Problems and New Directions for Electrostatics Research in the Context of Space and Planetary Science

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Abstract— **The lofting, transport, and stratification of particles, dust, and aerosols is a ubiquitous process occurring in many planetary environments. Thus atmospheric electricity and other electrostatic phenomena are very likely to be commonplace on many planetary bodies and moons. At present there are confirmed detections of lightning using optical and radio instruments at Saturn and Jupiter, generated by mechanisms thought to be similar to those found in terrestrial thunderstorms. The presence of lightning on Venus has been inferred through the detection of electromagnetic whistler waves in orbit. The atmosphere of Mars is one compelling example of a system that should possess active electrical processes arising from triboelectric charging, where dust storms are known to occur on local, regional, and global scales. Airless small bodies and moons are also not immune to charging phenomena, which are generated in their case by interactions between their surfaces, plasmas, and sunlight. Looking backwards in time to the early solar system, the dynamic mixtures of gas and dust found in the protoplanetary nebula could also be a likely abode of electrostatic activity. Here we review the current state and overall importance of electrostatic processes throughout the solar system in the past and present. Electrostatic activity on Mars is given focused attention, where recent observations designed to detect the presence of atmospheric electricity have been contradictory, thus leaving this tantalizing question open for additional experiments and future missions. I end by discussing current problems and intriguing new directions for electrostatics research in the context of space and planetary science, ranging from ground-based laboratory experiments, theory and modeling, and exciting new opportunities in the emerging re-usable suborbital vehicle program.**

I. INTRODUCTION

Collisionally driven charging processes – in which particulates over a wide range of size regimes and composition become electrically charged through frictional or other contact-related interactions – likely occur in many environments throughout in the solar system. The presence of water in many parts of the solar system also implies that large scale charging processes can occur via mechanisms similar to those found in terrestrial thunderstorms, such as in the atmospheres of the gas giants Jupiter and Saturn. Relatively dry, dusty Aeolian environments such as those found on Mars are conducive to triboelectric phenomena, in which atmospheric electricity is likely dominated by frictional charging. The electrical charging of small particulates such as the dust found in the regolith of small airless bodies is also commonplace, arising due to the interaction of these surfaces with plasma and photo electric currents. Thus most environments in the solar system are nearly universally electrified to varying degrees. The importance of these electrical processes includes their role in the production of unique trace chemical species in planetary atmospheres [1-3], as tracers of storm activity and atmospheric dynamics, and as tools to probe ionospheric structure [4]. Lightning, surface and dust charging are also a significant concern in terms of the safety of future human explorers destined for Mars, the Moon, and other solar system bodies [5-7].

The most dramatic manifestation of atmospheric electricity is undoubtedly in the form of lightning, i.e., the sudden release of charge that has accumulated over large spatial scales and to such a magnitude that the local breakdown potential of the atmosphere is exceeded. From centuries of terrestrial observations, we know that this is primarily caused by the differential charging of ice particles of varying sizes, shapes, and surface properties [8]. The actual physics behind the process of lightning itself remains in question, primarily because most measurements reveal that it is initiated well before the typical breakdown potential of the atmosphere is reached (~3 MV/m). In fact most measurements indicate that terrestrial lightning occurs in the presence of quasi-static atmospheric electric fields of order 10% that required for breakdown. Among the additional mechanisms contributing to the breakdown process include ionization from Galactic Cosmic Rays (GCRs) followed by runaway breakdown [9, 10]. Despite these ongoing debates in terms of the exact nature of lightning, its mere presence remains one of the best indicators of the presence of large scale charge separation processes at work in a planetary atmosphere. Once initiated, lightning produces far-reaching effects that are detectable from a variety of locations ranging from the surface to in orbit above the atmosphere. In addition to the obvious optical flash, lightning produces sferics, transient emissions in the Ultra and Very Low Frequency (ULF, VLF) regimes. These emissions are typically trapped between the surface and the ionosphere, and through multiple reflections can be detected globally over the surface. Additional electromagnetic (EM) modes known as Schumann Resonances (SR) are generated when the sferics coalesce into the resonant modes of the waveguide formed by the surface and the ionosphere [11]. On Earth, these modes manifests themselves as a discrete set of peaks starting in the Extreme Low Frequency (ELF) band, with the first mode found typically between 7-8 Hz (Fig. 1). Higher frequency emissions (HF) up to tens of MHz are generated by the lightning channel acting as a large antenna, and can penetrate the ionosphere and be detected in orbit. A certain class of lightning-generated VLF waves known as whistlers is guided above the ionosphere along magnetic field lines and is hence also visible from space. Lightning is also known to emit gamma radiation, leading to the generation of Terrestrial Gamma-ray Flashes (TGFs) [12]. The broad spectrum of EM phenomena associated with lightning has proven a useful tool in the detection of electrical phenomena on a number of planetary bodies.

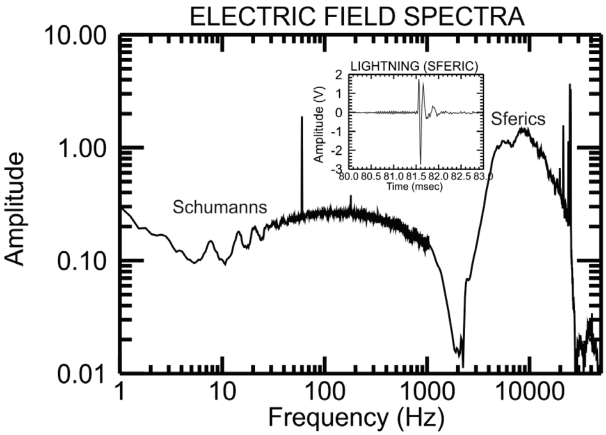

Fig. 1: Electric field spectra caused by terrestrial lightning. Discrete sferics are emitted from individual lightning strokes, and are reflected in the Earth-ionosphere waveguide. At lower frequencies, the Earth-ionosphere waveguide supports resonant modes starting at 7-8 Hz, known as Schumann resonances. The sharp null between the Schumann and sferic band marks a regime where the Earth-ionosphere waveguide is "leaky," allowing EM energy to escape.

II. GAS GIANT ATMOSPHERES

Measurements by the Voyager, Cassini, and Galileo missions have provided a rich data set indicating the prevalence of electrical discharges in gas giant atmospheres [13]. Voyager 1 recorded the first non-terrestrial example of lightning, witnessing clusters of bright optical flashes in the atmosphere [14]. These observations were corroborated by Voyager Plasma Wave System (PWS) measurements of whistler mode wave activity that implied a similar event rate as the optical measurements [15, 16]. These observations indicated that while Jovian lightning may occur less frequently compared to Earth, the individual events were several orders of magnitude more energetic. Later observations by the Galileo mission confirmed many of the initial observations by the Voyager missions, including the correlation with cyclonic shear zones and westward jets. Observations at Saturn are also consistent with transient electrical activity in its atmosphere – first identified as Saturnian Electrostatic Discharges (SEDs) from Voyager data [17]. These HF emissions possessed a frequency of occurrence and duration (5 seconds and ~50 milliseconds respectively) consistent with a lightning source, and were localized to originate from the equatorial belts of Saturn's atmosphere [18, 19]. The Radio Plasma Wave System (RPWS) onboard the Cassini mission confirmed the properties of SEDs measured by Voyager, detecting over ~5400 of these events, with an apparent correlation with a large storm system that lasted for several months [20]. Clear optical flashes at Saturn have not been detected until recently [21], due in part to the contaminating effects of ringshine on the nightside. In both Saturn and Jupiter, electrification is thought to occur in water-ice laden clouds; hence the charging mechanisms are likely similar to what occurs in terrestrial thunderstorms. Thus Jupiter and Saturn share many of the same open questions and problems as terrestrial thunderstorm research in terms of the details behind the charging mechanisms and the physics of discharge initiation. These issues are not covered in detail here, but can be found in several recent publications and review articles [4, 8, 13, 22-24]. It is also worth mentioning that there is limited evidence for similar processes on both Uranus and Neptune. Voyager 2 discovered emissions analogous to SEDs at Uranus, while sporadic whistler mode wave activity has been detected at Neptune. Since no other spacecraft have visited these worlds, further confirmation using optical means is lacking. Continued studies of the electromagnetic signatures of lightning on Uranus may be possible from the ground [22, 25].

III. VENUS AND MARS

A. Venus

Turning now to a terrestrial planet, the primary evidence for the occurrence of lightning at Venus is derived from the detection of EM waves [26-34]. As in the terrestrial and Jovian cases, putative lightning generated EM emissions at Venus propagate in the tell-tale whistler mode expected to escape the atmosphere into the ionosphere. However the interpretation of these signals as a unique result of lightning is not without controversy, as others have pointed out that the observed emissions could result from locally generated plasma instabilities from the ionosphere-solar wind interaction [35], and the Cassini fly-by failed to detect similar emissions [36]. While it could be argued that the Cassini observation occurred during a quiet period [4, 22], the debate regarding the connection of EM emissions and lightning persists to this day. Outside of EM emissions, a few studies also tentatively identified optical flashes consistent with lightning using observations from Earth [37] and the Venera 9 and 10 satellites [38, 39]. However, searches for optical flashes with the star tracker on the Pioneer Venus Orbiter (PVO) yielded no clear results [40, 41], and the optical instruments on the Venus Express mission have yet to witness lightning. Theoretical descriptions of the possible charging mechanisms in sulfur dioxide-laden Venusian clouds have failed to keep up with terrestrial cloud charging models [8], where much work remains to be done. Hence the existence and form of lightning on Venus remains an open question, and will likely only be resolved using measurements of wave activity in the HF regime coupled with confirmed detections of optical flashes or other visible evidence.

B. Mars

The planet Mars represents an intriguing case where atmospheric electrical phenomena should be abundant, presumably produced by triboelectric charging in the wind-blown, relatively dry Aeolian environment that characterizes much of its surface. Based on current knowledge, atmospheric electricity on Mars possesses some similarity with analogous phenomena on Earth. While the charging mechanisms on Mars are undoubtedly different, like their terrestrial thunderstorm counterparts, large scale electric fields can be generated when tribocharged dust grains are vertically stratified by convective instabilities, forming a structure with a macroscopic dipole moment that can subsequent undergo a discharge process [42-44]. The best terrestrial analogies for electrostatic charging on Mars may be found in volcanic plumes, which are known to generate significant amounts of airborne charge and can produce some of the most dramatic lightning displays known on Earth [45-47], as well as dust storms and dust devils, which are known to generate significant electric fields [48, 49]. Based on all known theory, laboratory experiments, and terrestrial analogs, Mars should contain an active electrodynamic atmosphere. Yet recent observational evidence for the presence of large scale discharge processes at Mars is persistently contradictory, and is thus worthy of special focus here.

All known natural systems involving the collisional motion of dust and particulates exhibit triboelectric effects. The atmosphere of Mars should be no exception, where dust storms are known to occur on local, regional, and global scales [50-53]. 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 [52, 54, 55]. Discharge processes on Mars, if present, would 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. Experiments conducted with agitated dry sand in a CO_2 gas at low atmospheric pressures similar to Mars have been shown to produce a visible glow accompanied by discrete, filamentary discharges, presumably caused by triboelectrification of individual grains [44]. Convective, Aeolian features such as the dust devils and storms on Mars likely create similar triboelectrically generated discharge effects, where the breakdown potential is only ~20 kV/m, compared to over 3 MV/m on Earth. 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 [56-58]. The result can be the formation of large scale charge separation due to any vertical sorting of dust grains by size. This picture is in direct analogy with terrestrial thunderstorms, but with the dipole moment in the opposite direction, since the charge aloft is now negative. Such structures may exist on regional and global scales on Mars during dust storms, and over smaller localized scales in individual dust devils.

Terrestrial field experiments and modeling heavily support the notion of an electrified Martian atmosphere. In 1999-2001, the Mars Atmosphere and Dust in the Optical and Radio (MATADOR) project set out to determine the electrical properties of terrestrial dust devils with the goal of gaining insight into their Martian counterparts. These and other experiments confirmed that substantial electrification can occur in typical terrestrial dust devils, ranging from ~3 kV/m to more than 100 kV/m at or near ground level, depending on the event size [48, 59-62]. On theoretical side, nearly every model demonstrates that potentials in the comparatively larger Martian dust devils can quickly reach discharge levels. As reviewed in [63], most models describing dust electrification on Mars assume simple charging mechanisms, with triboelectric processes modeled as a fixed exchange of charge per grain collision [57, 58]. A key outstanding question in the generation of electric fields in Martian dust activity relates to the mechanisms of charge relaxation processes that may be in operation on each dust grain, which ultimately may limit the maximum level of fields that can be sustained. Since the Martian atmosphere is likely much more electrically conductive than that at Earth, charge dissipation from grains may be an important issue to consider. *Zhai et al.* [64] 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, followed by a plateau and steady-state as triboelectric charging processes were balanced by charge dissipation into the atmosphere from individual grains. Under these conditions, electric fields approaching breakdown levels on Mars were still obtained assuming dust devils of only moderate size (~10m wide and ~1 km high.) The impact of absorption of ions and electrons and ions is also important to consider, as these will alter the current balance and atmospheric conductivity local to the event in question. *Jackson et al.* [65, 66] studied this aspect of the problem, and concluded that will these processes limit the maximum fields that can develop, significant electrification and corresponding electrochemistry continues to occur. Somewhat in contrast to these results, Kok & Renno constructed a charging model for the Martian saltation layer, and concluded that electric fields cannot reach breakdown levels due to the effects of charge dissipation and relaxation processes [67]. At the heart of these disparate results are large uncertainties in terms of the tribocharging efficiency (i.e., charge exchanged or produced per collision), and the balance between dissipative vs. charging currents in the dust system in question. Thus from a theoretical point of view, 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.

Intense searches for evidence of electrostatic discharges on Mars have been undertaken from a variety of spacecraft and Earth-bound observatories. In a novel concept, *Renno et al.* [68] proposed that electrical activity on Mars could be detected via the emission of microwave radiation. The emitted radiation would be non-thermal in nature, and more likely to be visible during dust activity when the thermal emission background is decreased. This possibility proves advantageous for several reasons, since these emissions would be visible through the ionosphere, and are also detectable using several large aperture receivers on Earth such as the Deep Space Network (DSN). In follow up work, using a 34m DSN antenna *Ruf et al.* [69] claimed definitive detection of non-thermal microwave emissions during a deep Martian dust storm covering over 150,000 km^2 occurring on June 8, 2006. The detection technique utilized a unique spectral analysis tool, in which the kurtosis of the signal was used to isolate the non-thermal components [70]. Moreover, modulations in the non-thermal component of the detected microwaves were interpreted as due to SRs, and they postulate that once produced these emissions can then trigger additional macro-scale discharges, in analogy with lightning stroke synchronicity proposed by *Yair et al.* [71]. The detection of SRs on Mars would be significant, as it would necessitate a source of energetic EM emissions within the atmosphere; based on this, the *Ruf et al.* results have been interpreted by some to represent evidence of lightning, with an intensity perhaps orders of magnitude greater than found on Earth.

Additional observations of Mars in the microwave regime were recently made by *Anderson et al.* [72] using the Allen Telescope Array (ATA). These observations were made between March and June of 2010 with over 30 hours of total observation time, and included several small-scale dust storms. In their work, they also witnessed modulations of the detected signal, in this case with a 10 Hz fundamental frequency. None of these modulations followed the expected pattern for Martian SRs [73] which was attributed to radio frequency interference (RFI). Overall there were no enhancements in the kurtosis spectrum (or *kurtstrum*) of the data that could be attributed to dust activity on Mars. While the kurtosis is highly indicative of a non-thermal component of a signal, this technique is also very efficient for the detection of human-generated RFI, indicating that caution is needed when attributing kurtstrum signatures to naturally occurring but presumably non-thermal sources.

Observations of the HF radio environment in orbit around Mars are currently being made by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument, which can detect radio emissions over a band of 0.1 to 5.5 MHz [74]. In a detailed study incorporating over 5 years of observations, Gurnett *et al.* [75] report no signals from dust activity, including during passes over several large dust storms. Coverage by MARSIS included the same storm studied by *Ruf et al.,* albeit some 20 hours earlier than the DSN observations (Fig. 2).

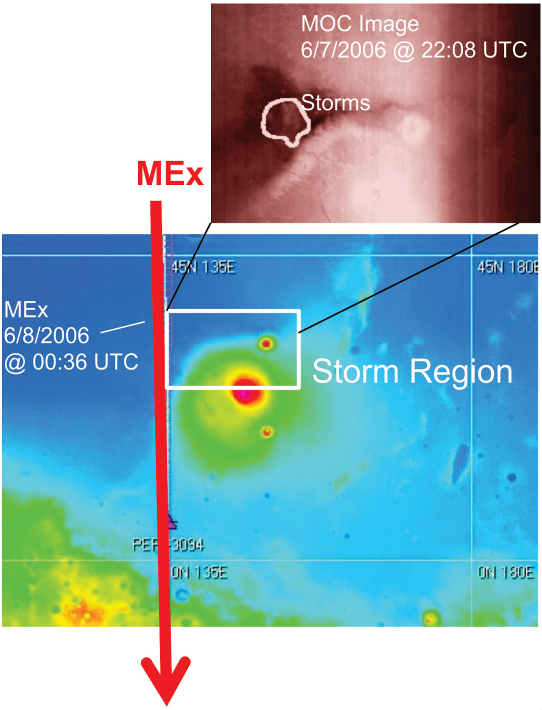

Fig. 2: Mars Express/MARSIS instrument trajectory over a large dust storm on June 8th, 2006 [76]. This is the same event measured remotely using the DSN [69].

Hence we are at an interesting cross roads in terms of definitive evidence for lightning discharges on Mars. All theoretical efforts, laboratory and field test experiments, and terrestrial analogies support the existence of an active electrical system on Mars in one form or another, and we have tantalizing evidence from at least one DSN observation of non-thermal microwave emission, which could be indicative of a discharge process. However there have been no HF emissions recorded in orbit around Mars in over 5 years of observations, and follow-up measurements in the microwave band by the ATA have demonstrated the possibility that modulations in the kurtosis signal can easily be the result of RFI. Furthermore, no optical evidence of either a glow discharge or lightning flashes have been recorded despite the nearly continual presence of high resolution imagers and spectrometers in orbit since 1997. The current state of affairs with respect to the possibility of lightning at Venus can serve as a guide to our view of similar phenomena on Mars. On Earth, the connection between whistler mode wave activity is firmly established; and yet the detection of similar signals at Venus has not settled the debate within the scientific community as to whether these signals represent definitive evidence for lightning. Using the same standard, the question of whether or not lightning is present at Mars should be subject to a similar debate; perhaps more so, when the specifics of the evidence in favor is examined in detail. In particular, the concept of SR as a lightning trigger is not firmly established even in the terrestrial case, with only one recent work that even hints at this possibility [77]. This places the assertion by *Ruf et al.* that the microwave emissions are modulated by SR in question. Moreover, it is difficult to explain how such an energetic discharge process as estimated by *Ruf et al.* could emit in the microwave regime but not be detectable by MARSIS. While microwave measurements have not been a common method to identify lightning discharges, there is some recent evidence that they could be used in this manner [78]; hence there is some hope that additional observations in the microwave and other bands may yet be illuminating in terms of the presence and nature of electrical discharge processes on Mars. At the moment, all possibilities remain open; (i) atmospheric electricity on Mars is severely limited by as yet unknown charge dissipation or other mechanisms, (ii) it is present as a continual, perhaps observable glow discharge during dust storms or dust devils, and (iii) under some conditions, circumstances allow for the large-scale, macroscopic build-up and separation of charge that leads to the Martian equivalent of terrestrial lightning.

IV. MERCURY, SMALL BODIES AND MOONS

Moons and small, relatively atmosphere-less bodies potentially encompass a full range of charging phenomena, spanning dynamic, weather-driven systems analogous to terrestrial cases to those completely dominated by interactions of their surfaces directly with the space environment. Titan is one compelling example of a moon with a thick atmosphere where there are aerosols, wind, and rain [79]. However all searches to date, including those by the Huygens descent probe and during over 35 passes by the Cassini spacecraft, have yielded no conclusive evidence of any atmospheric electricity [22]. Nonetheless, Titan remains a promising candidate for the presence of lightning on a planetary moon.

The surfaces of moons and small bodies without significant atmospheres are directly exposed to the space environment, which is host to a multitude of charging currents resulting from plasmas and illumination by the Sun. Unless protected by an atmosphere, all solid bodies in space acquire a net electric potential, as the system attempts to balance the flow of ion, electron, and photo-currents [80]. The system reaches equilibrium when the potential of the body floats to a value such that the sum of all of these currents is zero. In most situations, the essential dynamics can be understood in terms of an ion and electron plasma current at temperature T_i and T_e, and a photo-current [63]. In the solar wind plasma, in sunlight most bodies acquire a net potential between several to +10 V. In darkness, and in the plasma wakes of larger bodies, surface potentials are dominated by the electron current and can range from a few to several 100 V negative.

The Moon is an excellent example of solid-body charging in space. We know from the Apollo and Lunar Prospector missions that there exist dynamic, large scale variations in the surface potential ranging from several to thousands of volts. On the dayside and in the solar wind, photo-current charging tends to dominate, and potentials typically range from +5 to +10V. In the rarefied, hotter plasma of the lunar wake, plasma electron currents dominate the charging environment, producing typically potentials on the order of −10 to −100 V. During solar storms, and when the Moon passes through the influence of the terrestrial magnetosphere, the picture can change drastically, with potentials of up to −4 kV known to exist. These and other potential changes on the lunar surface have been documented extensively [81-85] over the past several decades. Dynamic changes in the lunar surface potential is a strong candidate for the production of Lunar Horizon Glow, in which lunar dust is levitated or lofted above the surface. This process is very likely to occur within a few meters of the surface, as implied by the video cameras of the Surveyor 7 lander, which captured images of scattered sunlight on the sunset horizon consistent with a dense population of dust between 5 to 10 μm in size [86]. Electrostatic forces associated with a change in the lunar surface potential as the photo-electron dominated dayside transitions to negative potentials on the nightside (or vice-versa) are a strong candidate for the generation of this dust population. More controversial is the possibility for a high altitude component of lunar dust, which may have been witnessed from the Apollo command module [87]. While some theories entertain the possibility that potential changes across the lunar terminator could result in the transport of dust to ~50 km altitudes [88], definitive observations have been lacking, despite multiple searches [89-91]. Most recently but as yet unpublished, instruments aboard the NASA Lunar Reconnaissance Orbiter (LRO) have failed to detect any component of high altitude lunar dust. Hence the role and importance of electrostatic forces in the transport and dynamics of lunar dust remains an open question. In 2013, NASA will launch the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission to address this question. LADEE contains both a dust detector and ultra-violet/visible spectrometer specifically designed to search for a high altitude component of lunar dust [92]. The planet Mercury is in many ways completely analogous to the Moon in terms of surface charging. Like the Moon it does not possess any appreciable atmosphere, and is exposed directly to the solar wind plasma; thus many of the same arguments follow in terms of the likelihood for surface charging and dust transport [93]. Compared to the Moon there are far fewer, if any relevant observations of surface charging and possible dust transport at Mercury, although some of these questions may be addressed by the ongoing NASA MESSENGER mission.

Other small airless bodies should be subject to a host of surface charging processes much like the Moon. The concept of “dust ponding” is well established for bodies such as the asteroid Eros, where electrostatic effects are believed to preferentially concentrate dust in shadowed regions on the dayside [94]. Many outer planet moons exist in a different plasma environment, dominated by the magnetospheres of their host gas giants. The surfaces of these worlds are also expected to become charged, but at different magnitudes and timescales depending on the details of their respective plasma environments. Saturn’s moon Rhea is one example [95], where preliminary observations from Cassini indicate that this moon may possess a potential of a few hundred volts [96]. Other airless moons of Saturn, as well as Jovian moons such as Callisto, Ganymede, Europa, and others, should all possess similar but unique properties in terms of plasma-induced surface charging processes.

V. PROTOPLANETARY ENVIRONMENTS

A last but potentially interesting topic is the question of the role of electrostatic phenomena in the gas and dust-rich environments of protoplanetary disks. For our solar system, this is the solar nebula – the gas and dust-rich environment left over after the formation of the Sun, during which the process of accretion began to operate, leading to the formation of the planets. The presence of dust in the solar nebula has led many to speculate on the possibility of lightning or other discharges occurring in this environment. One strong motivation for these models has been the search for a mechanism to produce chondrules – millimeter sized, glassy beads found within meteorites, whose origins remain a mystery, but may provide a window into the physical conditions of the early solar nebula. Their structure and composition imply flash heating to high (~1700 K) temperatures followed by fairly fast cooling. Lightning in the early solar nebula has often been invoked to explain the rapid heating necessary for chondrule formation [97-101]. Mechanisms of proposed dust grain charging range from ion/electron currents, local electric fields set up by acoustic waves, and charge separation formed by gusts of "wind" in the disk gas. *Desch & Cuzzi* [99] describe a collisional triboelectric charging model in the early solar nebula, utilizing the triboelectric series and known differences in dust grain contact potentials and capacitance to derive charging rates. Large electric fields develop due to concentrations of clumps of charged particles immersed in a background of negatively charged metal grains. Unlike the contemporary planetary environments, direct measurements of our own early solar nebula are impossible; nonetheless electrical activity remains one potential explanation for one of the outstanding mysteries of early nebula conditions with respect to chondrule formation.

Electrostatic interactions could play other potentially important roles in terms of planetesimal formation in the protoplanetary disk, which relies on the slow but steady aggregation of small, ~micron sized particles into larger structures that form the basis for planetary building blocks (planetesimals). Currently, most theories favor mechanisms of particle aggregation through collisions caused by Brownian motion for the smallest (submicron) grains, vertical settling, coupling to the gas rotation or gas turbulence. Aggregation occurs between particles via the Van der Waals force or other microscale static dipole interactions, and for the most part the particles are assumed to be non-magnetic and uncharged. The latter assumption is based on the presumed attenuation of UV and ionizing radiation deep within a protoplanetary disk [102]. However it is more than likely that some frictional charging is occurring in any system with dust collisions [99]. Once particle charging occurs, the resulting electrostatic interactions have been shown in several models and experiments to act as an accelerant in the dust aggregation process by increasing the effective cross section of each particle, decreasing aggregation times by several orders of magnitude [103]. One of the current conundrums in the planetary formation modeling community is the "decimeter" barrier, in which collisions between centimeter to decimeter sized aggregates require slow velocities in order to continue the process of aggregation without fragmentation. Since mean collision velocities necessarily increase with increasing aggregate size, fragmentation and/or bouncing begins to outrun aggregation and the process of planetesimal formation stops [102]. Electrostatic forces could provide a means to continue the process of aggregation, by re-attracting particles or smaller aggregates after bouncing or fragmentation [104]. The investigation of the importance of electrostatic forces in early solar nebula dynamics and in planetesimal formation has barely begun, and could represent potentially new and exciting research.

VI. CURRENT PROBLEMS AND FUTURE DIRECTIONS

The variety of environments across the solar system that are a host to electrostatic phenomena poses a challenge to terrestrial-based investigations. Despite this, terrestrial analogies are likely to remain important in our understanding of extra-terrestrial electrostatics. The abundant presence of water throughout the solar system implies that lighting, and related processes analogous to elves, sprites, and jets, is likely generated via similar mechanisms as it is on Earth. Thus our understanding of lightning on the outer planets in particular should advance hand-in-hand with terrestrial lightning and cloud electrification research. Non-water related thunderstorm activity is also very possible, for example in the methane and ethane rich clouds of Titan, or the sulfuric acid clouds of Venus. For bodies like these, continued observations coupled with unique laboratory experiments to determine the electrical properties of non-water clouds represent the only path forward. Only a limited number of laboratory experiments with simulated Venusian and Titan atmospheres have been conducted recently and in the past [105-107].

Mars presents us with a unique quandary at this time. Continued observations with the DSN and other ground-based assets may be informative. The Mars Atmosphere and Volatile Evolution (MAVEN) mission will fly the Langmuir Probe/Waves instrument, which will measure electromagnetic waves from ~Hz to several MHz in bandwidth, and may detect evidence of lighting in the form of whistlers. However as on Venus, even this signature will likely be left open for debate in terms of a lightning-generated origin. Definitive proof of atmospheric electrical activity on Mars may only be achieved through observations of lightning sferics, Schumann resonances, or other discharge related phenomena from within the atmosphere, which would necessitate measurements from the surface on a lander or a rover. Laboratory experiments involving electrostatic charging of Martian-analog dust have been ongoing for some time [108, 109]. The two fundamental key questions relate to the rate of dust charging followed by the importance of charge dissipation mechanisms. The former is a major focus of ongoing electrostatics research (for example, [110]). The second question relates to the sustainability of charge once it is generated. Mars has an atmosphere with an electrical conductivity that is likely several orders of magnitude higher than on Earth, hence charge dissipation via atmospheric currents should happen quickly, i.e., on the order of seconds or less. The ability of dust systems to maintain significant, coherent electric fields thus depends on the rate of particle charging being greater than the dissipation mechanisms. Thus experiments to examine charge relaxation on dust grains under Martian environmental conditions would be particularly valuable at this stage. Some terrestrial examples of particle charging suffer a similar quandary, for example volcanic ash clouds. However in terrestrial cases we have measurements which demonstrate that volcanic clouds remain electrified long after they should have dissipated their charge into the atmosphere [46]. The same could be true of Mars, but in neither case are the mechanisms understood. Additional work examining other charging mechanisms, such as frictile attraction [111], will undoubtedly prove useful in our understanding of similar phenomena on Mars.

As with Mars, laboratory experiments focused on lunar dust charging are ongoing [112-118]. New observational data on the lunar surface potential and its variations is currently being gathered by the ARTEMIS mission, which uses plasma and fields instrumentation on two spacecraft to study the lunar plasma environment. Among the open questions for future investigations includes the role of shadow/sunlit boundaries in lunar surface potential dynamics at both the macro and micro-scales. The upcoming LADEE mission will constrain the density, size, and charge distribution of any high altitude component of dust.

Protoplanetary disk environments represent a new and intriguing line of investigation for future electrostatics research. There are a multitude of experiments that have been conducted in this area that focus on collisional aggregation [104, 119-122] in a combination of ground-based and microgravity experiments. Microgravity is not only an appropriate environment for conditions in the early solar nebula, but is also a convenient one for revealing electrostatic effects. Experiments conducted on the U.S. Microgravity Lab (USML) series flew experiments designed to isolate electrostatic phenomena in a range of granular materials [123]. Without the complicating effects of gravity, these experiments found a universally attractive force between individual particles and larger aggregates, thought to be generated by the interaction of macroscopic electric dipole moments (Fig. 3). Such an attractive force could have a significant role in many dusty environments where differential charging occurs on individual particles, and greatly accelerate the aggregation process. USML experience indicates that these phenomena manifest themselves within minutes after particle dispersion. New opportunities in the emerging suborbital vehicles coming online may provide efficient, cost-effective platforms to conduct further experiments in this area [124, 125].

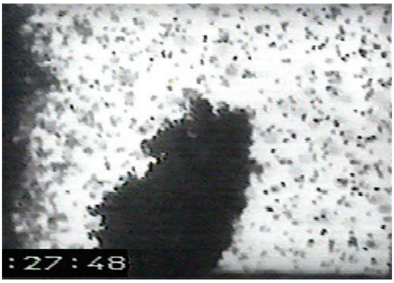

Fig. 3. Aggregation of ~400 mm quartz particles on the USML flights. Smaller particles were universally attracted to the large aggregate shown via electrostatic forces.

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