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Topical: Determining properties of the plasma just above the lunar surface

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Knowledge Gap: The Apollo missions of half a century ago found that mechanisms, spacesuits, and visibility were all adversely affected by lunar dust. The Apollo missions also strongly hinted that the dust was electrostatically charged with dust motion driven by electric forces. The USA is planning to initiate a substantial human presence on the Moon during the next decade for purposes of scientific exploration and economic resource exploitation. Dust is expected to be an important issue affecting the planned lunar missions as these missions will almost certainly involve substantial interaction with lunar dust. The problems resulting from this interaction with dust can only be addressed by understanding the nature of lunar dust. Since this nature is largely determined by the properties of the plasma just above the lunar surface, it is critical to understand the lunar plasma environment.

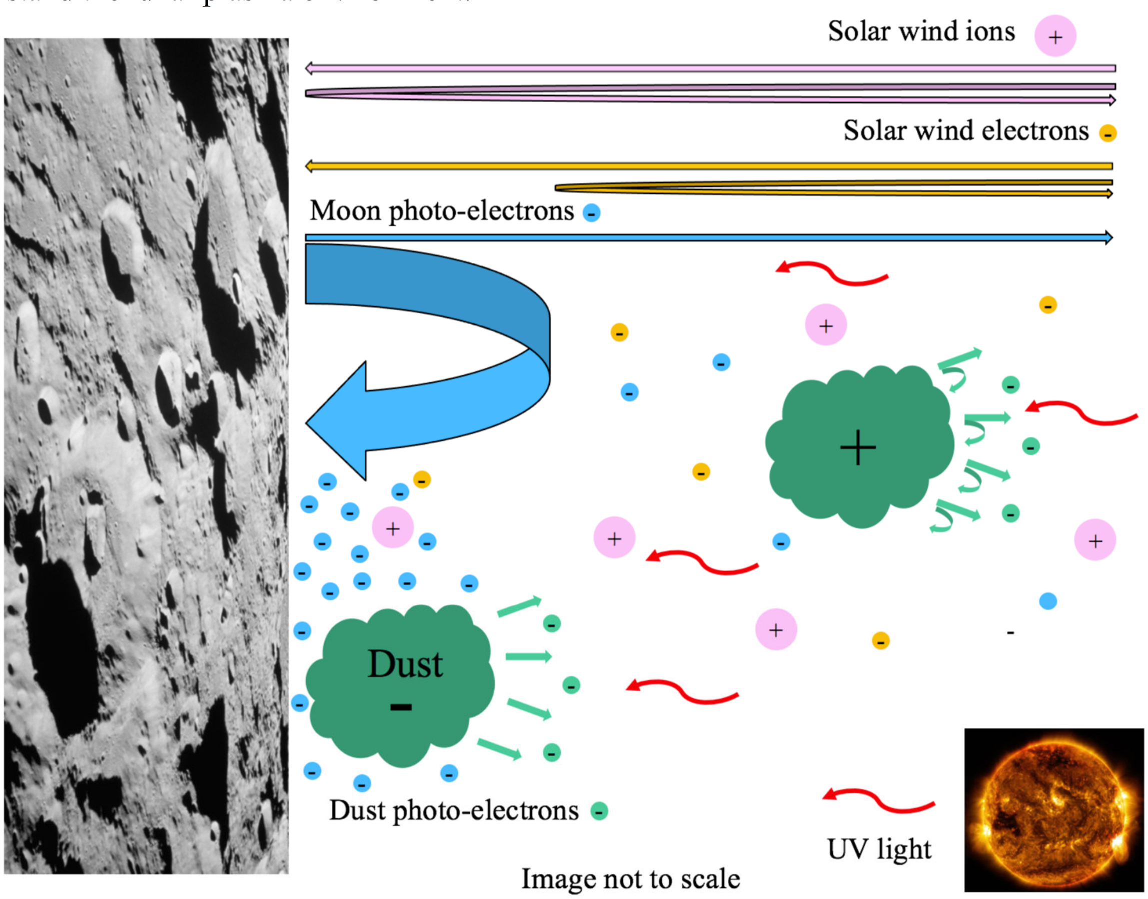

Figure 1 Plasma and dust environment above the lunar surface.

Current understanding of lunar plasma environment: Dust charging and the electric fields driving these forces both result from ambient plasma. The properties of this plasma are poorly characterized because of lack of significant measurements. Models suggest that, under solar illumination, the plasma above the lunar surface results from several complex interactions. These interactions include photo-ionization of the lunar surface ejecting electrons to form a negative charge cloud above the surface, negative charging of dust grains by this cloud, positive charging of dust at higher altitudes by photo-emission, and an inflow of solar wind electrons and ions. These effects, moreover, all depend on lunar time of day and on solar radiation such that, in addition to having a complicated spatial profile, the plasma also changes with time. Figure 1 sketches the various processes involved. Ultraviolet (UV) sunlight illuminates the lunar surface causing it to emit photo-electrons (blue curved and straight arrows). The emitted electrons form a cloud a few meters above the lunar surface where they produce a negative potential. Low energy solar wind electrons reflect from the repulsive potential of this negative cloud (yellow) while high energy solar wind electrons surmount the potential barrier to reach the lunar surface. Solar wind ions (mauve) see the negative cloud as a potential valley but can be repelled by the positive potential of the lunar surface, so only high-energy solar wind ions reach the surface. Recent lab studies show that electrostatically lofted dust likely bears negative charge due to the absorption of photoelectrons by microcavities between dust grains [Wang et al., 2016]. Dust grains (green) located slightly above the lunar surface remain negatively charged by collecting electrons from the electron cloud; this competes with UV sunlight causing dust grains to emit photo-electrons and so become positively charged. It is thus expected that negative charging will dominate near the lunar surface but at higher altitudes positive charging will dominate.

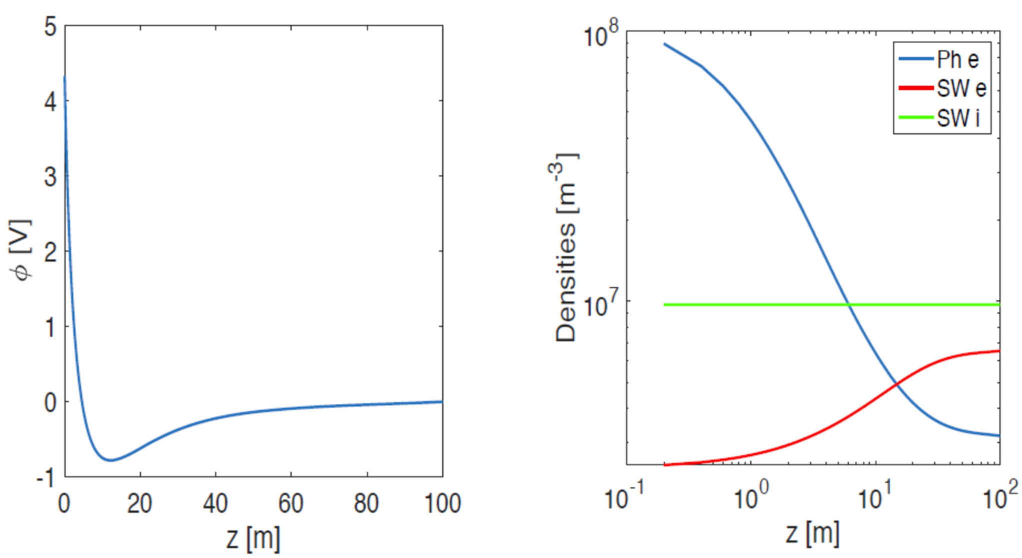

Figure 2 Electrostatic potential (left) and photoelectron ('Ph e') and solar wind ('SW e' for electrons and 'SW i' for ions) densities (right) versus altitude, obtained by a steady-state, kinetic model of the photoelectron sheath on the lunar surface.

Figure 2 (left) shows the electrostatic potential as a function of altitude *z* calculated from a one-dimensional, kinetic, steady-state model for the lunar sheath illuminated by the Sun at normal incidence (Hartzell et al., 2021). This model shows a non-monotonic behavior associated with the Moon's photoelectrons. At altitude $z = 0.1$ m the electrostatic potential is $\varphi \sim 4$ V and at $z \sim 10$ m the potential drops to a minimum of $\varphi \sim -0.8$ V. Figure 2 (right) plots the densities of the photo-emitted electrons, the solar wind electrons, and the solar wind ions. The electron density is dominated by the photoelectrons for z <10 m and the peak electron density is about 100 cm^{-3} (i.e., 10^8 m^{-3}). The potential and density profiles are expected to vary dramatically, depending on latitude and local time [Nitter et al., 1998].

The need for new information: Figures 1 and 2 are the results of a typical model and to date, there have been no measurements to which models such as this can be compared. This lack of plasma and electric field measurements hinders progress on fundamental understanding of lunar dust-plasma interaction physics and so on safe lunar exploration. The plasma and electromagnetic environment near the lunar surface control how dust is charged. Dust charging determines critical properties of dust such as whether dust hovers above the lunar surface, how dust sticks to surfaces, and whether dust is ejected by transient phenomena. However, so little is known about this environment that, for example, the plasma density predicted by existing theoretical/numerical models such as that shown in Fig. 2 spans several orders of magnitude. Specifically, the electron density predicted by most models is in the range 1-1000 cm^{-3} [Nitter et al. 1998, Poppe and Horányi 2010], but at least one model predicts 10^5 cm^{-3} [Popel et al. 2018]. The bulk electron temperature is predicted to be about 1-10 eV. Because of this uncertainty in the parameters, it is critical to make *in-situ* measurements of the local plasma and electromagnetic environment near the lunar surface. These measurements would provide essential inputs for dust transport models, for efforts to develop dust remediation techniques, and, ultimately, for supporting safe lunar exploration. Important scientific questions that measurements would help resolve include:

(i) what is the charge of dust particles on and near the lunar surface;
(ii) does dust levitation occur near the lunar surface;
(iii) do electrostatic forces determine dust flux above the surface or is this flux determined by another mechanism such as micrometeoroid bombardment;
(iv) do dust charging induced in the interstices at the surface and the subsequent repulsive force control dust lofting and mobilization as suggested by some recent laboratory experiments [Wang et al., 2016, Schwan et al., 2017, Carroll et al., 2020].

Filling the gap: Instruments to measure plasma and electric field properties near the lunar surface could be designed, built, and deployed in the next decade using existing or slightly more developed technology. By filling the gap in knowledge regarding lunar plasma properties, *in situ* measurements would determine which, if any, models are correct and also would provide guidance on how to address dust issues. Designing, building, testing and deploying such instruments in the next decade is feasible, but dedicated resources will be needed as well as the time to do the work.

Reference design example: To demonstrate feasibility, we discuss here an example of a possible instrument that would provide information for filling the knowledge gap. This instrument, called the Plasma Lunar Surface Probe (PLUS-Probe) and shown in Fig. 3, is a reference design developed by P. M. Bellan and G. L. Delzanno for measuring plasma properties on the lunar surface. The PLUS-Probe adapts and extends Langmuir probe methods previously used on spacecraft [Lai 1994, Olson et al. 2010] to the conditions near the lunar surface. However, because the lunar plasma environment differs significantly from previously explored space plasma environments, the design constraints differ considerably from those of spacecraft probes. Because of this difference, significant innovation is required to design a lunar Langmuir probe. For example, it is anticipated that without mitigation, photo-emission currents would likely overwhelm Langmuir probe currents and so confound density measurements. To avoid this, the PLUS-Probe design has shields to block Sun- and Moon-light and contains segments that are either optically absorbing or optically reflecting so that photo-emission currents can be gauged and then subtracted (see Fig. 3). Also, to avoid collecting dust, the probe scan frequency is arranged to exceed the dust plasma frequency [Bose et al., 2017]. Besides operating as a classical Langmuir probe, operation could also be as an impedance probe [Blackwell 2005] so agreement between two different modes of operation would provide confidence that the measured density is correct. It will be important to have confirmation that the novel aspects of a lunar Langmuir probe design indeed function as intended. To provide this confirmation before deploying a probe on the Moon, it would be critical to test the probe in a laboratory environment that replicates the lunar plasma environment as much as possible. It is expected that much will be learned from such laboratory tests so that an initial probe design will go through many iterations before it is attempted to use the probe on the Moon. It would consequently be advisable to establish an ongoing program for designing a lunar plasma probe and then testing this design in a lab under conditions simulating the lunar environment.

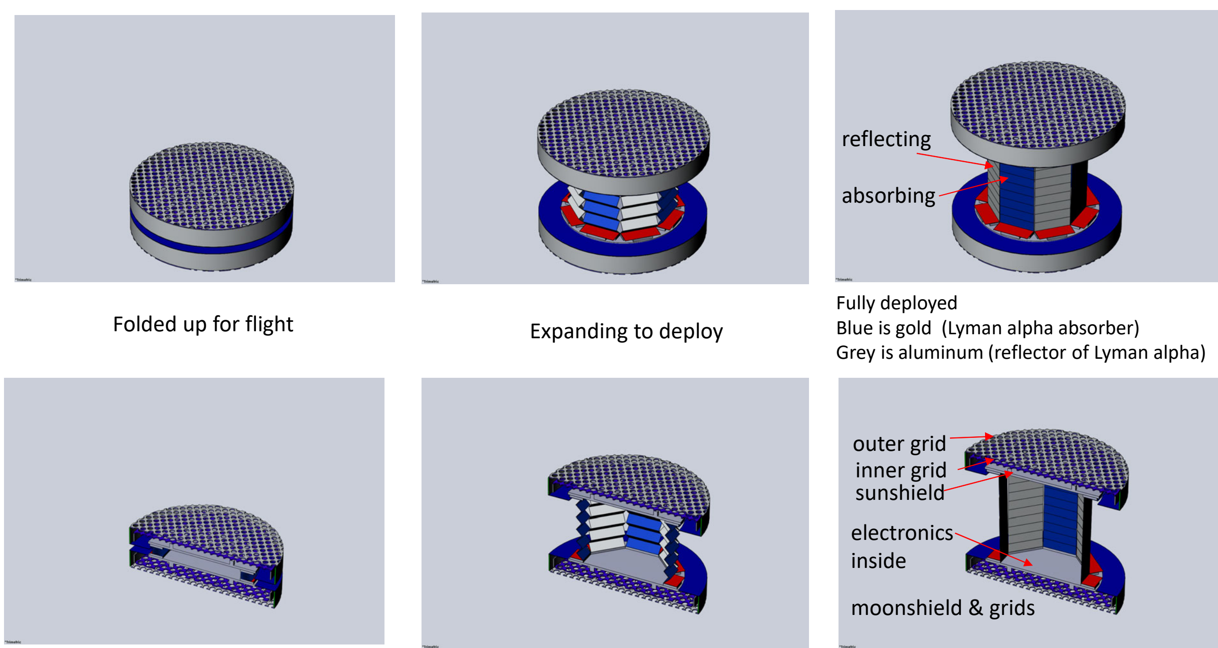

Figure 3 PLUS-Probe reference design showing deployment and layout of probe. Sun and Moon shields, indicated in bottom right figure, block direct and reflected sunlight to prevent photo-emission. Alternating optically absorbing and reflecting segments enable determination of residual photo-emission current so the confounding effects of this current can be removed.

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