ELECTRIC FIELDS ON THE MOON

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Abstract

With the primitive-virtual negative (PVN) charge of the Moon, which generates the inherent electric field of the moon, lunar electrical environment can be understood naturally why the electric charge accumulations should be on the surface and above the moon in the circumstance of space plasma, such as solar wind plasma, UV radiation, etc. Especially, the lunar dust levitation and the horizontal transport on the dayside surface of the moon are discussed, which are crucial elements to understand the glowing effect above the horizon and the streamers at the terminator of the moon.

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Introduction

As the closest earth's companion the moon is apparently the biggest and the brightest object in night sky on the earth. In addition, it is the first astronomical object visited by human beings; in July 1969, two astronauts, jumping around on a thick dusty surface of the moon, were seen on black and white TVs all over the world, it was exotic, mysterious, and even weird, dreary, though. Since human beings stepped on the Moon at first time in human history, it has been almost a half of century. Now, we know, there exist electric fields in dayside and nightside of the moon and an ionosphere above the moon; also, we found the sources of electric field -- how the electric charges can be generated on the surface of the moon in dayside and nightside and what might be the electric charge carriers in the ionosphere above the moon – airless planetary body.

Nevertheless, we neither know for sure yet why and how the electric field distributions are made on the surface and above the moon in dayside and nightside, nor how the electric charge accumulation is possible for the electric field on the surface and for the ionosphere above the moon. In particular, we cannot explain clearly how lunar dust particles are observed at high altitude above the airless surface of moon, in which the glowing effect above the horizon and the streamers at the terminator[2] of the moon can be explained, though. (McCoy and Criswell 1974) (Freeman and Ibrahim 1975) (Berg, Wolf and Rhee 1976) (Colwell, et al. 2007) (Renno and Kok 2008) (O'Brien and Gaier 2009) (Delory 2010) (Horanyi, et al. 2015) (McGovern 2015)

Let's review the phenomenological facts in electrical activities on the moon as followings. In dayside; on the surface of the moon, positive ions are generated by solar UV radiation and X-ray through the photoelectric effect on lunar dust particles, regolith, on the surface (Abbas, et al. 2005) (Sickafoose, et al. 2001) (Colwell, Horanyi and Robertson 2000); and some of photoelectrons manage to escape from the surface, which makes the excess positive charge distribution on the surface of the moon in dayside. The positive charge distribution is about 10 cm thickness above the surface of the moon; however, there is a negative charge distribution at $\sim 1\text{ m}$ above the surface. (Hartzell and Carter 2017) (Halekas, Delory, et al. 2019, Stubbs, Halekas, et al. 2008, Stubbs, Vondrak and Farrell 2005) Now, a simple but fundamental question arises as *how it is possible* because if an electric charge accumulation exists in macroscopic phenomena, for example, in interstellar plasma space including gravitational interaction, there should be a reason for it because electric interaction is much dominant to gravitational interaction and any other types of interaction in macroscopic phenomena. Meanwhile, in nightside; due to the pressure gradient force in the flow of solar wind plasma, the ambipolar electric field is formed in lunar wake, in which electrons are diffused in nightside of the moon easily due to their high mobility; the electric interaction inside solar wind plasma makes positive ions follow the diffused electrons, but positive ions are not in prompt as electrons, which makes the ambipolar electric field and lets the positive ions stay outside the wake, which is up to several kilometers above the lunar surface. (Calle 2011)

The objective of this writing is not about what it is but why and how it is – the reason to be, which are the most fundamental scientific inquiries. To understand naturally how the electric

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[2] boundary of lunar dayside and nightside hemisphere

charge distributions are made in dayside and nightside on the surface and above the moon, the primitive-virtual negative (PVN) charge of the moon is introduced, which generates the inherent electric field of the moon. (Kim 2008) (Appendix A -- Mass-Charge Interaction)

Electric Fields on the Moon

The moon has no global magnetic field and almost no atmosphere; thus, the surface of the moon is actually free accessible to space plasma, especially it is bombarded by solar wind plasma, X-ray, and UV radiation. As the inherent electric field source, the PVN charge of the moon is given as $Q_{pvn} \sim -C_{pvn} M_{moon}$[3], with which, however, the electric field intensity on the surface of the moon should be about $1/6$ of the inherent electric field intensity on the surface of the earth, which is corresponding to the ratio of gravity intensity of the moon to the earth, as $E_{h=0} \sim -20\ (\mathrm{N/C})$ in which h is height from the surface and the minus sign means that the electric field is pointing down as in the gravity of the moon. Then, it is natural to expect that in space plasma positive ions are attractive and negative ions are repulsive from the moon.

First, in dayside, lunar surface is being opened for solar wind plasma, UV radiation, and X-ray. Although it can be expected that positive ions in solar wind plasma should be pulled down to the surface of the moon, it has been known that the dominant positive ions on the surface are the positively ionized dust particles on the surface of the moon generated in photoelectric effect by solar UV radiation and X-ray.

Fig. (1) represents the schematic of electric field distributions on dayside and nightside of the moon, in which E_{pvn} is the inherent electric field of the moon. On dayside, E_+ is generated from the induced positive charge distribution; on nightside, E_- is from the diffused negative charge distribution, and E_+ is from positive charge distribution on the surface or in the ambipolar electric field formed along the boundary of lunar wake.

On dayside in Fig. (1): the positive charge distribution (red color) should be dependent on the solar zenith angle θ_z as its charge density $\rho_+(\theta_z) \sim \cos(\theta_z)$ since dominant positive charges in the distribution are known to be lunar dust particles ionized from photoelectric effect. From the induced positive charge distribution electric field E_+ (red color) can be supposed as shown in Fig. (1) due to the zenith angle(θ_z) dependency of the charge distribution. Hence, the net electric field (black color) points to lunar terminator, which means that positive ions are pushed toward lunar terminator region and, by the same token, negative ions and electrons are attracted towards the center on the dayside $(\theta_z = 0)$. Therefore, a negative charge distribution (blue color) is

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[3] $C_{pvn} \equiv 10^{-19}$ C/kg (Appendix A)

induced right above the positive charge distribution, which is known to be at a few meters above the surface. (Stubbs, Halekas, et al. 2008) (Poppe and Horanyi 2010)

In nightside of the moon, meanwhile, with the pressure gradient force generated in solar wind plasma along the lunar wake boundary and due to the high mobility of electron, there is abundance of electrons diffused into the void of vacuum in nightside of the moon while positive ions follows the diffused electrons and make ambipolar electric field with the diffused electrons. (Calle 2011)

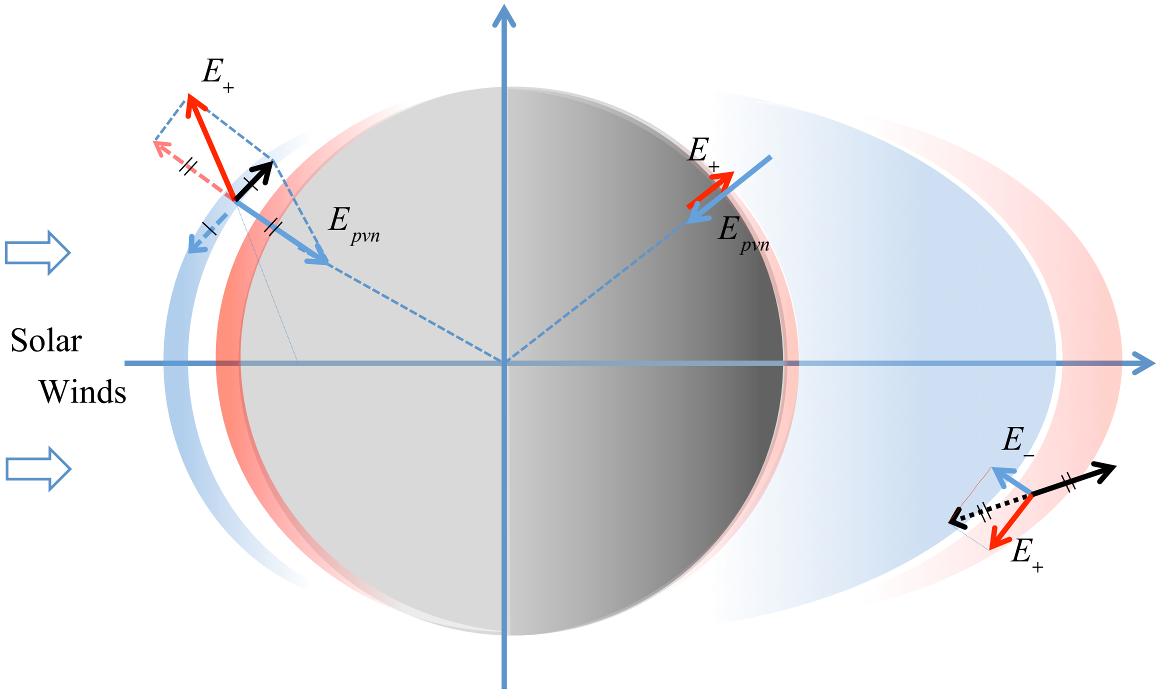

Fig. 1: dayside (LH) and nightside (RH) on the moon

The diffused plasma electrons are attracted to the positive charge distribution on the nightside surface of the moon and neutralize positive ions, which ends up until $\left|\vec{E}_{pvn}\right| = \left|\vec{E}_{+}\right|$ or $\left|\vec{E}_{pvn}\right| > \left|\vec{E}_{+}\right|$. However, if the kinetic energy for the diffused plasma electrons is considered, it should be continued until $\left|\vec{E}_{pvn}\right| > \left|\vec{E}_{+}\right|$; thus, the electric field on the nightside surface should be negative, which makes the electrons of lunar wake be pushed out further. On the other hand, the electric field E_{-} is expected from the diffused negative charge distribution and also from the excess lunar PVN charge effect as in $\left|\vec{E}_{pvn}\right| > \left|\vec{E}_{+}\right|$, and the electric field E_{+} is from the positive charge distribution in the ambipolar electric field, which is known to be at $\sim 1\,\mathrm{km}$ (Halekas, Lin and Mitchell 2003) or several kilometers above the surface (Calle 2011), in which the pressure gradient force (black color) for a unit charge carrier maintains to be equal to $\left|\vec{E}_{+}+\vec{E}_{-}\right|$ as shown in Fig. (1).

In the phenomenological facts that has been estimated and/or measured, the electric field intensity on the surface of dayside is known to be as $E_{\perp} \sim 4-10\ (\mathrm{Vm}^{-1})$ (Stubbs, Vondrak and Farrell 2005) (Stubbs, Halekas, et al. 2008) (Calle 2011), which means that the positive ion production in photoelectric effect is more than the amount just to neutralize E_{pvn} that is the inherent electric field of the moon.

As a matter of fact, the positive charge density on the dayside lunar surface depends on, first of all, the production rate of positively ionized lunar dust particles in photoelectric effect, which varies according to the flux amount of solar UV radiation and X-ray (solar wind plasma condition) and solar zenith angle θ_z (geometry), the efficiency of photoelectric effect, and the recombination rate of photoelectrons; the second, how many positively ionized lunar dust particles can be held on the surface with the inherent lunar electric field E_{pvn} in Fig. (1), and the electrostatic interaction among themselves, which generates the driving force for the lunar dust levitation above the surface and the horizontal transport towards the terminator region of the moon.

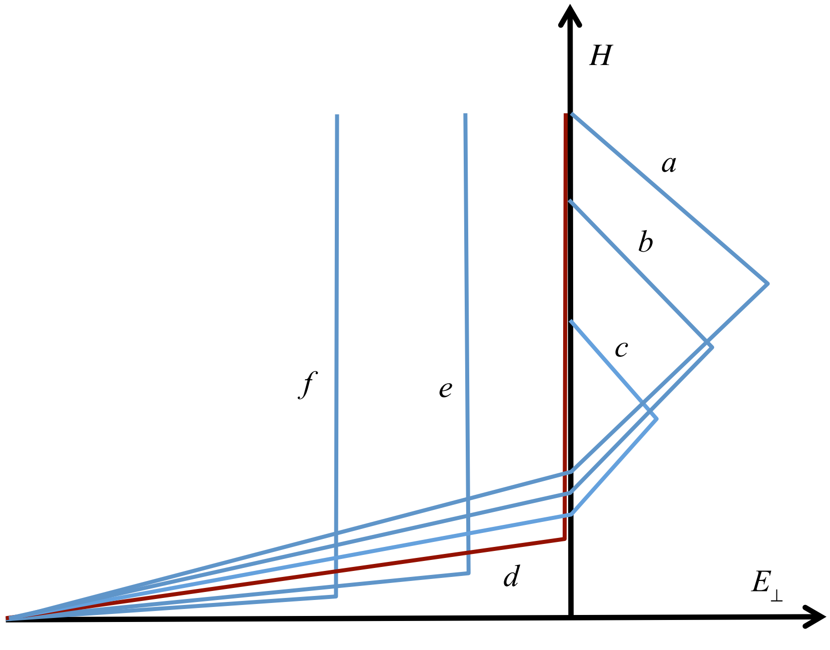

Fig. 2: surface electric fields on the moon

Although it is far from realistic, simple schematic profiles of electric field intensity on the dayside lunar surface can be drawn as shown in Fig. (2), in which $E_\perp$ is normal component of electric field and H is height from the surface of the moon. In Fig. (2), if the case a corresponds to the highest electric field on the surface, it should be at solar zenith angle $\theta_z \sim 0$ degree; towards the terminator region, the electric field intensity gets smaller, which corresponds to the case b, the case c, and so on. At nearby the terminator region $(\theta_z \sim 90^\circ)$, if $E_\perp \sim 0\ (\mathrm{Vm}^{-1})$, it corresponds to the case d, and if $E_\perp < 0\ (\mathrm{Vm}^{-1})$ (Stubbs, Vondrak and Farrell 2005, Farrell, et al. 2007, Stubbs, Halekas, et al. 2008), it corresponds to the case e or the case f.

In addition, it should be notified that there is a negative charge distribution induced on the dayside as shown in Fig. (1). Moreover, if the positive charge distribution on the surface is not enough to neutralize the inherent electric field of the moon, a negative electric field is expected on the surface of the moon $(\text{case } e, \text{case } f)$, which has been measured when the moon was located in the geomagnetic tail. (Halekas, Lin and Mitchell 2005) In particular, if impinging with high temperature electrons depletes the positive charge distribution on the nightside lunar surface in Fig. (1), the electric field on the nightside surface can be negative $(\text{case } e, \text{case } f)$ because of $|E_{pvn}| > |E_+|$; thus, the electrons in lunar wake are pushed out further, of which the possible case has been studied. (Halekas, Mitchell, et al. 2002)

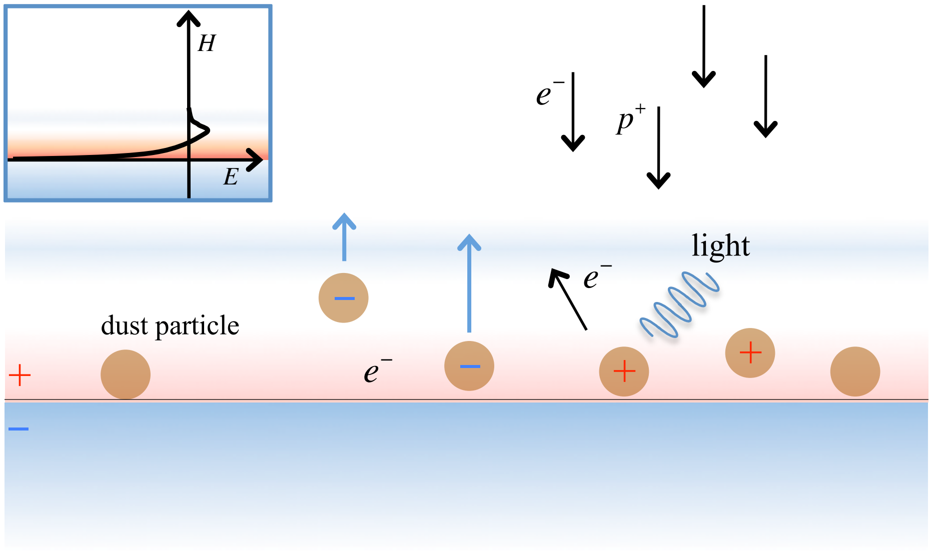

Fig. 3: schematic of dayside lunar surface

It has been known that on the dayside lunar surface the distribution of positively ionized lunar dust particles has ~10 cm depth including electrostatically levitating dust particles and a negative charge distribution is at ~1 m above the surface. Fig. (3) shows the schematic of the electric charge generation on the dayside lunar surface, which corresponds to the case a, b, or c in Fig. (2), and a schematic plot of electric field intensity vs. height. Under the inherent lunar electric field E_{pvn} (blue color) the positive charge distribution of lunar dust particles (red color) is induced, in which the positive charges are generated by photoelectric effect when solar lights (UV radiation and X-ray) hit on the lunar dust particles; however, those of which are supposed to be electrically neutral and stay at ground level, and some of photoelectrons manage to leave behind the positive charge distribution. Naturally, some of positively ionized dust particles, the size of which might be $\sim \mu\text{m}$ or smaller, can be levitated by electrostatic interaction among positive ions themselves, which makes the depth of positive charge distribution above the dayside lunar surface.

Considering that electron can be captured easily due to its high mobility, if the inherent electric field E_{pvn} of the moon as shown in Fig. (3) doesn't exist, it is questionable how those photoelectrons manage to escape through the positive charge distribution without being recaptured. Anyhow, the photoelectrons can be attached to neutral dust particles on the surface; then, the negatively ionized dust particles can be pushed up by the inherent electric field E_{pvn} of the moon and stayed above the positive charge distribution on the dayside lunar surface as shown in Fig. (1), in which the negative charges are attracted to the center of dayside above the positive charge distribution while the positive charges are pushed out towards terminator; moreover, which can explains the positive charge accumulation nearby the terminator region and the lunar *horizon glow* at the terminator. Then, what about streamers at the terminator region of the moon? It has been known to be due to the lunar dust particles lofted at altitude as high as ~10 km (Stubbs, Halekas, et al. 2008) or up to ~100 km (McCoy and Criswell 1974); then, the question is how the lunar dust particles can go up such high altitude.

Lunar Dust Levitation and Transport Phenomena

With the inherent electric field of the moon E_{pvn} there should be more positively ionized dust particles on the dayside lunar surface than without it because E_{pvn} helps to hold more positive charges, which enhances the levitation of positively ionized lunar dust particles above the surface; then, which boosts the mobility of the ionized dust particles for the horizontal transport. In fact, the levitation and the mobility of ionized lunar dust particles should be dependent on the solar zenith angle θ_z.

As shown in Fig. (4), on the dayside lunar surface the positive charge density $\rho(\theta_z)$ including the depth of levitation (dust plasma sheath) is dependent on solar zenith angle θ_z, in which ρ_c is the critical charge density, above which positive electric fields and below which negative electric fields appear on the top of positive charge distribution, owing to the E_{pvn} of the moon that makes $E_{h=0} \sim -20\ (\mathrm{N/C})$ right on the surface. For example, if the electric field intensity on the dayside lunar surface is, say, $E \sim 5\ (\mathrm{Vm}^{-1})$, the positive charge density $\rho(\theta_z)$ on the surface should be about 5 times higher than without the inherent electric field E_{pvn}. For solar zenith angle $\theta_z < \theta_z^c$ the case *a*, *b*, or *c* in Fig. (2) is corresponded and for zenith angle $\theta_z > \theta_z^c$ the case *e* or *f* in Fig. (2) is corresponded. For each case, moreover, a schematic plot of electric field intensity vs. height is added in Fig. (4), respectively.

To minimize the electric field intensity or due to the electrostatic interaction, the positive charge distribution, which consists of positively ionized lunar dust particles, spontaneously keeps trying to redistribute itself. Considering of the solar zenith angle dependency as $\Phi \propto \cos(\theta_z)$ for the flux of solar radiation on the surface, the horizontal transport should be radially outward from the center (subsolar point) on the dayside hemispherical surface, which is shown with an arrow in Fig. (4), and plasma electrons, diffused in nearby the terminator $(\theta_z \sim \pi/2)$, should neutralize the positive lunar dust particles in the transport.

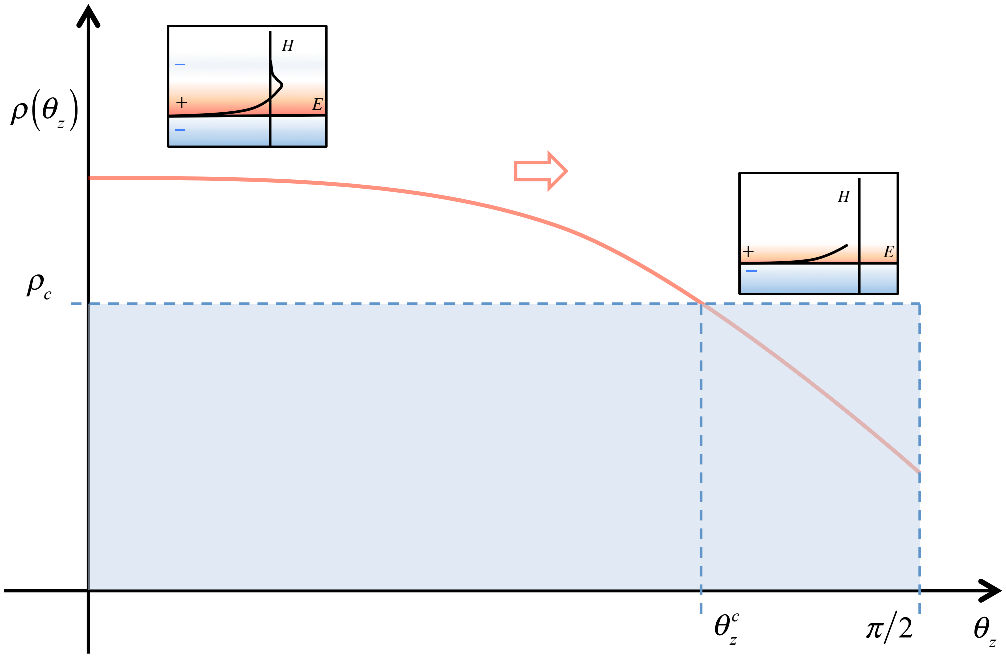

Fig. 4: schematic of positive charge density on the dayside lunar surface

However, the positive lunar dust particles, being transported nearby the terminator region, can be piled up if the diffused plasma electrons are not prompt to neutralize them. If that is true, anyway, we can be curious whether the phenomena at the terminator of the moon, such as lunar *horizon glow* and *streamers* at the terminator, occur always or not because the mechanisms are different for the source production of horizontal transport – photoelectric effect from solar UV radiation – and for the neutralization nearby the terminator by plasma electrons diffused in the region.

On the dayside surface nearby the terminator of the moon, if the electric field is negative – pointing downward, which has been estimated as $E \sim -3 \text{ or} -4 \text{ (Vm}^{-1})$ (Stubbs, Vondrak and Farrell 2005) (Farrell, et al. 2007) (Stubbs, Halekas, et al. 2008), and which corresponds to the case *e* or case *f* in Fig. (2) and the solar zenith angle $\theta_z > \theta_z^c$ in Fig. (4), it would be so easy for negative charged particles, which can be lunar dust particles attached by photoelectrons emitted from photoelectric effect in the region, to escape from the surface and move up such high altitude.

Summary & Discussion

Since the moon has almost no atmosphere, interplanetary space plasma, mainly solar wind plasma can reach to the surface of the moon and the UV radiation and X-ray interact directly with lunar dust particles on the surface, which generates so-called lunar dust plasma. Hence, lunar dust particles seem to play an important role in the electrical environment of the moon, and the dust plasma around the moon has to be concerned to understand the lunar electrical environment as well as space weather condition, especially solar activity. In some respects, however, the electrical environment of the moon seems to be simpler than the earth because there are two distinctive sides, dayside and nightside, of the moon, each of which has unique and consistent mechanism to maintain the electrical equilibrium with outer space overall except when the moon is in the earth's magnetic tail.

It is important to understand clearly how *lunar dust levitation* occurs and how many ionized dust particles can be held nearby the surface of the moon because the mobility of ionized dust particles in the horizontal transport comes from the dust levitation. The primitive-virtual negative (PVN) charge of the moon generates the electric field $E_{pvn} \sim -20 \text{ (Vm}^{-1})$ right on the lunar surface, and the electric field E_{pvn} holds positive dust particles to stay nearby the surface and helps photoelectrons and/or negative dust particles attached by the photoelectrons to escape through the positive charge distribution (depth of levitation). The more positive dust particles are on the surface of the moon, the more positive dust particles get lofted, and the higher mobility of lunar dust plasma is expected for the horizontal transport.

Once the primitive-virtual negative (PVN) charge of the moon is introduced, the lunar electrical environment can be understood naturally and qualitatively although models and/or theories in phenomenology should be followed in detail, including a model for lunar global electric circuit. The PVN charge of the moon should be included in lunar electrical environment. However, for an airless body like the moon, for example, an asteroid, of which the PVN charge is ignorable but its surface is similar to the moon’s, it is interesting to see whether the *horizon glow* and/or *streamers* at its terminator is observed or not.

In scientific inquisitions, a seemingly trivial problem might be considered ignorable; however, we should know, the problem never disappears especially if it is a fundamental one; rather, it will come back later more seriously in a different shape. We might have overlooked something fundamental in physical science.

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Appendix A

Mass-Charge Interaction

With the first principle given in 4-D complex space (Kim 1997, 2008), in which vacuum particles, each of which has positive electric charge, intrinsic magnetic moment (spin), and negative mass in the imaginary subspace, spontaneously react to get the equilibrium for net-mass density and net-charge density in the space, and align their spins to minimize the dynamic variation in the space or simply current effect of physical charges in the real subspace[4], the interaction between gravitational mass and electric charge appears naturally; thus, the primitive-virtual negative (PVN) charge is introduced for gravitational mass in electromagnetic interaction as $Q_{pvn} \sim -C_{pvn} M$, in which $C_{pvn} \equiv 10^{-19} \left[\mathrm{C/kg} \right]$, in which the electric interaction between locally isolated or single positive charge and a PVN charge is expected to be attractive to each other; but a negative charge and a PVN charge, repulsive to each other.

However, the principle of linear superposition, which has been used in gravitational interaction and electromagnetic interaction, is not applicable for the mass-charge interaction by the same principle, the first principle given in 4-D complex space, in general; instead, the source geometry such as mass distribution and electric charge distribution in the real subspace should be considered in the mass-charge interaction, especially for the interaction with positive charge distribution. On the other hand, the interaction between negative charge distribution and gravitational mass is always repulsive, which can be inferred if considering why gravitational interaction is attractive as following: In the imaginary subspace the vacuum particle distribution for a mass object is similar to the one for a negative charge, but it has not the negative charge in the real subspace as in the vacuum particle distribution of the negative charge; therefore, in gravitational interaction, the mass object doesn't need to take vacuum particles for its own to get the equilibrium for net-mass density; while in electric interaction, electric charges need to secure vacuum particles for their own to get the equilibrium for net-charge density. Instead, the mass object can share its vacuum particle distribution with other mass object; hence, gravitational interaction is attractive. (Kim 2017)

In the presence of gravitational field, electric charges are induced spontaneously to minimize the effect of mass-charge interaction or nullify it, in general. For example, Fig. (5) shows a gravitational mass and an electric charge inside a conductor under the gravitational field $\left(\vec{E}_{pvn} \right)$, and the induced electric charge distributions on both sides of the conductor against the gravitational field. If the strength of electric interaction is compared to gravitational interaction[5], the electric field inside the conductor should be none as expected $\left(\vec{E} = 0 \right)$, in which it can be considered as E_+ is generated from the induced positive charges; E_-, from the induced negative charges, respectively, and $E_+ = E_-$; thus, $E_{pvn} = E_+ + E_-$. On the other hand, the gravitational

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[4] It can be discussed for PVN charge, but the effect in macroscopic phenomena is too small.

[5] the ratio of interaction strength in general; $R \sim 10^{37-41}$

field inside the conductor should not be changed in the respect of the first principle in 4-D complex space. In Fig. (5), the induced positive charges generate G_+ that reduce the gravitational field intensity in half, and the induced negative charges generate G_- that is the same intensity as G_+ but in the other direction; thus, the effect of mass-charge interaction is nullified.

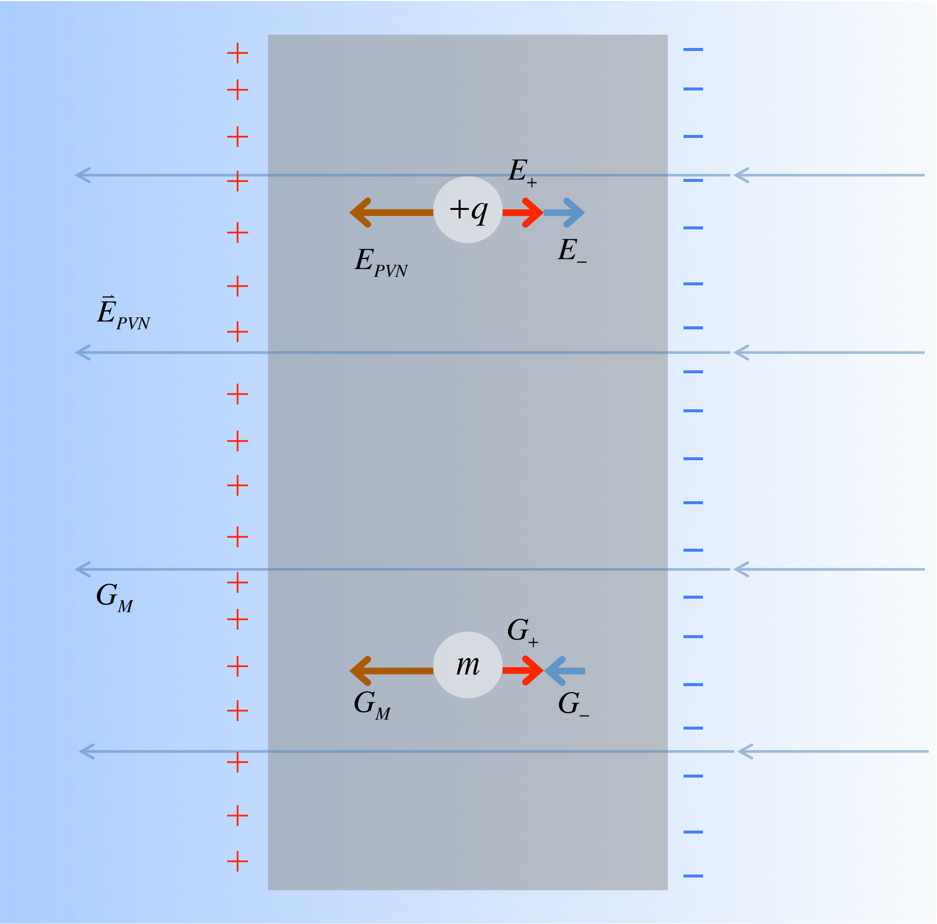

Fig. 5: ($E_{pvn} = E_+ + E_-$; $G_+ = G_-$ $+q$; unit charge, m; unit mass)

Meanwhile, in the case of concentric distributions of gravitational mass and induced electric charges as shown in the model of the earth's magnetic field (Kim 2008), the gravitational field can be affected by the induced electric charges. Moreover, although the possible variations of gravitational field during solar eclipse is minimal amount and temporal, the variation can be explained by the variation of electric charge distribution induced but delayed due to the electrical conductivity underground during the solar eclipse. In addition, it is natural to interpret the PVN charge corresponding to the mass of the earth as the inherent natural electric field source of the earth, which appears as $E_{h=0} \sim -130 \ (\mathrm{N/C})$ on the surface (Kim 2008).

As a simple case, let's think as shown in Fig. (6), in which a gravitational mass object is at the center with mass M and two concentric conducting spherical shells are at $r = R_1$ and $r = R_2$, respectively[6]. On the conducting shells, positive electric charge $+Q$ is induced at $r = R_1$; however, negative electric charge $-Q$, at $r = R_2$. To describe how gravitational field is changed with the positive electric charge $+Q$, a schematic plot is added in the figure.

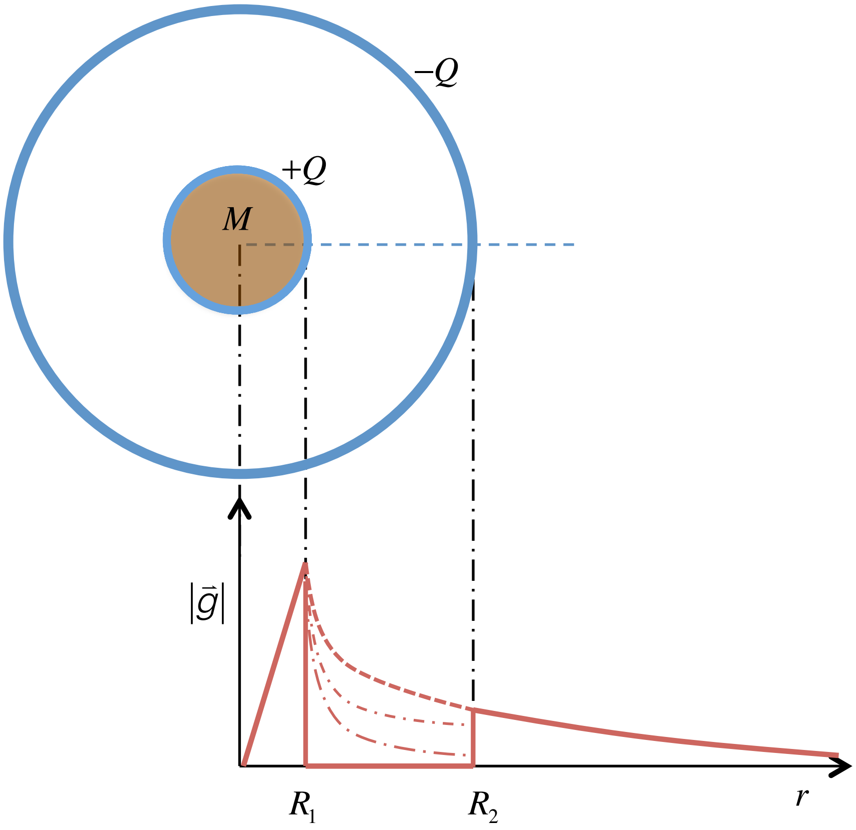

Fig. 6: gravitation vs. radial distance & interactions with electric charges

If $Q < |Q_{pvn}|$, in which Q_{pvn} is the PVN charge of mass object M, the gravitational field intensity in the region at $R_1 < r < R_2$ should be reduced if the vacuum particle distribution is

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[6] density of mass object is constant, and the mass of conducting shells is ignored.

considered with the first principle in 4-D complex space. If $Q = \left|Q_{pvn}\right|$, then, $Q_{net} = Q + Q_{pvn} = 0$; thus, $\left|\vec{E}\right| = 0$ and $\left|\vec{g}\right| = 0$. On the other hand, if $Q > \left|Q_{pvn}\right|$ although it is not naturally induced but should be enforced; then, $Q_{net} = Q + Q_{pvn} > 0$, thus, $\left|\vec{E}\right| > 0$ in direction away from the center $\left(\hat{r}_1\right)$, but $\left|\vec{g}\right| > 0$ in direction towards the center $\left(-\hat{r}_1\right)$. Now, if $Q < 0$ which means that some negative charges are enforcedly put on the inner conducting shell; then, $Q_{net} = Q + Q_{pvn} < 0$, thus, $\left|\vec{E}\right| > 0$ in direction towards the center $\left(-\hat{r}_1\right)$; however, gravitational field $\vec{g}$ is determined depending on the sign of $|Q| - \left|Q_{pvn}\right|$ because the interaction between negative electric charge $(Q < 0)$ and gravitational mass $\left(Q_{pvn}\right)$ is always repulsive. Although it is far from realistic, if $|Q| - \left|Q_{pvn}\right| > 0$, $\vec{g}$ is in direction away from the center $\left(\hat{r}_1\right)$; but, if $|Q| - \left|Q_{pvn}\right| < 0$, $\vec{g}$ is in direction towards the center $\left(-\hat{r}_1\right)$; however, $\vec{g}$ is expected to be zero if $\left|Q\right| - \left|Q_{pvn}\right| = 0$.