0. Executive Summary

The Lunar Environment And Dynamics for Exploration Research (LEADER) Center for Space Environments is a modeling-lab-data center of excellence designed to answer the overarching question: "How does the highly-variable energy and matter in the inner heliosphere affect volatile stability, plasma interactions, dust migration, and surface micro-structure at the Moon, and how will this dynamic lunar environment change in response to human presence? As humans begin to establish a permanent presence on the Moon and utilize resources found there, they will need to be aware of the environmental challenges this creates – to understand the health challenges this may impose on our astronauts, as well as the effects explorers will have on the fragile lunar environment. Hazards to astronauts and critical systems include radiation damage, studied by LEADER's Fatemeh Rahmanifard (2020); extreme surface charging events including dielectric breakdown, or "sparking," in cold soil on the Moon studied by LEADER'S Andrew Jordan [Jordan, 2021]; and effects lunar dust will have on human health and mechanical systems. LEADER's Christine Hartzell chairs JPL's Lunar Dust Mitigation Science Definition Team. Finally, the nature and extent of the effect explorers and their systems have on the lunar environment has been explored by LEADER's Parvathy Prem who studied the effect of rocket exhaust on the lunar exosphere [Prem et al., 2020]. Explorers are exposed to space plasma and charged particle radiation and this environment creates a human system plasma-charging hazard as well as a radiation human health issue. In the next year, the team will determine the amount of shielding required to protect human habitats against charged particle radiation under different solar cycle conditions.

1. Team Project Report

1.1. LEADER Theme 1: Environmental Connection to Volatiles

LEADER Co-Is are modeling the past, present and future of lunar volatiles: from ancient volcanic atmospheres, to the contemporary sodium exosphere, to future spacecraft-generated exospheres.

> This year, LEADER Co-Is continued to investigate the lunar environmental connection to volatiles through space and time: from water at the lunar surface to sodium in the upper exosphere, and from ancient volcanic atmospheres to future spacecraft-generated exospheres.

Co-I O. J. Tucker led an investigation into the effect of magnetospheric shielding on solar wind interactions with the lunar surface and exosphere. Tucker et al. (2020a) predict that measurements of the OH surface concentration at low latitudes on the night side and of the degassed H_2 exosphere while in Earth's magnetotail could elucidate the role of the solar wind in the lunar hydrogen cycle. Meanwhile, Co-I Jason McLain investigated hydrogen implantation and OH production through laboratory experiments, in which samples of fused silica and lunar regolith were irradiated by a high-energy H_2^+ beam. Co-Is Dana Hurley and Bill Farrell were part of a team who discovered a 6 μm signature of molecular water on the sunlit lunar surface (Honniball et al., 2020), while Co-Is Dana Hurley and Andrew Poppe contributed their expertise as co-authors on a paper by Li et al. (2020) on the unexpected detection of hematite at lunar high-latitudes. Co-I Prem made major contributions to the report by the National Academies Committee on Planetary Protection: Planetary Protection for the Study of Lunar Volatiles (2020).

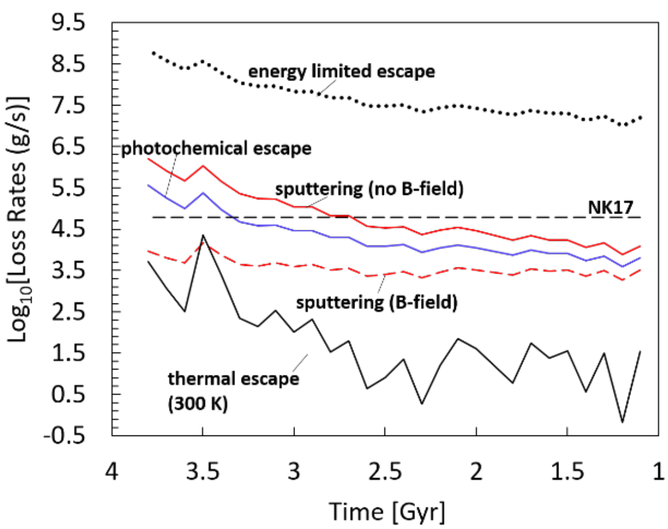

Figure 1. Tucker et al. (2021) calculated loss rates of an early CO-dominated volcanically-generated transient atmosphere. This figure compares the previously assumed loss rate (Needham & Kring) to updated loss rates driven by thermal processes (Jeans escape and energy limited escape) and non-thermal processes (photochemical escape and sputtering, with/without a paleo-magnetic field). Loss rates vary significantly over time due to variations in volcanic outgassing. Estimated lifetimes of transient atmospheres range from ~1000 years to ~1 My.

PI Rosemary Killen and colleagues continued their observations of the lunar sodium corona with the Goddard Lunar Coronagraph located at the Winer Observatory in Sonoita, Arizona. Complementing these long-term, ground-based observations, Co-I Menelaos Sarantos and colleagues analyzed LADEE data to characterize variations in exospheric sodium with local time as observed from orbit. Highlights of this work include the discovery of a correlation between high exospheric column density and increased ion flux to the lunar surface (Killen et al., 2021) and variations in exospheric structure that may be due to inhomogeneities in the distribution of sodium on the lunar surface (Sarantos et al., under review).

There has been renewed interest recently in the possibility that the Moon may once have had a volcanically-generated atmosphere. Co-I O.J. Tucker led work that, for the first time, considered in detail the physical mechanisms that may have led to the loss of such an atmosphere (Tucker et al., 2021). In related work, Co-I Hurley modeled the exospheric transport of CO_2 to polar cold traps. Initial results indicate that the amount of CO_2 released by a 500 m radius comet or a pyroclastic eruption volume of 75 km^3 could supply a 1 mm thick layer of CO_2 to sub-55 K cold traps (Hurley et al., 2019).

Looking ahead to future studies of the lunar exosphere from the Moon's surface, Co-I Parvathy Prem led an investigation into the fate of spacecraft exhaust gases released during a nominal lunar landing. Prem et al. (2020) found that exhaust water vapor may persist in the lunar environment for longer than two lunar days, presenting both an important opportunity to study volatile interactions with the lunar regolith in situ, as well as a need to account for exhaust gases in measurements of surface and exospheric volatiles. LEADER Co-Is continue to model the transport of spacecraft exhaust volatiles to understand the environmental impact of lunar landings and to support CLPS instrument science objectives.

1.2. LEADER Theme 2: Dust Tribocharging and Chemistry

Several members of the Dust-Tribocharging & Chemistry theme (Drs. Elsila-Cook, McLain and Schaible) experienced a significant delay in their work due to restrictions on experimental work due to the COVID pandemic. Fortunately, these investigations have been able to restart now that restrictions are easing. Dr. McLain has been building a new experimental setup to study space weathering of lunar soils. This LEADER experiment is nearing completion and will enable *in situ*/*in vacuo* reflectance infrared spectra during/after proton irradiation of a suite of Apollo era soils. Dr. McLain monitors IR reflectance spectra of the lunar soils, particularly hydroxyl radical formation, to determine conversions rates and hydroxyl stability. Dr. McLain and Dr. Elsila-Cook will also use this new experimental apparatus to deposit *in vacuo* organic and prebiotic molecules on proton irradiated lunar soils. The polymerization or degradation of these organic molecules will be measured in Dr. Elsila-Cook lab at GSFC using chromatographic separation of soil extracts coupled with mass spectrometry.

> Dust Theme members are developing experimental, computational, and analytical models to understand the chemistry of space weathering, the effect of dust on biological materials, and the electrical interactions of regolith grains.

Dr. Schaible is a SSERVI NASA postdoc fellow at GATech working with both LEADER and REVEALS to study dust grain electrification and reactivity. Dr. Schaible has designed a new technique to reliably deposit electrostatically charged lunar dust analogs onto biomolecular films. This new technique will be utilized to analyze both biofilm damage and dust grain passivation. A Faraday tube assembly is under development to passively measure the extent of electrostatic dust grain charging. Dr. Schaible is also designing a mechanism to insert and remove the biofilms from the grain interaction region to send to the GSFC Analytical Astrobiology Lab (Dr. Elisa-Cook) in order to measure the chemical reactivity potential of the electrified dust grains.

Dr. Hartzell's investigation of triboelectric charging of regolith has both experimental and computational components. This investigation will inform future efforts to model the tribocharging induced by exploration vehicles. Given the restrictions on experimental work, the focus this year was on computationally modeling the exchange of charge between regolith grains in LIGGGHTS, an open source Discrete Element Method simulation that models the interactions of hundreds of thousands of grains. The goal is to replicate the Dr. Hartzell's tribocharging experiment test-stand in LIGGGHTS to enable validation of the tribocharging model and LIGGGHTS implementation. A post-processing charge transfer method has been implemented and Dr. Hartzell and her student are in the process of testing different charge exchange models to attempt to match the experimental results. Figure 2 shows the type of output generated from the computational and experimental models.

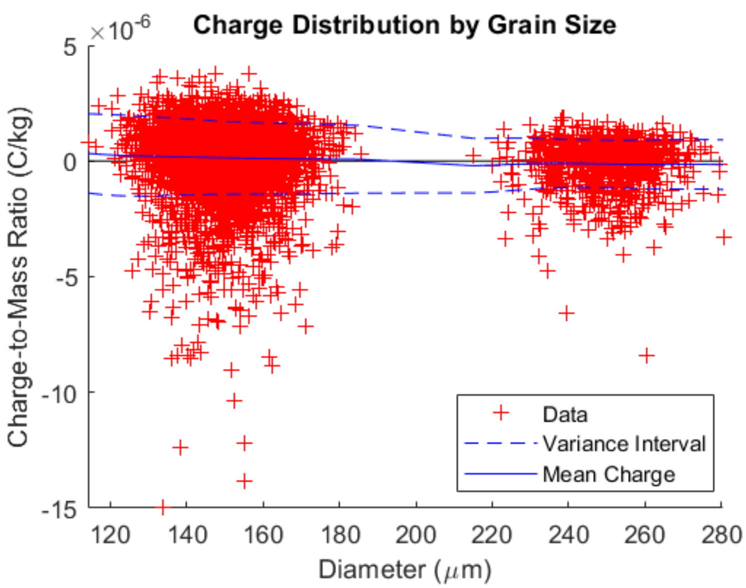

Figure 2. Example charge distribution generated using a triboelectric charge exchange model implemented (via post-processing) with LIGGGHTS.

Dr. Marshall has been investigating the relationship between adhesion and aeolian dust mobilization. Conventional threshold models for aeolian transport of dust & powders assume an adhesion component between grains that enhances bulk cohesiveness and results in higher wind thresholds as grain size diminishes. This had led to a general belief that dust on Mars should be difficult to lift. Yet the evidence suggests otherwise –dust is regularly mobilized at very moderate wind speeds. It is proposed that adhesive forces are actually making threshold easier rather than more difficult. This occurs by the production of high porosity microscopic structures during dust deposition with adhesion forces accommodating the structural vacancies. Dr. Marshall's work suggests that conventional aeolian threshold curves provide no 'dust compressibility' factor and therefore erroneously predict high thresholds for particulates smaller than about 70 microns. These results impact our understanding of dust entrainment by aerodynamic, electrostatic, and gravitational/centrifugal forces on Earth, Mars, Titan, asteroids, and other Solar System bodies.

1.3. LEADER Theme 3: Plasma-Surface-Object Interactions

The LEADER plasma team continued its successful campaign to understand lunar plasma-surface-object interactions. The LEADER team focuses on answering the question: "How does plasma interact with the lunar surface, its tenuous atmosphere, and exploration systems for past, present, and future conditions?"

> The Plasma Theme uses models and validating data sets to derive the plasma environment at our Moon and at Phobos in the solar wind and in planetary geomagnetic tails. The lunar models are used to determine the charging and discharging of human systems for exploration activities

The LEADER plasma team conducted fundamental data analysis and theoretical investigations primarily focused on moons and their interaction with the surrounding plasma environment. Beyond the terrestrial system, LEADER members investigated the multi-faceted plasma-surface interactions at Phobos, finding a complex pattern of weathering by solar wind and Martian ions on the moon's surface [Nénon et al., 2019, 2021].

A number of LEADER analyses of observations from Earth's Moon focused on the complex interaction of the Moon with the Earth's magnetospheric environment, a fundamentally different physical interaction than that of the Moon with the solar wind. LEADER studies found that lunar ions can be accelerated by magnetic forces in the magnetotail lobes [Cao et al., 2020a], and that the resulting accelerated ions can be used as a tracer of magnetospheric convection [Cao et al., 2020b]. These effects also perturb the local environment in a number of other ways, resulting in observable perturbations to the magnetotail plasma around the Moon [Kistler et al., submitted]. The outflow of ions from the terrestrial environment into the magnetotail may also affect the lunar surface and its chemical nature [Li et al., 2020].

Meanwhile, in the terrestrial magnetosheath, the lunar wake can be severely distorted and affected by upstream space weather influences [Rasca et al., 2021].

Other Moon-focused LEADER studies looked at fundamental physical processes, including the interactions between the ambient solar wind plasma and the small-scale lunar magnetic fields [Chu et al., submitted; Deca et al., 2020], and the structure of the lunar wake near polar craters [Rhodes et al., 2020a,b]. The latter case has implications for exploration, given the very low-density plasma present in polar craters, and LEADER team members conducted detailed investigations of the implications for tribocharging of exploration systems (see Fig. 3) [Rhodes et al., 2020c].

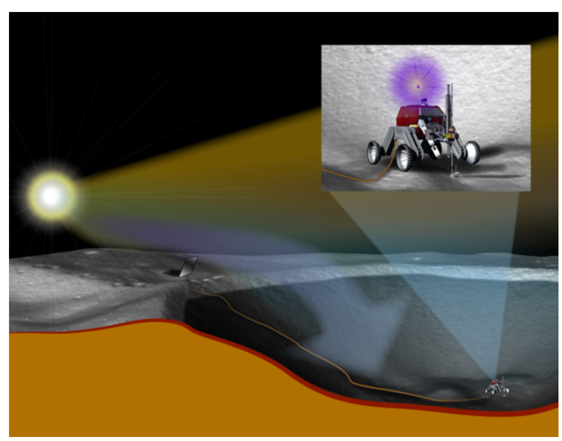

Figure 3. Schematic illustration of plasma flow over a lunar polar crater, and its effects on exploration systems.

Indeed, LEADER continues to actively explore the synergy between science and exploration. LEADER team members have been actively engaged in exploration planning, providing inputs to JSC exploration teams and to MSFC's development of environmental specifications in support of the Artemis human exploration program.

1.4. LEADER Theme 4: Interaction with the Space Radiation Environment

The Moon is exposed to two primary types of space radiation: galactic cosmic rays (GCRs) and solar energetic particles (SEPs). SEPs can alter lunar soil through a process called dielectric breakdown ("sparking"), and both GCRs and SEPs can affect the radiation exposure of astronauts on or near the Moon. LEADER has made important strides in understanding both aspects of how radiation affects the Moon and its environment.

1.4.1. Evidence for dielectric breakdown weathering on the Moon

Co-I Andrew Jordan has found the first observational evidence suggesting that solar energetic particles cause dielectric breakdown, or "sparking," in cold soil on the Moon [Jordan, 2021]. He has shown that a combination of meteoroid impacts and dielectric breakdown ("sparking") can explain how the reflectance of the lunar maria varies with latitude. This implies that the solar wind plays at most a minor role in space weathering, and it may explain why lunar swirls are brighter and more immature than their surroundings. This work lays the foundation for future experimental and data analysis that the LEADER team will perform, and it will help our understanding of space weathering on other airless bodies that are exposed to high fluxes of energetic charged particles [e.g., Jordan, submitted to *Icarus*].

1.4.2. Predicting the next solar cycle

LEADER has shown that the Sun is moving into a new period of persistently low solar activity. This affects predictions for the permissible mission duration for astronauts at or near the Moon.

Co-I Fatemeh Rahmanifard has led work showing that the Sun is moving into a new period of persistently low solar activity—a secular solar minimum [Rahmanifard et al., 2020]. Consequently, galactic cosmic ray radiation doses will likely be even higher than already unprecedented levels seen during the previous solar cycle, limiting deep space missions for astronauts to 290 days (45-year old male astronauts) and 204 days (female). She is building on this work to create a product that can predict future solar cycles [Rahmanifard et al., in preparation].

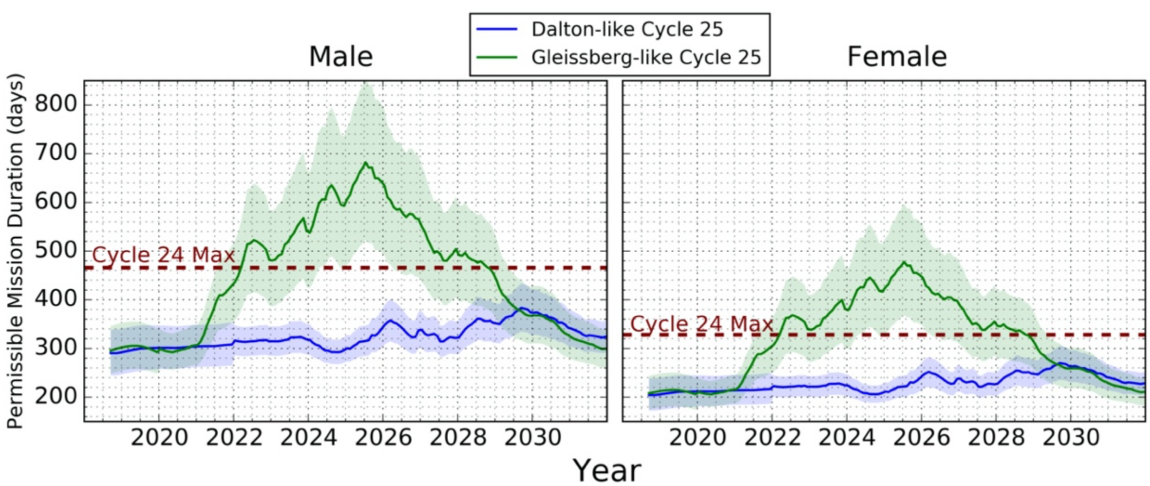

Figure 4. Permissible mission duration for two possible scenarios in the next solar cycle: either a Dalton- or Gleissberg-like cycle. Left: 45-year-old male astronaut. Right: 45-year-old female astronaut. Dashed maroon line shows permissible mission duration for male (female) astronauts at the maximum of solar cycle 24. (Figure from Rahmanifard et al. [2020].) ***radiation_figure.jpg***

In addition, Co-I Jody Wilson is leading work to predict the maximum number of sunspots in the next solar cycle (cycle 25) via patterns in sunspot number. This method is highly accurate in predicting the subsequent cycle from the one preceding, improving on previous studies [Wilson et al., 2020, AGU abstract]. These two approaches led by Rahmanifard and Wilson will enable LEADER to develop robust predictions of the radiation environment and the resulting permissible mission duration on or near the Moon during the next solar cycle.

1.5. Other LEADER Science Activities

1.5.1. Artemis EVA and HLS support

LEADER team members Kelsey Young, Bill Farrell, Andrew Poppe, and Jasper Halekas have been actively engaged in JSC exploration teams and in MSFC's development of environmental specifications in support of the Artemis human exploration program. LEADER co-I Young has been the GSFC-JSC liaison directing JSC engineering teams to GSFC science personnel who can support the EVA and Human Landing System (HLS) efforts. She has organized internal GSFC efforts and transmits ongoing study results (including our LEADER results) to the GSFC management. More tactically, LEADER team members have contributed to the Design Specifications for the Natural Environment (DSNE) including description of the lunar plasma environment expected at the surface and at Gateway orbits. Former DREAM2 post-doc Heidi Haviland is now a civil service scientist at MSFC who assisted in the organization of these DSNE input and reached out to the LEADER team members for the added support. Engineering teams at JSC are creating space suit requirements and are examining expected electrical potentials associated with photoemission, plasma charging and boot-regolith tribocharging. LEADER team member Farrell has given 2 presentations to the group on this subject and is involved in discussions with these engineers. JSC engineers are also involved in dust adhesion and tribocharging analysis and LEADER team member have been asked to provide input to these endeavors.

1.5.2. Decadal Survey involvement

LEADER Co-I's were authors on seven decadal white papers. Prem, Hurley and Farrell each led one; we were co-authors on papers led by Lucey, Richey, Tavares, and Watkins. Hurley, Prem and Farrell presented to the Decadal Mercury and Moon panel. Farrell is sitting on the Mercury and Moon Decadal panel.

1.5.3. CLPS program involvement

LEADER work is being used to define objectives and requirements for the CLPS mass spectrometer (PITMS and SEAL) and Radio/Plasma wave (ROLSES).

1.6. LEADER Publications

Cao, X., J. Halekas, A. Poppe, F. Chu, K.-H. Glassmeier, The Acceleration of Lunar Ions by Magnetic Forces in the Terrestrial Magnetotail Lobes, J. Geophys. Res., 125 #6, 2020a. 10.1029/2020JA027829

Cao, X., J. S. Halekas, F. Chu, M. Kistler, A. R. Poppe, K.-H. Glassmeier, Plasma Convection in the Terrestrial Magnetotail Lobes Measured near the Moon's Orbit, Geophys. Res. Lett. 47 #20, 2020b 10.1029/2020GL090217

Chu, F., J. S. Halekas, X. Cao, J. P. McFadden, J. W. Bonnell, Electrostatic Waves and Electron Heating Observed over Lunar Crustal Magnetic Anomalies, J. Geophys. Res., submitted

Deca, J., D. J. Hemingway, A. Divin, C. Lue, A. R. Poppe, B. Lembege, and M. Horányi, Simulating the Reiner Gamma Swirl: the Long-term Effect of Solar Wind Standoff, J. Geophys. Res. Planets, 125 # 5 2020. 10.1029/2019JE006219

Hartzell, C. M., and Carter, D. P. "Uncertainties in Regolith Tribocharging and Paths Forward," Conference abstract: Impact of Lunar Dust on Human Exploration meeting, Feb 2020.

Honniball, C. I., Lucey, P. G., Li, S., Shenoy, S., Orlando, T. M., Hibbitts, C. A., Hurley, D. M. and Farrell, W. M. (2020). Molecular water detected on the sunlit Moon by SOFIA. *Nature Astronomy*. https://doi.org/10.1038/s41550-020-01222-x

Hurley, D. M., Hayne, P. O., Needham, D. H., Kring, D. A., and Magaña, L. O.* (2019). Carbon in Lunar Polar Regions, *AGU Fall Meeting*, P43C-3478. https://ui.adsabs.harvard.edu/abs/2019AGUFM.P43C3478H/

Jordan, A. P. (2021) Evidence for dielectric breakdown weathering on the Moon, *Icarus*, doi:10.1016/j.icarus.2020.114199

Jordan, A. P. (under review), Reevaluating how charged particles cause space weathering on airless bodies, submitted to *Icarus*

Killen, R. M., Morgan, T. H., Potter, A. E., Bacon, G.*, Ajang, I.*, and Poppe, A.R. (2021). Coronagraphic observations of the lunar sodium exosphere 2018- 2019, *Icarus*, 355, 114155. https://doi.org/10.1016/j.icarus.2020.114155

Li, S., Lucey, P. G., Fraeman, A. A., Poppe, A. R., Sun, V. Z., Hurley, D. M., and Schultz, P. H. (2020). Widespread hematite at high latitudes of the Moon. *Sci. Adv.*, 6, eaba1940. https://doi.org/10.1126/sciadv.aba1940

Kistler, M., J. Halekas, J. McFadden, J. Z. D. Mieth, Distribution and variability of plasma perturbations observed by ARTEMIS near the Moon in the terrestrial magnetotail, Adv. Space Res., submitted

McLain, M. J. Loeffler, Casey Honniball, W. M. Farrell, J. W. Keller, and R. Hudson. Hydroxylation of Apollo 17 Soil Sample 78421 by Solar Wind Protons. JGR Planets. submitted.
Nénon, Q. and A. R. Poppe, On the long-term weathering of airless body surfaces by the heavy minor ions of the solar wind: inputs from ion observations and SRIM simulations, Plan. Sci. J., 1 #3, 2020. 10.3847/PSJ/abbe0c

Nénon, Q, et al., Implantation of Martian atmospheric ions within the near-side regolith of Phobos, *Nature Geosci.*, in review.

Prem, P., Hurley, D. M., Goldstein, D. B., and Varghese P. L. (2020). The evolution of a spacecraft-generated lunar exosphere, *JGR: Planets*, 125, e2020JE006464. https://doi.org/10.1029/2020JE006464

Rahmanifard, F., W. C. de Wet, N. A. Schwadron, M. J. Owens, A. P. Jordan, J. K. Wilson, C. J. Joyce, H. E. Spence, C. W. Smith, and L. W. Townsend (2020), Galactic cosmic radiation in the interplanetary space through a modern secular minimum, *Space Weather, 18*, e2019SW002428, doi:10.1029/2019SW002428

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Rhodes, D. J., W. M. Farrell, and J. L. McLain, Tribocharging and electrical grounding of a drill in shadowed regions of the Moon, *Adv. Space Res.*, 66, 753-759, 2020c. 10.1016/j.asr.2020.05.005

Sarantos, M. and S. Tsavachilidas, The boundary of alkali surface boundary exospheres of Mercury and the Moon. *Geophys. Res. Lett.* 47, doi: 10.1029/2020GL088930

Tucker, O. J., Killen, R. M., Johnson, R. E., and Saxena P. (2021). Lifetime of a transient atmosphere produced by lunar volcanism. *Icarus*, in press. http://arxiv.org/abs/2011.14545

Tucker, O. J., Farrell, W. M., and Poppe, A. R. (2021). On the Effect of Magnetospheric Shielding on the Lunar Hydrogen Cycle. *JGR: Planets*, in press. https://arxiv.org/abs/2012.04100

Wilson, J. K., H. E. Spence, N. A. Schwadron, A. W. Case, M. D. Looper, A. P. Jordan, W. de Wet, and J. Kasper (2020), Precise detections of solar particle events and a new view of the Moon, *Geophysical Research Letters, 47*, e2019GL085522, doi:10.1029/2019GL085522

2. Inter-team/International Collaborations

2.1. Inter-team Collaborations

LEADER team members are in continual contact and collaboration with other SSERVI teams, science mission teams, and Exploration architecture teams. Examples of LEADER interactions with other SSERVI teams include:

REVEALS: LEADER's Farrell is part of the REVEALS Science Advisory Board and the team works together on modeling and lab efforts regarding solar wind implantation and surface hydroxylation at the Moon and other airless bodies. The two teams share **NASA Post-doc Micah Schaible, funded via SSERVI-Central NPP award** to perform lab work on the biochemistry and electrical passivity of irradiated surfaces.

NESS: LEADER and NESS share collaborators in understanding and assessing the space environmental effects on a sophisticated and sensitive radio astronomy system. We currently supported NESS colleagues on assessing the lunar dust and electrostatic environment, and how to better-ground the radio system.

TREX: LEADER team members Hurley and Farrell are working with TREX lead Hendrix on the UV signature of surface water at the Moon. REVEALS team members are also involved. O.J Tucker has been collaborating with Lynnae Quick of SSERVI's TREX team, considering the conditions of the lava outcrops leading to an early Moon atmosphere.

RISE2: LEADER team members are collaborators on irradiated grain reactive chemistry that feeds into Rise4's grain cell survivability work.

IMPACT: LEADER maintains strong cross-team collaboration including post-doc opportunities for students, like A. Poppe who did his thesis work under CCLDAS and is now a key LEADER team member. LEADER modelers (Poppe, Zimmerman) are working with IMPACT team members (Daca, Wang) on magnetic anomaly and grain-grain surface charging studies.

2.2. International Partners

Sweden: LEADER team members continue close interactions with investigators at the Swedish Institute of Space Physics in Kiruna Sweden. LEADER Collaborator Shahab Fatemi relocated from UCB to Kiruna and is working closely with LEADER's NPP Anthony Rasca in modeling the plasma flow about the Moon in the geomagnetic tail.

3. Public Engagement

The LEADER team responded to this year's changing constraints by focusing on digital public engagement efforts. Team members visited virtual classrooms and lecture halls, contributed to social media posts and articles sharing their work, joined large-scale online STEM engagement events, and more.

3.1. Support for Digital Events

LEADER team members took active roles in online community events in 2020. Tucker participated in #BlackInGeoScienceWeek on Twitter, contributing to a Q&A session as well as a panel discussion entitled "Making an Impact in Planetary Science." Prem served as a mentor-judge at the SACNAS (Society for Advancement of Chicanos/Hispanics and Native Americans in Science) Conference, meeting one-on-one with students to discuss their research and career goals. Misra reviewed virtual posters and oral talks as a judge for the Outstanding Student Paper award at the AGU 2002 Fall Meeting. LEADER also supported International Observe the Moon Night, an annual, worldwide public engagement initiative which was estimated to have reached an unprecedented 500,000 participants this year. Barry began serving on this event's coordinating committee in April 2020 and answered questions from the public as part of the #ObserveTheMoon #AskNASA session during the event itself.

Additional LEADER team contributions to virtual events included Nenon's recorded talk about the Martian atmosphere's leakage to Phobos for AGU's Science Theater (available for public viewing at https://bit.ly/37XtM2E), Tucker's leadership of Moon and Mercury session planning for the Division of Planetary Science (DPS) Meeting, and Tucker's presentations on the lifetime of the early Moon atmosphere at both the National Society of Black Physicists Meeting and the NASA Exploration Science Forum.

Figure 5: NASA social media post featuring P. Prem's research on lunar lander exhaust. (Captured Dec 29, 2020.)

3.2. Online Content Creation

Recent research led by Rahmanifard and Prem caught the attention of science writers who, with Rahmanifard and Prem's help, promoted their work to broad audiences. Rahmanifard's study examining the current solar cycle and its possible effects on cosmic radiation was featured in a Space Weather Archive article (https://bit.ly/3rFRCrF). Prem's simulation of lunar lander exhaust gases appeared in releases from JHU/APL and NASA (https://bit.ly/3pCXv79, https://go.nasa.gov/39UN1ex). Prem and Barry collaborated to compose a series of social media posts highlighting Prem's research for NASA's Moon and Artemis Twitter accounts (Figure 5).

3.3. Virtual Visits and Other Activities

Several classrooms received visits from LEADER scientists in 2020. Prem participated in the 'Skype a Scientist' program, connecting with AIM Academy in Pennsylvania, Pacific Crest Middle School in Oregon, and PS 199 Jesse Isidor Straus in New York City. Tucker joined classes at Boys of Latin Philadelphia Charter School to discuss water on the Moon. For other audiences, Halekas and Killen presented comprehensive lectures on plasmas and exospheres, respectively, to the Taiwan Mini-Moon Series (https://bit.ly/35kfjfg), Tucker gave an invited seminar for New York University Abu Dhabi's Space Weather Series, Barry shared information about LEADER's work as part of a presentation to the National Science Teaching Association's Aerospace Advisory Board, and Prem gave an interview in Malayalam with the Dubai-based radio station Hit 96.7 FM.

4. Student/Early Career Participation

Undergraduate Students

1. Michael Kistler: University of Iowa, Plasma Team, graduated, pursuing a career in education.
2. Lexi Leali: University of Iowa, Plasma Team.
3. Giovanni Bacon: Embry Riddle Aeronautical University intern at GSFC with Killen, Volatiles Team.
4. Irima Ajang: Howard University intern at GSFC with Killen, Volatiles Team. (pursuing a medical degree)
5. Elijah Catalan: Howard University Intern at GSFC with O. J. Tucker, Volatiles Team. Presently a PhD student in UCLA's Institute of Environment and Sustainability, has gotten into field and lab research.
6. Ajani Smith-Washington: Howard University intern at GSFC with Menelaos Sarantos and Rosemary Killen, Volatiles Team. Presently applying for graduate school.

Graduate Students

7. Jennifer Bates: University of Maryland, Working with Christine Hartzell on Dust.

Postdoctoral Fellows

8. Feng Chu: University of Iowa (now moved to Los Alamos National Lab), Plasma.
9. Xin Cao: University of Iowa, Plasma.
10. Dylan Carter: University of Maryland, Dust (has now secured a permanent position as a contractor for the Air Force at Edwards AFB near Rosamond, CA).
11. Quentin Nenon: University of California Berkeley, plasma (has an additional two years)
12. Parvathy Prem: JHU/APL (now in a permanent position at APL), Volatiles.

New Faculty Members

13. Fatemeh Rahmanifard: University of New Hampshire, Radiation.
14. Wouter de Wet: University of New Hampshire, Radiation.
15. Christine Hartzell: University of Maryland, Dust: obtained tenure.

5. Mission Involvement

5.1. PI, Co-I, and Guest Investigator roles

Shown below are LEADER team member roles on current and planned missions. (PSD= NASA's Planetary Science Division, HSD= NASA's Heliophysics Science Division, AES=NASA's Advanced Exploration Systems Division).

1. PSD/CLPS/Collier/Co-I and Instrument Lead LEXI
2. PSD/CLPS/Colaprete/PI of NIRVSS
3. PSD/CLPS/Hurley/Co-I on SEAL
4. PSD/CLPS/Prem/TM on SEAL
5. PSD/CLPS/Elphic/PI of NSS
6. PSD/CLPS/Stubbs/Co-I on MAG
7. PSD/CLPS/Bale*/PI on LuSEE
8. PSD/CLPS/Poppe/Co-I on LuSEE
9. PSD/CLPS/Halekas/Co-I on LuSEE
10. PSD/CLPS/MacDowall*/PI of ROLSES, Co-I on LuSEE
11. PSD/CLPS/Farrell/Co-I on ROLSES, PITMS, SEAL, MAG
12. PSD/Lunar Reconnaissance Orbiter/ Keller/Deputy Project Scientist
13. PSD/Lunar Reconnaissance Orbiter/Schwadron/CRaTER PI
14. PSD/Lunar Reconnaissance Orbiter/Spence/CRaTER Co-I and former PI
15. PSD/ Lunar Reconnaissance Orbiter/Jordan/CRaTER Co-I
16. PSD/ Lunar Reconnaissance Orbiter/Wilson/CRaTER Co-I
17. PSD/ Lunar Reconnaissance Orbiter/deWet/CRaTER Co-I
18. PSD/ Lunar Reconnaissance Orbiter/Rahmanifard/CRaTER Co-I
19. PSD/ Lunar Reconnaissance Orbiter/Stubbs/CRaTER Co-I
20. PSD/ Lunar Reconnaissance Orbiter/Stubbs/LAMP Co-I
21. PSD/Lunar Reconnaissance Orbiter/Hurley/LAMP Co-I
22. PSD/Lunar Reconnaissance Orbiter/Stubbs/Participating Scientist
23. PSD/Lunar Reconnaissance Orbiter/Prem/MiniRF/TM
24. PSD/LADEE/Elphic/Project Scientist
25. PSD/LADEE/Delory/Deputy Project Scientist
26. PSD/LADEE/Colaprete/UVS PI
27. PSD/LADEE/Hodges/NMS Co-I
28. PSD/LADEE/Stubbs/Guest Investigator
29. PSD/LADEE/Glenar/Guest Investigator (named on the Stubbs GI proposal)
30. PSD/LADEE/Hurley/Guest Investigator
31. PSD/LADEE/Halekas/Guest Investigator
32. PSD/LADEE//Poppe/Guest Investigator (named on Halekas GI proposal)
33. PSD/LADEE/Sarantos/Guest Investigator
34. PSD/OSIRIS REx/Marshall/Co-I and former lead of Regolith Working Group
35. PSD/OSIRIS REx/Lim*/Co-I
36. PSD/OSIRIS REx/Hartzell*/Participating Scientist
37. PSD/Phoenix/Marshall/MECA Co-I
38. PSD/MAVEN/Halekas/Co-I and lead build of ion spectrometer
39. PSD/MESSENGER/Killen/Co-I
40. PSD/Curiosity/L. Bleacher/Communications
41. PSD/Cassini/Farrell/RPWS/Co-I
42. PSD/Janus/Hartzell/Mission Scientist
43. AES/Lunar IceCube/Clark/Science PI
44. HSD/ARTEMIS/Halekas/Deputy PI

45. HSD/ARTEMIS/Delory/Co-I
46. HSD/ARTEMIS/Poppe/TM
47. HSD/WIND/Collier/Deputy PI
48. HSD/WIND/Farrell/WAVES and MFI Co-I
49. HSD/Parker Solar Probe/Farrell/Co-I
50. HSD/Parker Solar Probe/Schwadron/Co-I
51. HSD/IBEX/Schwadron/Co-I
52. HSD/Tracers/Halekas/Co-I and Instrument lead
53. HSD&ESA/Solar Orbiter/Collier/Co-I Heavy ion sensor (GSFC lead)
54. HSD&ESA/SMILE/Collier/Co-I
55. HSD/CuPID cubesat/Collier/Co-I and instrument lead
56. ESA/BepiColumbo/Killen/Co-I
57. DoD (Space Test Program)/FASTSAT/Collier/Co-I and instrument lead
58. DoD (Space Test Program)/USAF DSX/Farrell/Co-I and search coil build lead

5.2. Mission Consulting

5.2.1. xEVA team at JSC

- LEADER team member Farrell invited to present 'The Lunar Plasma Environment' in November 2019 at a Technical Interchange Meeting (TIM) team meeting.
- LEADER NPP Anthony Rasca presented at the EVA workshop in Feb 20.
- Leader team member Farrell invited to present 'Dynamic aspects to human system charging on the lunar surface' at Apr 20 xEVA team meeting.
- Leader team wrote section D.1.3.18 on lunar surface charging for xEVA document on the environment: EVA-CR-00077_EVA-EXP-0039 in Apr 20.
- Based on LEADER inputs, the xEVA team decided to examine dust tribocharging of human systems while roving. A document was created to perform triboelectric studies (the Electrostatic properties testing section in 'NASA Classifications and Standards for Testing with Dust').
- xEVA team members frequently contact LEADER team members to ask environmental questions about the Moon, including about magnetic fields, suit design, tribocharging, and the Gateway environment.

5.2.2. HLS team at MSFC (Rob Sugg's team)

- LEADER NPP Dov Rhodes worked with MSFC/HLS team member Emily Willis on getting NASCAP spacecraft charging software operating.
- LEADER team members worked with MSFC HLS team in a foundation document 'Lunar Plasma Environment for NASA Crewed Missions' including a description of LEADER model results of lunar surface charging.
- LEADER team members Tim Stubbs and Bill Farrell reviewed and updated the 'Design Specifications for the Natural Environment (DSNE)' document (SLS-SPEC-159-Cross-program DSNE-Revision H).

5.2.3. Gateway Exosphere Instruments

- Winter of 2019-2020, LEADER co-I Tim Stubbs led a response team to determine how the Gateway could be used as a platform to study the exosphere and dust environment. This was part of the Gateway Utilization: Request for Payload in response to a Jacob Bleacher request.
- GSFC's Mehdi Benna and LEADER's Farrell were part of Tim's team coming up with concepts and reviewing his material.

5.2.4. JSC Dust chamber studies

- JSC's Don Barker received funds to build a dust adhesion test chamber. He contacted IMPACT's Mihaly Hornayi and LEADER's Bill Farrell to consult on the architecture.

- Farrell frequently consults with Don on this and other topics.

5.3. <u>Mission Concepts</u>

1. PiPELiNE, a long-lived lunar polar rover, **PI Hurley**: This mission concept was submitted as a white paper to the Decadal Survey for Planetary Science and Astrobiology. On request from the Moon/Mercury panel on the Decadal Survey, Hurley presented to the panel the science motivation for the concept, which is based on results from LEADER (and DREAM2) research and the aggregation of understanding by many members of the lunar volatiles community.
2. Aeolus: A Mars wind observing mission, **PI Colaprete**.
3. The Lunar Dust Mitigation SDT, Chair, **Christine Hartzell**, is identifying and developing instruments for a future multi-user facility (analogous to the science facilities on the ISS) on the lunar surface to investigate dust-plasma interactions. The SDT is funded by BPS and STMD. Some of the instruments focus on detecting electrostatic lofting, detecting electrostatic levitation, and characterizing the near-surface plasma environment (via Langmuir probe). Other mitigation-focused payloads include a device to assess the dust clearing efficacy of mitigation techniques, including the KSC Electrostatic Dust Shields, as well as technologies to remove dust from surfaces via induced electrostatic lofting.
4. PRISM proposals are under development (**Tim Stubbs, Menelaos Sarantos, Bill Farrell**).
5. Continue the development of a combined ion and neutral atom spectrometer system to study the hydrogen albedo from the lunar surface arising from solar wind input and sensing the surface conversion to surface outflowing molecular hydrogen ions, energetic atomic H, and other trace H-bearing species (**Collier, McLain, Keller, Farrell**)

6. Awards

1. **Parvathy Prem** was honored at APL's Annual Diversity Recognition Luncheon for her role in organizing a screening of the documentary "Can We Talk?" (https://www.kendallmooredocfilms.com/can-we-talk) followed by a discussion with the filmmaker, Prof. Kendall Moore.
2. **Christine Hartzell** received the Planetary Science Division Early Career Award in March 2020.