CHARACTERIZING TERMINATOR SPACE WEATHER WITH ARTEMIS III. H. Fuqua Haviland[1*], W. M. Farrell[2], J. S. Halekas[3], E. M. Willis[1], V. N. Coffey[1] , D. L. Gallagher[1], C. D. Fry[1] , J. R. Espley[2]. [1]NASA Marshall Space Flight Center, [2]NASA Goddard Space Flight Center, [3]University of Iowa. *Corresponding author: heidi.haviland@nasa.gov.

Introduction: This white paper discusses key open plasma physics science questions that can be addressed by the Artemis III 2024 mission which will send astronauts to the lunar surface within six degrees of the south pole. A detailed characterization of lunar surface plasma, along with its driving space weather, is important for basic research [1], knowledge of possible hazards identification for robotic and human operation [2], and provides context for correctly interrupting induced fields for interior EM sounding [3]. Measurements at the lunar surface provide the best opportunity to definitively resolve these questions and can also be used to study magnetotail plasma phenomena at the Moon's location [e.g., 1]. While there are several interesting areas for plasma physics investigations enabled by the Artemis missions, we focus here on surface charging and the solar wind(SW)-surface sub cycle of the on-going volatile processes. We begin with a brief review beginning with Apollo-era investigations, and then discuss solar inputs to plasma populations and ongoing surface processes. Plasma physics science objectives are stated, along with a brief discussion of the instruments required for these investigations, and Artemis astronaut deployment options.

Plasma Science Objectives.

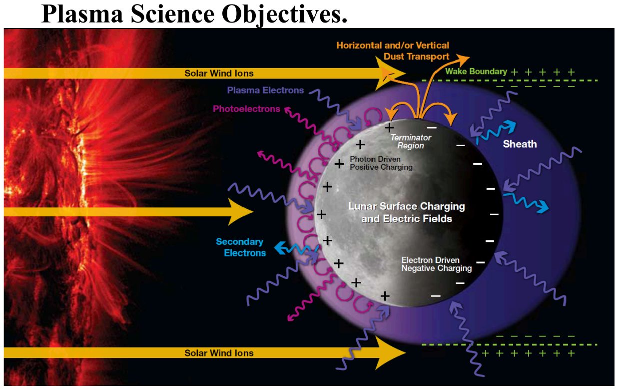

Figure 1. Day and nightside plasma environments at the Moon when immersed in the solar wind [1].

The solid surface of the Moon interacts directly with dynamic space plasmas and solar illumination which drive active electrodynamic processes [4]. These processes contribute to charging, electrostatic dust lofting, and surface weathering. In addition, SW ions implant within the dayside regolith. This results in hydrogenation, hydroxylation, and possible hydration during the reprocessing of regolith producing H, H_2, methane and possibly water [5]. This SW-surface interaction is a subcycle of the hydrogen/water/volatile cycles experienced at the Moon which includes micrometeoroid impacts [e.g., 6], and volatiles ejected from permanently shadowed regions (PSR) [e.g., 7] or by space weathering of crater central peaks [e.g., 8]. The poles provide direct opportunity to study the lunar terminator, where the dayside and nightside surface potentials can be several 10s of volts, which has been proposed to cause electrostatic dust lofting [9]. SW flow being horizontal at the poles, enables topology such as mountains or crater walls to be an obstacle to the flow which generates local mini-wake phenomena [10-12]. Tribocharging, the buildup of charge due to moving on the surface, is especially a concern in regions without photoemission.

Background. Apollo experiments provided the first plasma measurements at the surface of the Moon. The SW Composition experiment (Fig.2) detected solar material, the A17 LACE mass spectrometer provided observations of Ar, He, and Ne ions [13], the ALSEP SIDE instrument measured surface potentials [14] , and the A14 ALSEP CPLEE instrument measured low energy charged particles [15]. In lunar orbit, Apollo 15, 16 subsatellites, Explorer 35, Lunar Prospector, Kaguya, LADEE, LRO, and ARTEMIS missions provided valuable contributions towards characterizing the electromagnetic plasma and dust environments with varying solar conditions, including extreme events [5]. However, surface plasma densities and temperatures need to be measured with modern instruments to constrain our current understanding of plasma processes which relies on simulations [1]. The ion and electron analyzers would be designed with the optimal energy range and energy/angle resolutions along with dust mitigation similar to the CPLEE. With current technology, the particle analyzers and electric and magnetic field instrumentation will benefit significantly from hardened avionics and the use of field-programmable gate arrays (FPGAs) to obtain quality measurements during longer periods of interest. Also, surface measurements at several locations including both the SW dayside and nightside, at the terminator, and within the magnetosphere including magnetosheath, magnetotail lobes, and plasma sheet would improve the current state of knowledge.

For ~75% of the Moon's orbit, the surface is exposed to the free streaming SW, consisting of hot protons and cold electrons, Fig. 1. The dayside lunar surface absorbs these particles, and photoemission dominates charging the surface a few volts positive. A current layer has been proposed on the dayside, at or within the surface, confining induced magnetic fields [see 16 for review]; however, this layer has yet to be detected. While on the nightside of the Moon, a vacuum cavity forms, generating current systems and a trailing plasma wake structure. In dark, plasma depleted regions, the surface potential is a few hundred volts negative, depending on solar zenith angle, relative to the SW. This effect is on km scales. A second effect on the m-scale, has been observed [17], the potential drop across the near surface sheath which also contributes to surface charging. Solar energetic particle events can cause extreme charging up to several thousand volts negative. The Moon also traverses the Earth's magnetotail in the remaining portion of its orbit, experiencing the various plasma environments of the magnetosheath, lobes, and plasma sheet. The electrical conductivity of the lunar regolith is very small, in contrast to the highly conducting plasma. For a review, see [18]. In addition, the electromagnetic environment of the lunar surface has been used to measure interior electrical conductivity. We note the characterization of surface plasma provides important context for the correct interpretation of these induced fields, especially within the nightside wake cavity [19].

Key open plasma physics science questions:

- *How are plasma surface processes at the polar terminator related to external drivers, including solar radiation, meteoritic influx, and SW plasma?*
- *What is the lateral potential difference across the terminator? Does this vary vertically?*
- *Is potential difference responsible for dust lofting?*
- *Do surface observations verify simulations which predict a standing plasma double layer over/around terminator?*
- *Under what circumstances does charging by the lunar surface plasma pose a threat to operations? What are the spatiotemporal surface charging and discharging plasma, especially in shadowed, plasma-depleted regions?*
- *How does the plasma-sputtering of ice in PSR crater floors contribute to volatile cycles?*
- *Does the predicted dayside current layer exist at or just above the lunar surface?*

Instruments. Packages deployed on landers should include electric potential, an electron analyzer and mass analyzed ion analyzer, a fluxgate magnetometer, an electric field instrument, and dust detector. Measurements would provide the electric and magnetic fields including any perturbations, and ion and electron distributions along with the derived plasma densities, temperatures, and velocities.

Artemis enabling deployment. With the aid of astronauts, these instrument packages could take data at several points within the landing site and could include measurements of lunar dawn and dusk. Lateral observations provide characterization of across the terminator. The potential differences could also be measured vertically extending up from the surface to 2-3 m. This scale size would be of value in characterizing the dayside photoelectron sheath and possible current layer at or near the surface.

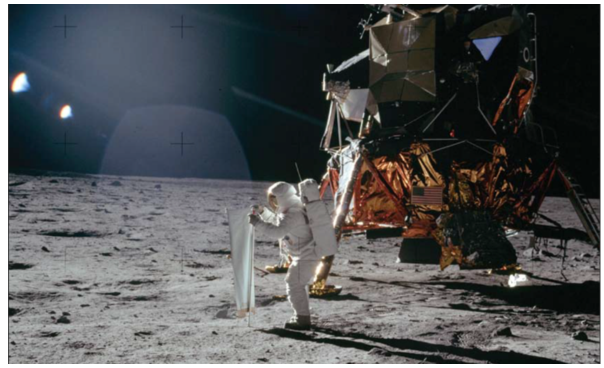

Figure 2. Apollo 11 astronaut deploying the SW composition experiment [NASA].

Conclusions. The surface of the Moon and its electrodynamic plasma processes warrants further observation with the Artemis 2024 mission. Astronaut deployment provides the opportunity for multiple measurement locations characterizing the landing site plasma laterally and vertically. Moreover, the Moon is one of several airless bodies in our Solar System which include asteroids, moons, and Mercury; increased knowledge of plasma processes at the lunar surface improves understanding of airless bodies [18]. In addition, this mission would be a great opportunity to make simultaneous surface-orbit plasma measurements using the currently orbiting Artemis science satellites [20]

References: [1] NASA. (2007). Heliophys. Sci. & the Moon. [2] NASA. (2020). SLS-SPEC-159 DNSE, Rev H. [3] Grimm et al, this issue. [4] Delory (2010). In Proceedings *ESA Annual Meeting on Electrostatics* (pp. 1–18). [5] Farrell et al. (in press). The Dust, Atmosphere, & Plasma at the Moon, 1–92. [6] Benna et al (2019). *Nat. Geosci.,* 12(5), 333–338. [7] Farrell et al. (2015). *GRL*, *42*(9), 3160–3165. [8] Klima et al. (2013), *Nat. Geosci*., 6, 737-741. [9] Farrell et al. (2007). *GRL*, 34(14), 3–7. [10] Farrell, et al. (2010). *JGR*, 115(E3), 1–14. [11] Rhodes & Farrell (2020). *PSJ*, 1(1), 13. [12] Zimmerman et al. (2011). *GRL*, 38(19), 3–7. [13] Hoffman et al. (1973). In *LPSC,* 4, 2865. [14] Freeman & Ibrahim (1975). *The Moon*, 14(1), 103–114. [15] O'Brien & Reasoner (1971). *NASA* SP-272, 193. [16] Sonett (1982). *Rev. of Geophys. & Space Phys*., 20(3), 411–455. [17] Halekas et al. (2008). *JGR-SP*. 113(9), 1-16. [18] Halekas et al. (2010). *PSS*. 59(14), 1681–1694. [19] Fuqua Haviland et al. (2019). *GRL*, 46(46), 4151–4160. [20] Angelopoulos (2011). *SSR*, 165(1), 3–25.