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Electrical Phenomena on the Moon and Mars

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***Abstract*—The Moon and Mars represent intriguing and divergent case studies where natural electrical processes may occur in environments beyond our more familiar terrestrial experience. The windy, Aeolian environment of Mars likely produces substantial electrical activity via the tribo-electrification of individual dust grains that occurs during atmospheric disturbances. While there may be some analogies between atmospheric electrical processes on the Earth and Mars, the highly rarefied, dry Martian atmosphere imposes unique conditions that govern the charging and discharge dynamics of particulates. In contrast to the wind-swept surface of Mars, the Moon is a small airless body whose surface is directly exposed to variable space plasmas and solar irradiation. Measurements during the Apollo missions, together with more recent data from orbital spacecraft, indicate that there are active and dynamic charging processes occurring on and near the lunar surface. One possible consequence of dynamic lunar electrical activity may be the levitation and perhaps large scale transport of lunar dust. For both the Moon and Mars we only have indirect evidence at best for the existence of electrical activity of any real global consequence. This paper is a brief, semi-tutorial review that discusses the background and history behind these investigations, highlights key ongoing research, and describes future efforts that will help resolve the fundamental, outstanding questions that remain.**

I. INTRODUCTION

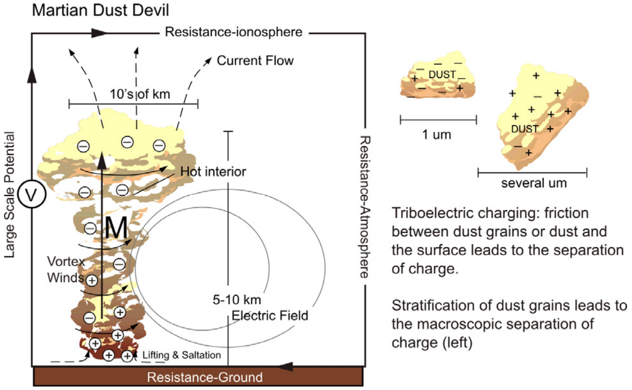
The presence of quasi-electrostatic fields in planetary environments is becoming increasingly important to understand as we realize its interconnection with the lofting, transport, and stratification of nearly any type of particle, dust, or aerosol. Atmospheric electricity is thus very likely a ubiquitous process operating on many planetary bodies and moons. Gas giants are likely abodes of significant atmospheric electrification due to particles and condensates within cloud layers [1-3], with confirmed detections of lightning using optical and radio/plasma instruments at both Saturn and Jupiter [4, 5]. For the inner planets, there is the possibility of lightning on Venus [6], and hence the presence of significant electric fields. Aerosol electrification almost certainly occurs on Titan [7], along with resulting discharge processes [8, 9]. Small bodies without substantial atmospheres are not exempt from electrical processes, as plasma and photocurrents cause charging of their surfaces [10].

Our motivation to study extraterrestrial electrical phenomena arises from several considerations, ranging from basic research to safety issues associated with future human and robotic exploration of the solar system. On Earth, extensive measurements of terrestrial lightning are conducted as part of fundamental atmospheric research and for the more practical desire to help ensure aircraft and space launch vehicle safety [11, 12]. The role of lightning in terrestrial atmospheric chemical processes is of continuing interest [13]. As on Earth, atmospheric electricity undoubtedly has some role in the atmospheric chemistry of other planets [14], and may also pose a hazard to future human explorers in these environments [15]. The wide array of atmospheric conditions found on other worlds may also provide a natural laboratory within which we can study the fundamental physics of discharge processes under a variety of conditions.

II. MARS

A. A Simple Theory

The atmosphere of Mars is one compelling example in our solar system that should possess active electrical processes, where dust storms are known to occur on local, regional, and global scales [16-19]. These events are expected to generate substantial quasi-static electric fields via triboelectric (i.e., frictional) charging, perhaps up to the breakdown potential of the Martian atmosphere [20-22]. Relatively simple experiments readily demonstrate manifestations of triboelectric phenomena under conditions similar to Mars, where the Paschen breakdown voltage in the thin atmosphere is estimated to be ~20 kV/m. Eden & Vonnegut [23] agitated dry sand in a CO_2 gas at low atmospheric pressures similar to Mars, and observed a visible glow accompanied by discrete, filamentary discharges, presumably caused by triboelectrification of individual grains. Convective, Aeolian features such as the dust devils and storms on Mars likely create similar triboelectrically induced discharge effects. Under many circumstances, particularly when dealing with a dust population of similar composition, contact electrification tends to result in negative charge on smaller grains and a more positive charge on larger grains [20, 22, 24]. Large scale electric fields could then be generated from the vertical separation of charge, as lighter, negatively charged grains are lofted upwards while heavier, positively charged grains remain closer to the surface. Such charge separation may easily occur in the ubiquitous dust activity that characterizes the surface of Mars. At the smallest scales, warm-cored, convective vortices known as dust devils range from 100 m – 1 km in width, 10-15 km in height, and occur daily at almost all locations throughout the planet [18, 25, 26]. At larger spatial scales, seasonally-dependent local and regional storms can cover areas ranging from ~10^4 km^2 to nearly global scales [16], while every 2 or 3 Mars years a global dust storm takes place, immersing the majority of the surface for months at a time. These events may produce large scale charge separation with a structure shown in Fig. 1, with the lofting of lighter, negatively charged grains producing a large scale net dipole moment [21]. This charge structure on Mars is in direct analogy with terrestrial thunderstorms on Earth, where dust replaces ice as the electrifying agent, and whose dipole moment is reversed. As is the case for thunderstorms on Earth, the thousands of individual dust devils and fewer but larger regional dust storms occurring at any one time on Mars may act as current generators, driving a global electric circuit and producing a fair weather electric field indicating the strength of the global atmospheric charge load [27].



Triboelectric charging: friction between dust grains or dust and the surface leads to the separation of charge.

Stratification of dust grains leads to the macroscopic separation of charge (left)

Fig. 1. Simple model of large-scale electrification produced by the transport of dust grains occurring during Martian dust devils and storms (From [28]).

B. Dust and Storm Charging Models

Nearly every laboratory experiment or observation of naturally occurring dust motion reveals the presence of electric fields caused by some charging mechanism, which is usually triboelectric in nature. Terrestrial dust devils routinely produce electric fields in excess of 20 kV/m, and can support charge concentrations up to 10^6 electrons/cm^3. Fig. 2 shows the vertical electric field produced by a dust devil during terrestrial field tests designed to assess potential electrical hazards on Mars [20, 29]. There is some direct evidence that Martian dust is at least partially electrically active, with the Sojourner rover wheels showing clear signs of dust adhesion [30]. Thus whether or not the atmosphere of Mars possesses some degree of electrification is seldom debated. It is a description of the details of the charging mechanisms for individual grains, and the discharges that may be present, that remains highly uncertain. For dust charging, factors such as dust collision frequency, composition, shape, surface properties and coatings can make a substantial difference in the efficiency of triboelectric processes. Discharge processes occur in a CO_2 atmosphere with a surface pressure between 0.6-1.0 kPa, i.e., at <1% of Earth's sea level pressure, with vastly different electrical properties. Whether discharges occur in a continual fashion due to dissipative, coronal currents in the more conductive Martian atmosphere, or in more dramatic, large scale events (i.e., lightning) remains an open question.

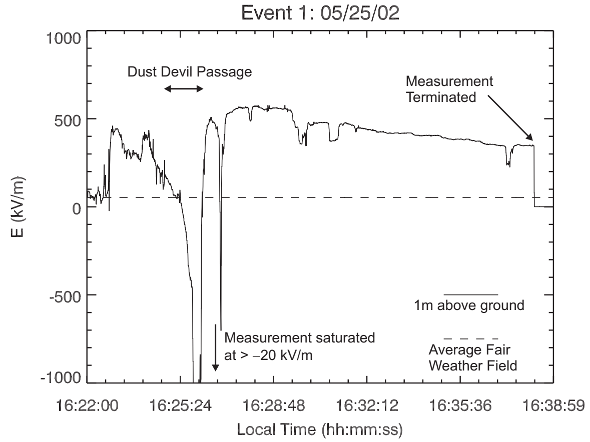


Fig. 2. Measurements of the vertical electric field obtained both outside and within a terrestrial dust devil roughly ~30m in width that occurred in the desert outside Tucson, Arizona in May, 2002 [20]. The charge suspended in the event is opposite in sign to what is found in thunderstorm electrification; thus the normally positive fair weather electric field (~50 V/m, dotted line above) reverses to strong negative values (more than –20 kV/m in this example) as the dust devil passes over the detector.

Most models describing dust electrification on Mars assume simple charging mechanisms that are related to triboelectric processes and terrestrial analogies. Indeed – the physics of the triboelectric process remains mysterious even for typical terrestrial materials [31], which many times rely on the empirically derived triboelectric series for quantification. Based on the experiments of Ette [24] and others, Melnik and Parrot [22] developed a 2D numerical model that assumed a charge rate Δq equal to ~1 femto-Coulomb (fC) per micron of radius (r_s) per collision as typical under Martian conditions:

$$\Delta q = (1 \text{ fC}/\mu\text{m}) r_s \qquad (1)$$

In another numerical model designed specifically for the case of dust devils on Mars, Farrell et al [20] used Equation (1) and also derived a modified form of a collisional dust charging rate from Desch and Cuzzi [32] that takes into account mutual particle capacitance and surface properties:

$$\Delta q = 2668(\Delta\Phi / 2\text{V})(r_f / 0.5\mu\text{m})e \qquad (2)$$

where $\Delta\Phi$ is the difference in surface triboelectric potentials between two grains, $r_f = (r_1^{-1}+r_2^{-1})^{-1}$ is the reduced radii r_1, r_2 of the colliding particles, e is an elementary charge, and V is a unit of Volts. It is not surprising that both models yield rapidly growing electric fields that increase exponentially, easily in excess of the ~20 kV/m theoretical breakdown potential of CO_2 at the surface pressure on Mars.

Notably lacking from these and other models was consideration for any dissipative processes that could serve to limit the accumulation of charge on individual grains. Due to the low pressure of the Martian atmosphere, galactic cosmic rays (GCRs) and ultraviolet (UV) photons play a much larger role in the ionization of the atmosphere than on Earth, whose surface is generally shielded from ionizing radiation at altitudes below 15 km. Using a combination of modeled and experimentally derived profiles of the atmosphere and electron density for Mars, the electrical conductivity of the atmosphere has been estimated to be ~10^{-12} S/m [33], several orders of magnitude higher than on Earth. Thus from Earth to Mars, characteristic timescales for charge dissipation decreases from minutes to seconds. Zhai et al [34] accounted for the atmospheric conductivity in a 2D quasi-electrostatic finite element model of a dust devil. This approach produced an exponential rise in the electric field similar to the models above, followed by a plateau and then steady-state as triboelectric charging processes were balanced by charge dissipation from individual grains combined with conduction currents through the atmosphere. Under these conditions, electric fields approaching breakdown levels on Mars were still obtained assuming dust devils of only moderate size, roughly ~10m wide and ~1 km high. Since to a large degree potentials scale with the amount of suspended charge, it would still possible many dust devils observed on Mars to initiate electrical breakdown, which are typically larger than this scale.

The lower gravity and dynamic pressure on Mars raises the possibility that dust grain motion may be dominated by a combination of fluid and electrical forces, rather than just fluid forces alone. For small particles in suspension, there is currently no observational or theoretical evidence that this is the case – and hence charge generation and separation in Martian dust events likely arises as a consequence of fluid forces with little or no feedback from electric ones [35]. An exception may be in the saltation layer – the lowest meter or so in a dust devil or storm in which heavier, sand-sized particles are entrained in the flow, undergo short semi-ballistic trajectories, and generate secondary particles upon impact. Kok and Renno [36] integrated a dynamic saltation model with triboelectric charging effects to conclude that electric fields alter the trajectories of sand particles, keeping them closer to the surface and thus increasing the overall density of the saltation layer. Measurements of electric fields of up to ~160 kV/m in this layer [37] appear consistent with this theory, indicating that in at least some regimes electrodynamic in addition to fluid forces may be important to consider for dust dynamics in environments such as Mars.

C. Lightning on Mars?

While the possibility for significant dust electrification on Mars is rarely disputed, there is great uncertainty as to the nature and form of any large scale discharges that may be present. To date, there have been no direct detections of what could be considered Martian lightning. Recent searches using the Deep Space Network (DSN) indicate that nonthermal microwave emissions may be present during dust storms that may be indicative of discharge activity [38]. However, similar searches from the Mars Express spacecraft using the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument in passive receiver mode have yielded no corroborating results [39]. The ease with which most models predict electric fields up to ~20 kV/m levels indicates the possibility for breakdown to occur; however the role of dissipative processes in dust charging events remains highly uncertain, and hence whether or not charge separation can be maintained over sufficient temporal and spatial scales for lightning to be generated on Mars remains a mystery. Adding to this mystery is the continual controversy as to what process initiates terrestrial lightning, since it has become clear that electric fields in thunderstorms usually achieve only a fraction of the magnitude necessary to meet traditional breakdown criteria [40]. Various triggers have been proposed, including GCRs that induce electron avalanches or "runaway breakdown" (RB) that enable lightning [41, 42]. The possibility of lightning on Mars will undoubtedly pose just as many questions as in the terrestrial case once we have definitive evidence of its existence.

D. Atmospheric Chemistry

Whether or not lightning occurs, there is the possibility that atmospheric electrical processes on Mars may have an impact on atmospheric chemistry. On Earth, lightning is believed to play a major role in nitrogen fixation, second only to anthropogenic and biological sources [43]. If any large scale discharge processes resembling lightning occur on Mars, trace species can result due to the "freezing out process" occurring in the shock wave near the discharge event [14]. Such processes can produce CO, O_2, NO, and O in the atmosphere of Mars, and may thus have had some role in atmospheric evolution. Recent work has examined the potential impact of pre-lightning electrification on Mars' atmospheric chemistry, by examining the role of electrons energized by storm electric fields in the ionization and dissociation of CO_2 and H_2O. Delory et al [28] used a plasma physics model to demonstrate that for electric fields >10 kV/m, appreciable amounts of CO/O^- and OH/H^- could be generated. Subsequent chemical reactions of these species would result in significant amounts of hydrogen peroxide [44] or other super-oxides, substances which are thought to be responsible for the apparent chemical reactivity of the soil analyzed by the Viking missions. Subsequent work has examined this process in more detail, including loss terms that may serve to partially mitigate these effects through absorption of electrons by dust and local changes in atmospheric conductivity [45, 46].

E. Open Questions and Future Directions

To summarize, to date there is only tantalizing evidence as to whether Mars possesses an active electrodynamic environment. While experience in the laboratory and in the terrestrial environment supports this notion, direct observations are few and ambiguous. Laboratory experiments are ongoing and may shed light on mechanisms of dust charging [47, 48], and dust charging models will undoubtedly improve by incorporating more sophisticated physical descriptions of the discharge process [49]. However, definitive progress will only be made through measurements of electrical activity in and near the Martian environment. From orbit around Mars, the appearance of circularly polarized, whistler-mode electromagnetic waves during dust storms would argue strongly for the presence of lightning in analogy with similar arguments being made for Venus [50]. On the surface, a relatively simple experiment to measure radio waves in the lightning sferic band (~1-20 kHz) would also provide a similar confirmation, as would the detection of global resonant electromagnetic modes in the Schumann band (<100 Hz) indicating the presence of lightning generated waves trapped in the surface-ionosphere cavity [51, 52]. Lacking a definitive detection of lightning, a measurement of the vertical fair-weather electric field could provide an estimate for the degree of charge separation occurring in dust devils and storms at global scales [27] via the atmospheric electric circuit. These measurements are for the most part straightforward, and will serve to guide future modeling efforts by confirming whether or not lightning is present, and the degree to which the atmosphere of Mars is electrified. Opportunities for orbital measurements may arise through continual analysis of receiver data from MARSIS on Mars Express, and from the

Langmuir Probe/Waves instrument on the upcoming Mars Atmosphere and Volatile Evolution (MAVEN) mission scheduled for launch in 2013. Among all future possibilities for relevant measurements, observations from the surface are the most likely to produce a significant step in our understanding of the true nature of atmospheric electricity on Mars. Despite attempts by several research groups, no instruments measuring electromagnetic phenomena have yet made their way to the Martian surface. Such instruments may be included on future landed network platforms [53], which would ideally study the entire electro-meteorological system, including AC and DC fields combined with wind velocity, temperature, pressure, and dust properties.

III. THE MOON

A. *The Electric Moon*

The Moon possesses no appreciable atmosphere and thus the fluid forces that cause electrostatic charging on Mars are absent. However, as an airless body illuminated by solar UV and immersed in the solar wind and terrestrial plasmas, the Moon's surface is subject to a variety of processes that can cause significant charging on quasi-DC timescales that fall within the electrostatic regime. Thus on the Moon, the Aeolian winds on Mars are replaced by incident plasmas and photons as the prime driver for charging phenomena at the surface. At its most fundamental level, an understanding of electrical phenomena on the surface of the Moon is essentially a dusty plasma physics problem.

All objects in space will charge to an electric potential that represents the equilibrium obtained by the various charging currents that are present [54]. Space plasmas provide one source of currents, from both ion and electron flux that is incident on any given surface. Equilibrium is obtained when the total current arriving at an object is zero; in darkness, i.e., in the absence of photocurrents, the ion and electron currents must cancel. In many situations the ion and electron temperatures T_e and $T_i = T$ are equal. As a result, the electrons move at velocities faster than ions by a factor proportional to the square root of the inverse ratio of their masses, $(m_i/m_e)^{1/2}$. Hence at any one time, there are more electrons arriving at the surface than ions. The result is an accumulation of negative charge, which in turn begins to repel some electrons and attract ions. At equilibrium a sufficient number of electrons are repelled and ions attracted in order to balance what remains of the incident electron current. Thus shadowed surfaces in space plasmas tend to charge to negative potentials. For a surface at a potential $V < 0$, the electrons follow a Boltzmann distribution, resulting in an incident electron current I_e of the form:

$$I_e = A n_e e \sqrt{\frac{kT}{2\pi m_e}} e^{eV/kT} \tag{3}$$

where A is the area of surface under consideration, n_e is the electron density, e is an elementary charge, k is Boltzmann's constant, m_e is the electron mass, and T is the electron/ion temperature. The ions, meanwhile, are attracted to the surface, and thus form a saturated current I_i of the form:

$$I_i = An_i e\sqrt{\frac{kT}{2\pi m_i}} \tag{4}$$

Where n_i is the ion concentration at temperature T, and m_i is the ion mass. Using a simple assumption for equilibrium of $I_e = I_i$, the floating potential V may be solved for as:

$$V = -\frac{kT}{e}\ln\left(\frac{J_{oe}}{J_{oi}}\right) \tag{5}$$

where J_{oe} and J_{oi} are the saturated thermal electron and ion current densities, respectively. Due to the higher thermal electron current, objects and surfaces tend to charge negative by an amount a few times kT/e when immersed in a plasma and in darkness. This value may range from a few volts to several thousand volts negative for the range of plasma conditions encountered by the Moon and other solar system objects.

When in sunlight, there is an additional current generated by a significant production of photoelectrons in response to incident solar UV photons. These departing photoelectrons assist the incident ion current in achieving equilibrium with the surface. In fact, at a few nano-Amperes/cm^2, photo-currents tend to dominate the other ion and electron plasma currents in the system, whose magnitude may be lower by several orders of magnitude or more. For most plasma conditions, the result is an excess of electrons leaving the surface, which then charges positively in order to attract a portion of these back, until overall current balance between photoelectron and plasma currents is achieved. Neglecting the small ion currents, an expression for the surface potential V becomes [55]:

$$V = \frac{kT_p}{e}\ln\left(\frac{J_{op}}{J_{oe}}\right) \tag{6}$$

where T_p is the photoelectron temperature, J_{op} is the photoelectron saturation current density (~4 nA/cm^2 at the Moon), and J_{oe} is the saturated electron current density in the solar wind, $\sim n_e e(kT_e/2\pi m_e)^{1/2}$ In practice, all surfaces exposed to the sun in space acquire a potential ranging between +5 to +10 V. Above these surfaces there is a region of non-uniform charge distribution and an accompanying electric field called the Debye sheath, or plasma sheath, where non-neutral effects dominate. The Debye length provides a characteristic spatial scale beyond which the plasma is quasi-neutral, i.e., the influence of charge is shielded by the motion of other charges nearby. Due to the high number densities of photoelectrons on the dayside, the Debye sheath is sometimes referred to as a photoelectron sheath, whose length scale and potential is dominated by the photoelectrons. On the lunar dayside, the sheath distance is on the scale of meters, while it may reach kilometer scales on the nightside.

While the preceding example is simplistic, and neglects a host of other potentially important effects governing the lunar surface potential, it nonetheless serves to illustrate an obvious and yet profound point regarding the environment of the Moon. On the dayside, the lunar surface is exposed to the sun's UV rays and thus nearly always charges to a positive potential typically less than +10V. However, across the terminator, the influence of photoelectrons begins to vanish and the surface begins to charge negative according to (5). Roughly coincident with the nightside is also the lunar plasma wake, a region of extreme plasma rarefaction produced by the physical obstacle that the Moon presents to the solar wind flow. In this region, plasma densities are low (<1 particle/cc) and temperatures are higher, driving nightside potentials to even larger negative values. Thus at the largest scales there is a significant change in the potential of the lunar surface across the terminator boundary. Additional fluctuations in the potential of the lunar surface can be caused by changes in plasma conditions; for example, when the Moon transitions from the solar wind and into the Earth's geomagnetic tail, a hotter, more tenuous plasma causes nightside potentials to increase substantially. Similarly, rapid changes in plasma conditions and solar illumination associated with solar storms can also produce large changes in the lunar surface potential. Thus in contrast to a dead and static environment, the lunar surface in fact supports active electrodynamic processes, driven by space weather rather than atmospheric disturbances as on Mars (Fig. 3). It is also worthy to note that what is true for the Moon is also true for individual dust grains in space, which charge to potentials <+10V in sunlight, and to negative potentials in shadow.

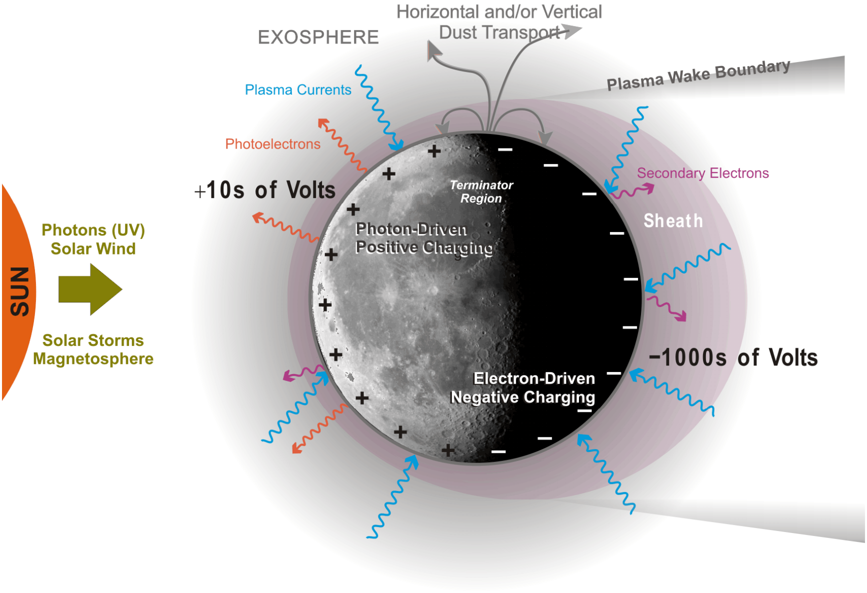


Fig. 3. The Moon is immersed in a dynamic environment in which incident plasmas and solar illumination cause differential charging to occur across the terminator region. Additional variations in the lunar surface potential occur during solar storms and passages through the Earth's magnetotail, where magnetospheric plasmas are encountered.

B. Lunar Surface Charging

The Apollo missions provided some of the first opportunities to measure the lunar surface potential directly. During the Apollo 12, 14, and 15 missions, the Suprathermal Ion Detector Experiments (SIDE) were deployed on the lunar surface as part of the Apollo Lunar Surface Experiment Package (ALSEP). Using measurements of the acceleration of ions at the lunar surface, dayside potentials of +10V and nightside potentials in the range of –10 to –100V were measured, in rough agreement with what one could expect from simple current balance arguments [56]. More recently, Halekas et al. developed a methodology to determine the potential of the lunar surface remotely using the Magnetometer/Electron Reflectometer (MAG-ER) instrument on the Lunar Prospector spacecraft [57], in which negative potentials were measured in shadow. In subsequent work, variations in the lunar surface potential were derived according to illumination and plasma conditions [58, 59]. In general, LP observations support the large scale picture shown in Fig. 3, with positive dayside potentials and typical nightside potentials of ~ –100V (Fig. 4). Negative potentials varied strongest with crossings through the terrestrial plasma sheet and during solar energetic particle events, where values as large as –4 kV were recorded. Many of these extreme charging events could be explained using straightforward current balance assumptions similar to those described above, with some notable exceptions [60, 61]. An intriguing case involves the measurement of negative surface potentials even in sunlight, when photo-emission should clearly dominate and drive the surface positive. This result is currently unexplained, although it may be related to our current understanding, or lack thereof, of the structure of the lunar plasma sheath as discussed below.

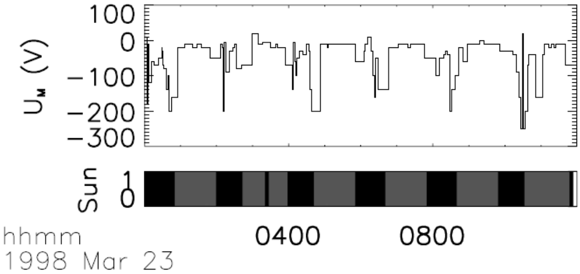


Fig. 4. The potential of the lunar surface U_M determined by remote observations by the Magnetometer/Electron Reflectometer instrument on the Lunar Prospector spacecraft, from [61]. The spacecraft is in a polar orbit at an altitude of ~100 km with a ~2 hr orbital period. Black regions in the bar below the plot indicate areas of shadow, and gray show where measurements were taken in sunlight. In general, potentials of several hundred volts negative are common on the nightside and in the lunar wake.

C. Dynamic Lunar Dust

Dynamic variations in the lunar surface potential may cause the levitation of lunar dust through electrostatic forces [62, 63]. Evidence for this process became apparent prior to the Apollo missions, using imagery from the television system on the Surveyor series of landers designed to act as robotic precursors to the human landings that would follow. Fig. 5 shows an observation of Lunar Horizon Glow (LHG) observed by the Surveyor 7 lander, in which the camera is looking towards the western sunset horizon. The horizontal bright feature is consistent with the forward scattering of sunlight by dust roughly 5-10 μm in size, at less than one meter above the surface, and whose range was approximately at the physical horizon, about ~150m away [62, 64]. The dust densities implied by the intensity of the feature are too high by many orders of magnitude to be explained as secondary ejecta from meteoritic influx. While the occurrence of this phenomena in association with the lunar terminator may be coincidental, it is also consistent with where the lunar surface potential undergoes a significant variation as stronger (and more negative) electric fields develop in darkness.

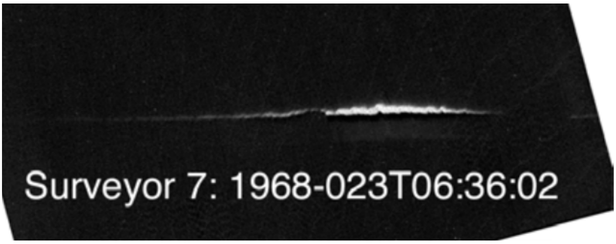


Fig 5. Observations of Lunar Horizon Glow (LHG) from the television cameras on the Surveyor 7 lunar lander. The horizontal bright feature is on the western horizon during sunset (from [64]).

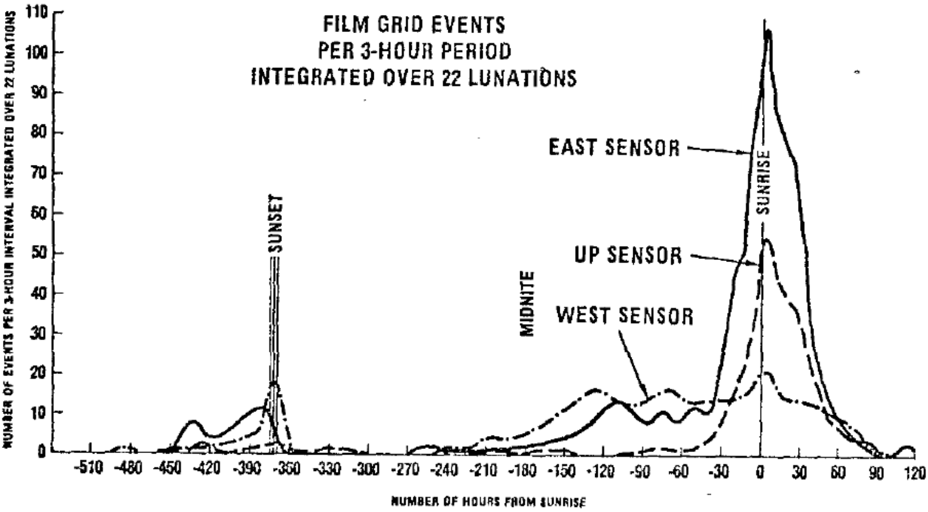


Fig. 6. Original data from Berg et al [65] showing impact rates recorded by the LEAM experiment. The impacts are consistent with high fluxes of relatively slowly moving charged lunar fines with peak activity occurring around the sunrise terminator.

Additional evidence for dust motion near the terminator regions of the lunar surface arose from measurements obtained by the Lunar Ejecta and Meteorites (LEAM) experiment, deployed on the surface during the Apollo 17 mission to monitor the influx of cosmic dust to the Moon. The signature of impact events recorded by LEAM were unlikely caused by cosmic dust, but were consistent with the presence of high fluxes of slower moving, highly charged lunar fines [65]. Moreover, the count rate for these events peaked near the terminator regions of the Moon, particularly during sunrise (Fig 6), reinforcing the notion that these events are likely generated by a change in the lunar surface potential. Recently, O'Brien et al [66] described direct evidence for the movement of lunar dust in response to solar illumination, using the cleaning rates of solar cells on the Dust Detector Experiments (DDEs) as part of the ALSEP surface packages. These and the previous results all demonstrate that lunar dust levitation is probable, and is likely caused by potential changes induced by the variability of solar illumination and plasma conditions.

There is also some evidence that these processes may also produce a high altitude component of lunar dust, on ballistic trajectories reaching 50 km or more [63]. The primary line of evidence stems from eyewitness accounts by astronauts in the Apollo command module (CM), who witnessed bright "streamers" over the terminator regions [67]. Fig. 7 shows an example sketch made by E. A. Cernan, who witnessed this feature from the Apollo CM prior to crossing the lunar sunset terminator. The elliptical feature over the lunar horizon at T-6 minutes prior to the appearance of the sun (upper left) is the background expected by Zodiacal light. The features of interest are the bright "streamers" that suddenly appear around T-2 minutes. As with the LHG recorded on the lunar surface, this feature was witnessed in a geometry in which solar illumination from behind the horizon could be scattered into the field of view by a lofted dust population. Like the Surveyor images, the intensity of these observations also implies a dust density far in excess of what would be expected from secondaries produced by impacts. Their fast time variability (seconds to minutes) was inconsistent with any features known to emanate from the Sun. Additional analysis of the astronaut sketches, coupled with examination of coronal photography obtained from the CM, indicate that if the feature resulted from dust, it was a population ~100 km above the surface with a characteristic size of ~0.1 μm and a scale height of ~10 km [68, 69]. Other evidence for a high altitude component of lunar dust includes observations from the Lunokhod-2 photometer [70] and the star tracker camera of the Clementine mission [71].

The assertion that the Moon may have an active, dynamic dust population at such high (~100 km) altitudes is not without controversy. It has been pointed out that these features could be generated by constituents in the lunar exosphere, the tenuous, collisionless lunar atmosphere, where species such as Na and K undergo resonant scattering emission of sunlight [72]. These emissions, visible from telescopes on Earth [73], can have intensities >1 kR, and thus be visible to the dark-adapted human eye. There is also as yet no clear evidence on the lunar surface for the existence of compositional or optical boundaries consistent with large scale, dynamic dust transport. Thus whether large scale dust transport exists, or if it has any role in global processes, remains an open question. Many do agree that small scale dust levitation on the Moon is likely, and on other small airless bodies as well, including Eros [74] and the planet Mercury [75].

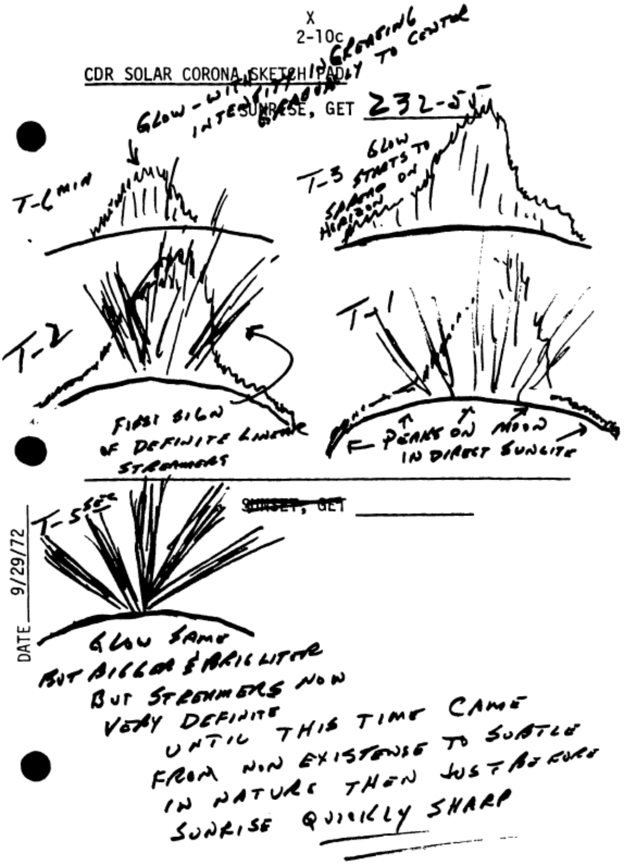


Fig. 7. Sketch by E. A. Cernan who witnessed the appearance of "streamers" over the lunar sunset terminator. These are superimposed on the expected background from Zodiacal light (elliptical feature evident at T-6 min from orbital sunrise).

D. *Open Questions and Future Directions*

While plasmas and dust have been studied together and separately in both the lab and space, the presence of the lunar surface introduces many uncertainties that have yet to be resolved. While the photoelectric effect is well understood, the energy distribution of photoelectrons stimulated from the complex, unconsolidated lunar regolith is poorly constrained, with only a few laboratory measurements indicating that they are distinctly non-Maxwellian [76]. Plasma sheaths have been generally thought to be well understood, with a simple exponential spatial dependence of the electric field as one approaches the plasma-surface interface. However the photo-emissive properties of the lunar regolith may in fact produce a unique spatial variation in the electric field that is non-monotonic in nature, in which a region of negative potential is encountered prior to the larger positive potential expected at the surface due to the photoemission current. This sheath configuration has been shown to be possible both analytically [77] and more recently simulated using a 1-D particle-in-cell code [78]. If true, this configuration of the sheath fields could explain measurements made by the MAG-ER instrument on LP indicating negative potentials in sunlight under some circumstances. This field structure would also have implications for dust dynamics, in that oscillatory motion of dust within the sheath potential well would in effect appear as levitation. Progress in this area will be enabled by a better knowledge of the detailed photoelectron energy distribution at the Moon.

Electric fields generated in the lunar plasma sheath serve to illustrate a simple example of how electric fields vary over the lunar surface. However the electric fields in the area of most interest – near the lunar terminator – are in reality likely to be much more complex. Farrell et al [79] have examined the importance of electric fields generated by the formation of the lunar wake, where enhanced electron fluxes may create large negative potentials at the surface near the terminator regions. These fields could explain the fast moving dust detected by LEAM. Additionally, smaller scale variations in lunar topography at higher latitudes can form "mini-wakes," and lead to enhanced surface charging in small, localized plasma voids [55]. The impact of these new electric field structures on the electrical environment at the lunar surface are now just beginning to be explored.

Other uncertainties include the importance of secondary electron emission – the ejection of an electron from the surface in response to incident ions and electrons in the plasma currents. For sufficiently high incident particle energies of a few hundred eV or more, the efficiency of this process can be greater than one and thus lead to a significant contribution to the overall current balance of the system. While this effect is probably not important in the solar wind due to the low densities and energies of the incident plasma, it could represent a significant current source in darkness and in more energetic plasmas encountered in the geomagnetic environment or during solar storms.

The prospect for large scale dust transport remains an open question. An increased understanding of the lunar surface potential will certainly help address this problem. Details regarding dust charging mechanisms also need to be explored. Charging by plasma and photocurrents were touched upon earlier; additionally, lunar dust may be subject to triboelectric charging mechanisms. The regimes in which frictional, plasma, or photocharging processes are important remains to be settled. Dust adhesion and cohesion on the lunar surface is also relatively unconstrained, and is important to understand in order for dust lifting processes to be realistically modeled. Ongoing laboratory experiments will help address some of these open questions [80-86].

Two upcoming lunar missions will reveal more details about the lunar plasma and dust environment – in essence, the "lunar weather" outlined in Fig 3. These include the Acceleration Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) multi-spacecraft mission that will measure the plasma conditions in the lunar wake, and extend measurements of the lunar surface potential to both positive and negative regimes [87]. The upcoming Lunar Atmosphere and Dust Environment Explorer (LADEE) will determine if there is any appreciable dynamic dust transport occurring on km or larger scales [88]. The newly formed NASA Lunar Science Institute is also worth mentioning, which has funded several teams of researchers to study the dynamics of the variable dusty plasma environment of the Moon. Ultimately, as is the case for Mars, measurements on the lunar surface are the best hope for definitive resolution to many of the outstanding issues. A minimum surface package would include instruments to measure ion and electron energy distributions, electric fields, and dust properties, including size, charge, and density.

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