunar dust plasma environment and the distorted electrostatic field. Therefore, dust grains over the terminator can not reach the altitude of 100km and it is dominated by horizontal movement.

4 Conclusion

We reanalyzed the dynamic mechanism and the movement of the charged dust on lunar sunlit surface and compared with LADEE observations and DFM results. This study focused on the electrostatic migration of ejected grains in Debye sheath after they are charged in a plasma environment above lunar surface. It suggested that these positive charged grains moving in "bombing mode" or "jumping mode" depended on the charge-mass ratio and properties of Debye sheath. For a specific Debye sheath with 1m height and 5V/m electric intensity, only the small grains with radius $<0.37\mu m$ move in "jumping mode", and the migration lifetime of these grains can last the whole lunar day. Usually, those jumping grains cannot deposit after they leave the surface unless the charge quantity or the electric field changes. On the other hand, the maximum migration altitude is depended on v_D and it hardly reach 1km with saturation charge in a Debye sheath with 1m height and 5V/m electric intensity in lunar day. In lunar night, the maximum migration altitude can reach about 50km for stronger electric field intensity in Debye sheath. This work helps us to interpret the data of LADEE that the dust events last a relative short time in high orbit and dust number density increase several orders in low orbit.

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