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A DYNAMIC FOUNTAIN MODEL FOR DUST IN THE LUNAR EXOSPHERE

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ABSTRACT

From the Apollo era there is much evidence to show that the lunar "horizon glow" and "streamers" observed at the terminator are caused by sunlight scattered by dust grains originating from the Moon's surface. A simple dynamic dust "fountain" model has previously been proposed to explain observations of submicron dust "lofted" to altitudes of ~100 km. In this model charged dust grains follow ballistic trajectories, subsequent to being accelerated upwards through a narrow sheath region by the surface electric field. Described here are the effects of including a more realistic exponentially decaying electric field (consistent with Debye shielding of a charged surface in a plasma). Also discussed are the different mechanisms by which highly charged dust grains can be generated at the lunar surface; in particular, the possible effects of triboelectric charging are considered. Dust in the exosphere will affect the optical quality of the lunar environment for astronomical observations, as well as interfere with future robotic and human exploration activities.

1. INTRODUCTION

During the Apollo era of exploration it was discovered that sunlight was scattered at the terminators giving rise to "horizon glow" and "streamers" above the lunar surface [1,2]. This was observed from the dark side of the Moon during sunset and sunrise by both surface landers and astronauts in orbit (e.g., Fig. 1). These observations had not been anticipated since the Moon was thought to have a negligible atmosphere or exosphere. Subsequent investigations have shown that the sunlight was most likely scattered by electrostatically charged dust grains originating from the surface [2,3,4,5,6]. This dust population could have serious implications for astronomical observations from the lunar surface [7] and future exploration [8].

The lunar surface is electrostatically charged by the local plasma environment and the photoemission of electrons by solar UV and X-rays [9,10]. Under certain conditions, it has been suggested that the like-charged surface and dust grains act to repel each other, such that the dust grains are ejected from the surface [2,3,4].

A dynamic "fountain" model has recently been proposed, as illustrated in Fig. 2b, to explain how sub-micron dust can reach altitudes of up to ~100 km [11]. Previously, static dust levitation models tended to focus on heavier micron-sized grains near the surface (Fig. 2a), and did not explain the presence of much lighter grains at higher altitudes. By relaxing the static constraint, [11] showed that highly charged grains can be "lofted" to high altitudes under the action of dynamic forces. Here we aim to improve the dynamic fountain model by including a more realistic electric field [12], as well as discussing the different ways in which dust grains can become highly charged at the lunar surface.

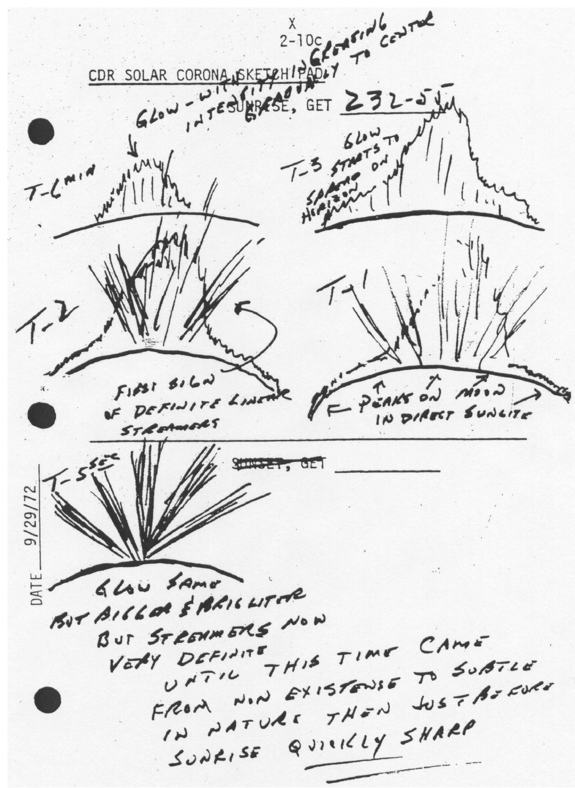

Figure 1. Sketches of sunrise with "horizon glow" and "streamers" viewed from lunar orbit by astronaut E.A. Cernan (commander) during Apollo 17. Time before the first appearance of the Sun is indicated in minutes (T−6 min, T−3, T−2, T−1) and seconds (T−5 sec) [4].

2. APOLLO-ERA OBSERVATIONS

Horizon glow (HG) observed by the Surveyor-7 lander was most likely caused by electrostatically levitated ≈5

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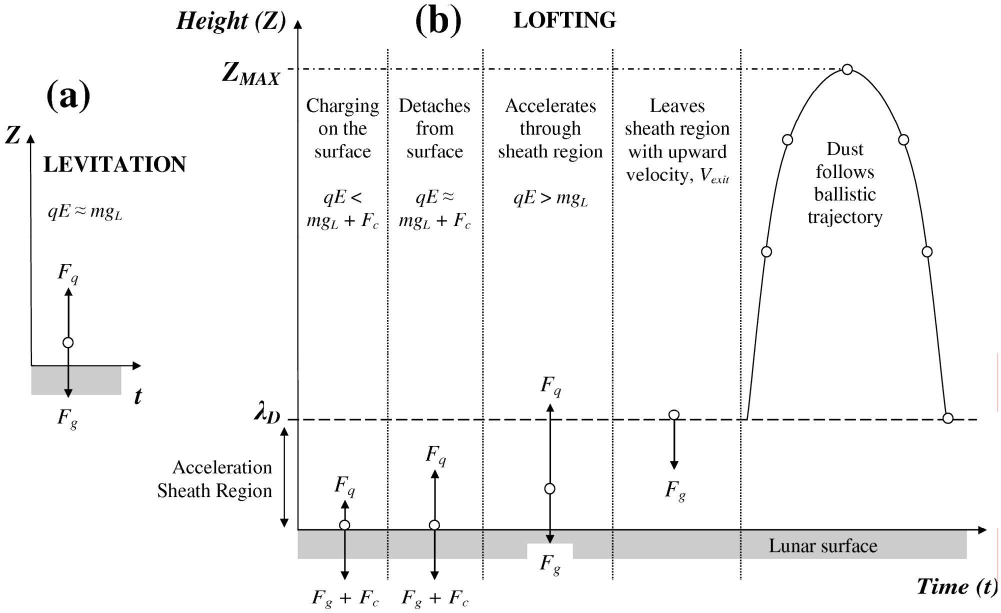

Figure 2. Schematic comparing (a) the static levitation concept [2,3] with (b) the evolution of a dust grain in the dynamic fountain model [11].

μm dust grains at heights of Z ~ 10 cm near the terminator [3]. HG observations were ~10^7 times too bright to be explained by secondary ejecta from micro-meteoroid impacts [2,3].

The Lunar Eject and Meteorites (LEAM) experiment left on the Moon by Apollo 17 directly detected the transport of charged lunar dust [5]. The dust impacts were observed to peak around the terminator regions, thus suggesting a relationship with the HG observations. See also Fig. 3 of [8] (in this proceedings).

Astronaut observations of orbital sunrise revealed HG and streamers above the lunar surface varying on ~1–100s timescales, as shown in Fig. 1. This indicated that they were produced by light scattering in the lunar vicinity from particles that were present sporadically [4], as indicated in Fig. 3. The HG had a scale height of ~10 km, so was unlikely to be caused by gases in the lunar exosphere [6]. HG also appeared as "excess" brightness in photographs taken from orbit of the solar corona above the lunar terminator. Excess brightness could not be accounted for by a co-orbiting cloud of spacecraft contaminants [1]. This evidence strongly suggested the presence of a variable lunar "atmosphere" of ~0.1 μm dust extending to Z > 100 km created by some electrostatic suspension mechanism [4,5].

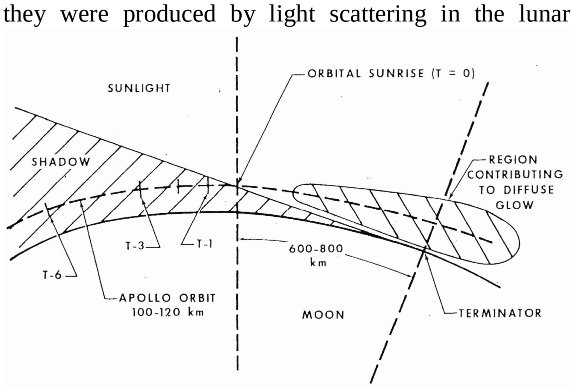

Figure 3. Schematic showing a cross-section of the Moon in the plane of the Apollo orbit (dashed line) [1]. This depicts the physical situation consistent with the observations shown in Fig. 1.

3. DYNAMIC DUST FOUNTAIN MODEL

Fig. 2 shows a schematic comparing (a) the static levitation concept [1,2,3] with (b) the evolution of a dust grain in the dynamic fountain model [11]. In the levitation model the dust grain finds a point near the surface where the electrostatic (F_q) and gravitational (F_g) forces acting on it are about equal and opposite, and it is thus suspended. Note that more rigorous dust levitation calculations have been made by, e.g., [13] and [14], and this phenomenon has been reproduced in the laboratory by [15] amongst others.

In the dynamic fountain model [11], once the dust grain has attained sufficient charge to leave the lunar surface (i.e., $F_q > F_g + F_c$), it is accelerated upward through a sheath region. This sheath region was assumed to be a plasma Debye length, λ_D, thick. Also note that F_c is the force of grain cohesion at the surface. The dust grains in question are so small that initially $F_q >> F_g$, such that the dust grains leave the sheath region with a large

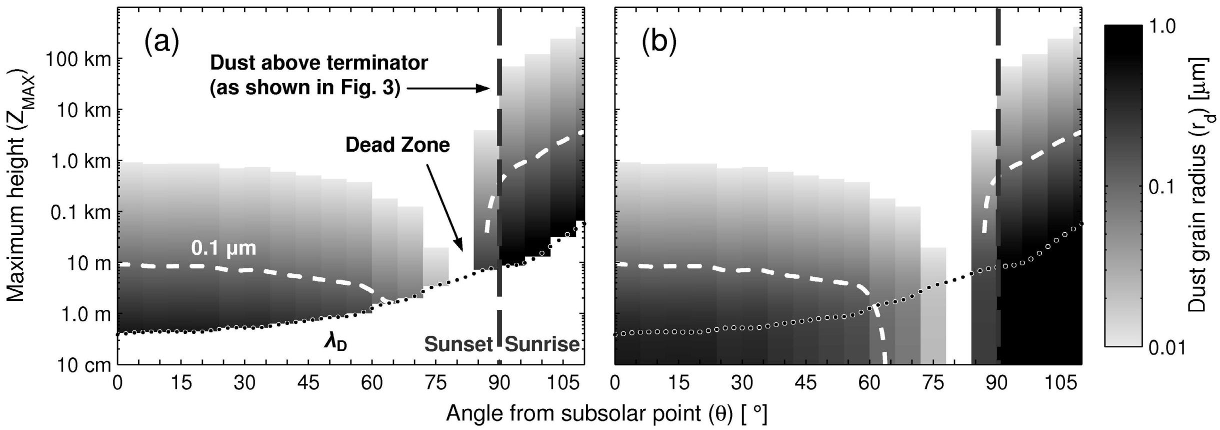

Figure 4. Fountain model predictions for Z_{MAX} as a function of θ and r_d, using (a) Eq. 1 [11] and (b) Eq. 2.

upward velocity (V_{exit}). Subsequently, they follow a near-parabolic trajectory back toward the lunar surface since the main force acting on them now is gravity.

From our calculations we estimate that in the terminator region the repulsive force F_q on a grain with r_d = 0.1 μm can be more than 200 times greater than F_g; while for a grain with r_d = 0.01 μm it can be as much as 2.0×10^4 times greater. However, for micron-scale grains the force of cohesion between grains, F_c, can be much greater than F_g. So in this model we implicitly assume that when a particular grain is fully charged F_q is just able to overcome F_c, and it is ejected from the surface.

The effects of radiation pressure are neglected in this model since we are only considering dust dynamics in the direction radially away from the lunar surface. For a grain with r_d = 0.1 μm, the acceleration away from the Sun due to radiation pressure is ≈0.012 m s^{-2}. Compared to the near-surface acceleration due to electrostatic forces and the acceleration due to lunar gravity, the effects of radiation pressure are clearly negligible. However, non-radial acceleration due to radiation pressure could become more significant if the dust grain spends prolonged periods above the surface.

Given the assumptions described above, [11] calculated the maximum height reached by a dust grain of radius, r_d, to be

$$Z_{MAX} = \frac{3\varepsilon_0 \phi_S^2}{\rho g_L r_d^2}. \tag{1}$$

In Eq. 1, ϕ_S is the electrostatic potential at the lunar surface, ρ is the dust grain density (i.e., specific gravity of lunar regolith × 10^3 kg m^{-3}), and g_L is the acceleration due to lunar gravity. Note that Eq. 1 is only valid when the initial electrostatic acceleration exceeds lunar gravity (i.e., $a_q > g_L$).

However, if we include an electrostatic potential that decays exponentially above the lunar surface, as is expected for Debye shielding of a charged surface in a plasma, we find that

$$Z_{MAX}\left[1-\exp\left(-\frac{Z_{MAX}}{\lambda_D}\right)\right]^{-1} = \frac{3\varepsilon_0 \phi_S^2}{\rho g_L r_d^2}. \tag{2}$$

In section 4 we discuss and compare the effects of including an exponentially decaying surface potential in the lofting model, as described by Eq. 2, with the previous model described by Eq. 1.

4. MODEL PREDICTIONS

Surface charging in the model is photo-driven on the dayside and plasma electron-driven on the nightside [9,11]. Fig. 4 shows Z_{MAX} as a function of r_d and angle from the subsolar point, θ, for typical solar wind conditions, as predicted by (a) Eq. 1 [11] and (b) Eq. 2. Results in Fig. 4(a) predict dust lofting at most locations on the lunar surface, apart from in the region just sunward of the terminator labeled the "Dead Zone" ($\theta \approx$ 80°), where $\phi_S \approx 0$. We note here that the location of this so-called Dead Zone varies depending on the ambient plasma environment of the Moon, see [10]. At the terminator, dust grains with r_d < 0.1 μm are predicted to be lofted to Z ~ 1 – 100 km.

However, as can be seen in Fig. 4(a), no charged dust grains reached their Z_{MAX} below $Z = \lambda_D$, as a result of the simplifying assumptions used by [11]. Since the main objective of [11] was to explain the high-altitude dust, it was assumed that lofted dust grains would convert all the available electrostatic potential energy to kinetic and gravitational potential energy within the sheath region ($Z < \lambda_D$). (This was a reasonable assumption, since in an exponentially decaying electrostatic surface potential, a grain travels through 63% of ϕ_S by $Z = \lambda_D$ and 86% of ϕ_S

by $Z = 2\lambda_D$.) This meant that any grain that could be lofted (i.e., $F_q > F_g$ at the surface) would be predicted to at least reach $Z = \lambda_D$. Naturally, this had the greatest affect on the heavier grains, as shown in Fig. 4(a).

Fig. 4(b) shows the predictions for Z_{MAX} using Eq. 2. At high altitudes, the predictions are identical to those shown in Fig. 4(a) using Eq. 1. This indicates that for high altitude dust the assumptions made by [11] about the surface potential were justified. However, at lower altitudes the predictions are considerably different. As expected, when using Eq. 2 the range of predicted Z_{MAX} extends below $Z = \lambda_D$. Near the terminator, grains with $r_d \sim 1$ µm are predicted to reach $Z_{MAX} \sim 10$ cm, which is consistent with the Surveyor observations discussed in section 2.

5. DISCUSSION

When dust grains are able to achieve lofting heights where $Z_{MAX} >> \lambda_D$, then Eq. 2 reduces to Eq. 1, hence the identical predictions at high altitudes. However, when $Z_{MAX} < \lambda_D$ the exponential term in Eq. 2 can begin to dominate the determination of Z_{MAX}.

On the lunar dayside, the positively charged dust grains ejected from the surface must travel through the photoelectron sheath. The flux of electrons from this sheath acts to charge these grains more negatively. It has been predicted that the larger slower moving grains will spend sufficient time in the sheath to charge negative and be attracted back to the positively charged surface [13,14]. However, if a grain is moving just fast enough, then it is possible for it to get above the sheath to a region where photocharging can maintain its positive charge. In this situation it is possible for the grain to become stably suspended in the surface electric field at a point where $F_q \approx F_g$, as illustrated in Fig. 2a. This phenomenon is referred to as "electrostatic levitation", and it is likely that some of the dust grains in Fig. 4(b) with $Z_{MAX} \sim \lambda_D$ would be levitated.

Our initial calculations indicate that the grains reaching $Z_{MAX} >> \lambda_D$ travel through the photoelectron sheath so rapidly that the change in grain charge is negligible. For example, a positively-charged grain with $r_d = 0.1$ µm traveling through the photoelectron sheath at the subsolar point would only become ≈1% less positive; whereas a similar negatively-charged grain traveling through the plasma sheath at the terminator would lose a mere ≈0.01% of its negative charge.

In this study, as in [11], we have assumed that the dust grains on the lunar surface charge to the same potential as the surface as a whole, and the capacitance of the individual grains on the surface is the same as if the grains were isolated in the ambient plasma, i.e., $C = 4\pi\varepsilon_0 r_d$ [16]. This assumption is supported by the results of laboratory experiments using dielectric grains on a dielectric sphere immersed in a plasma [17]. Previous theoretical work has suggested that the charge density on the lunar surface would be so low that, on average, micron-sized dust grains would hold only a fraction of an electron charge, which would be insufficient for them to be electrostatically ejected [18]. This inconsistency between experimental observation and theoretical prediction raises the possibility that the electrostatic charging of a dusty surface in a plasma is more complicated than had been anticipated.

Under certain conditions it is likely that triboelectric charging plays an important role in causing dust grains to become highly charged at the lunar surface [19]. Triboelectric charging is caused by both a difference in contact potentials and frictional transfer of charge between grains in contact. Laboratory experiments using JSC-1 lunar simulant have shown that individual grains of $r_d \approx 50$ µm can acquire a triboelectric charge of $\sim 10^5$ electrons via inter-grain contacts [19]. Dust grains on the lunar surface would acquire triboelectric charge when separated by a disturbance, such as a meteoroid impact or a lunar quake. Tribocharging of dust grains is expected to be limited on a photocharged surface due to the increase in electrical conductivity [19]. This suggests that tribocharging would be most effective on the lunar nightside and areas of the dayside where $\phi_S \leq 0$ [10], which would include the region around the terminator. If the tribocharging probabilities for dust grains on the lunar surface are well described by the Gaussian fit in Fig. 8c of [19], then it is possible that a small fraction will acquire an extremely large amount of charge (limited only by field emission for negatively charged grains [12]) and be electrostatically lofted as described in [11]. It is also possible that these processes combine, such that a grain is tribocharged as it is electrostatically ejected from the surface.

6. CONCLUSIONS

We show how lunar surface electric fields are important for dust transport, as observed during the Apollo era. As expected, the inclusion of an exponentially decaying surface electric field in the lofting model has no effect on the lighter dust grains reaching high altitudes ($Z_{MAX} >> \lambda_D$), as seen by comparing Figs. 4(a) and 4(b). However, nearer the surface ($Z_{MAX} \sim \lambda_D$), it becomes much more important for the heavier grains. As discussed in section 5, it is these grains that would be electrostatically levitated [14,15].

Some uncertainty still exists as to how dust grains are able to become highly charged on or near the surface. In the lofting model we have assumed that the dust grains charge on the lunar surface in the same way as if they were isolated in the ambient plasma [17]. However, it is very likely that triboelectric charging plays an important role in dust grains becoming highly charged. Whatever the initial mechanism for dust charging, the fountain model is currently the only viable explanation for how <0.1 μm dust reaches $Z_{MAX} >> \lambda_D$.

From a comparison with Mie scattering predictions [7], our results suggest that submicron dust grains could contaminate astronomical observations of infra-red, visible and UV light over a significant portion of the lunar surface, and not just near the terminator. This is one of many ways in which dust could interfere with science and exploration activities on the Moon [8]; therefore, a thorough understanding of lunar dust behavior is necessary in order to effectively prepare for future robotic and human missions to the Moon.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. McCoy, J.E., Photometric studies of light scattering above the lunar terminator from Apollo solar corona photography, *Proc. Lunar Sci. Conf. 7th*, 1087–1112, 1976.

2. Rennilson, J.J. and Criswell, D.R., Surveyor observations of lunar horizon-glow, *The Moon*, 10, 121–142, 1974.

3. Criswell, D.R., Horizon-glow and the motion of lunar dust, *Photon and Particle Interactions with Surfaces in Space*, D. Reidel Publishing Co., Dordrecht, Holland, pp. 545–556, 1973.

4. McCoy, J.E. and Criswell, D.R., Evidence for a high altitude distribution of lunar dust, *Proc. Lunar Sci. Conf. 5th*, 2991–3005, 1974.

5. Berg, O.E., et al., Lunar soil movement registered by the Apollo 17 cosmic dust experiment, *Interplanetary Dust and Zodiacal Light*, Springer-Verlag, Berlin, pp. 233–237, 1976.

6. Zook, H.A. and McCoy, J.E., Large scale lunar horizon glow and high altitude lunar dust exosphere, *Geophys. Res. Lett.*, 18, 11, 2117–2120, 1991.

7. Murphy, D.L. and Vondrak, R.R., Effects of levitated dust on astronomical observations from the lunar surface, *Proc. Lunar Planet. Sci. Conf. 24th*, 1033, 1993.

8. Stubbs, T.J., et al., Impact of dust on lunar exploration, *Proceedings of the conference 'Dust in planetary systems' held in Kauai/Hawaii, Sept. 2005*, ed. H. Krüger, A.L. Graps, ESA-SP, this issue, 2006.

9. Manka, R.H., Plasma and potential at the lunar surface, *Photon and Particle Interactions with Surfaces in Space*, D. Reidel Publishing Co., Dordrecht, Holland, pp. 347–361, 1973.

10. Stubbs, T.J., et al., Lunar surface charging: A global perspective using Lunar Prospector data, *Proceedings of the conference 'Dust in planetary systems' held in Kauai/Hawaii, Sept. 2005*, ed. H. Krüger, A.L. Graps, ESA-SP, this issue, 2006.

11. Stubbs, T.J., et al., A dynamic fountain model for lunar dust, *Adv. Space Res.*, 37, 59–66, 2006.

12. Whipple, E.C., Potentials of surfaces in space, *Rep. Prog. Phys.*, 44, 1197–1250, 1981.

13. Nitter, T. et al., Levitation and dynamics of charged dust in the photoelectron sheath above surfaces in space, *J. Geophys. Res.*, 103, A4, 6605–6620, 1998.

14. Colwell, et al., Dust transport in photoelectron layers and the formation of dust ponds on Eros, *Icarus*, 175, 159-169, 2005.

15. Sickafoose, A.A., et al., Experimental levitation of dust grains in a plasma sheath, *J. Geophys. Res.*, 107, A11, 1408, doi:10.1029/2002JA009347, 2002.

16. Goertz, C.K., Dusty plasma in the solar system, *Rev. Geophys.*, 27, 2, 271–292, 1989.

17. Sheridan, T.E., et al., Observation of dust shedding from material bodies in a plasma, *J. Geophys. Res.*, 97, 2935–2942, 1992.

18. Singer, S.F., and Walker, E.H., Electrostatic dust transport on the lunar surface, *Icarus*, 1, 112–120, 1962.

19. Sickafoose, A.A., et al., Experimental investigations on photoelectric and triboelectric charging of dust, *J. Geophys. Res.*, 106, 8343–8356, doi:10.1029/2000JA000364, 2001.

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