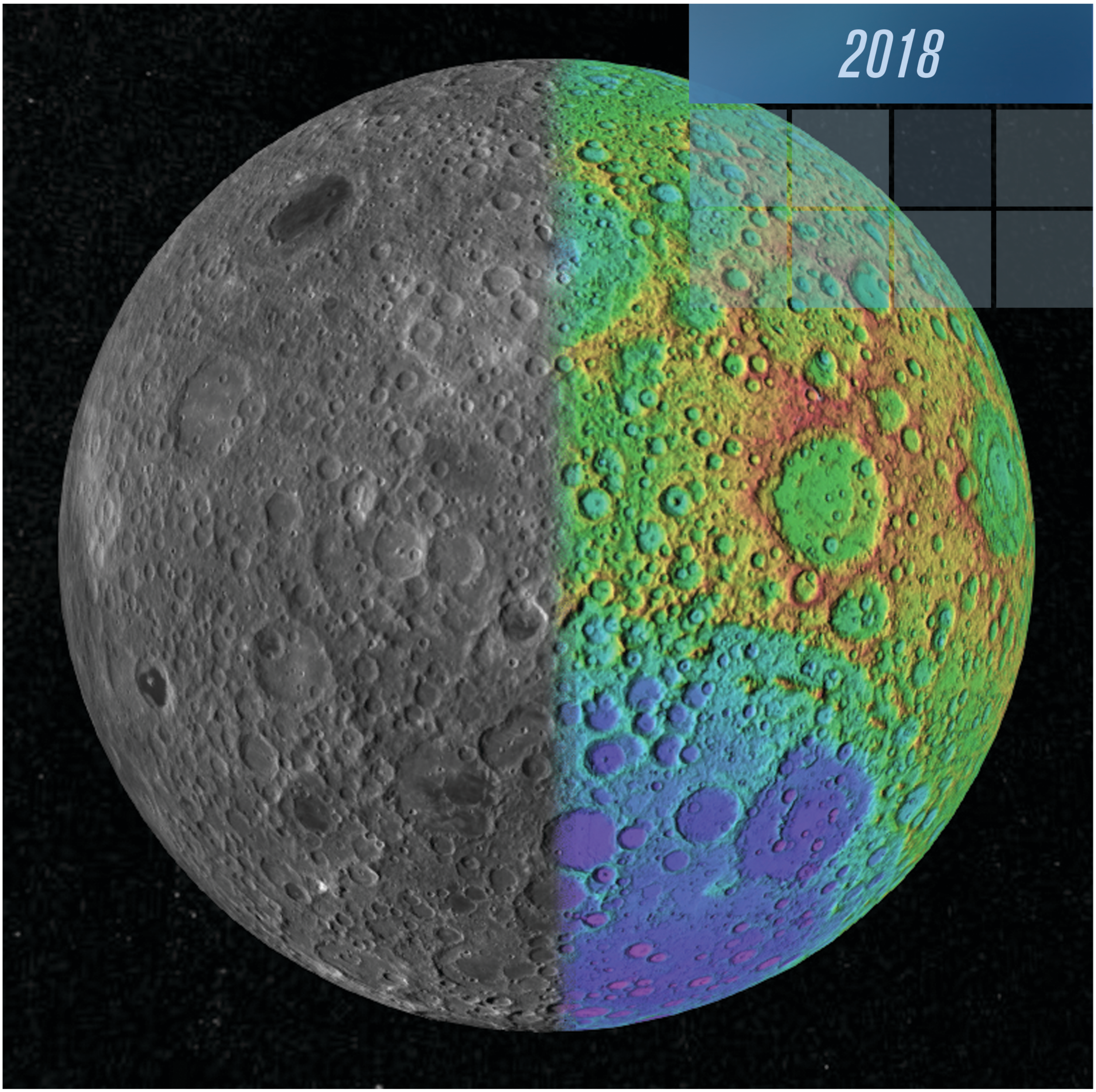
SSERVI ANNUAL REPORT

2018



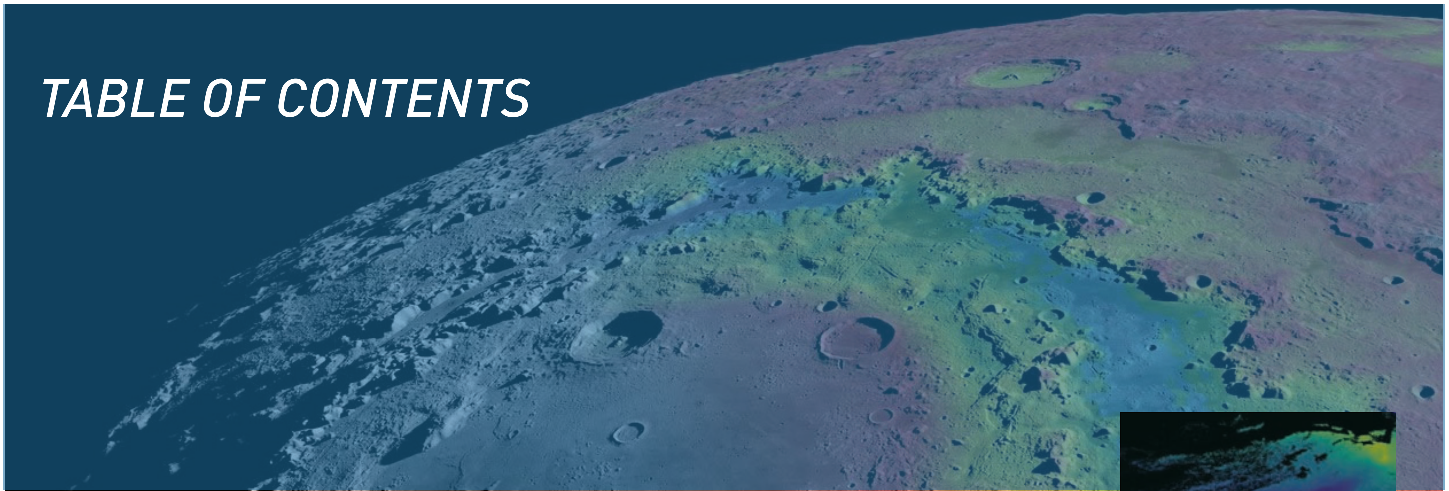
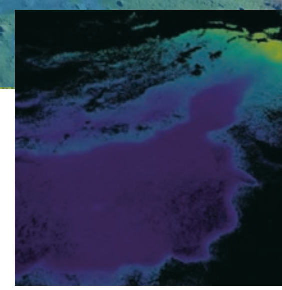
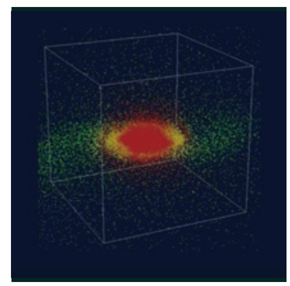
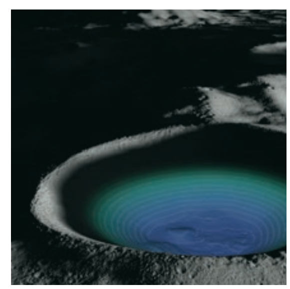
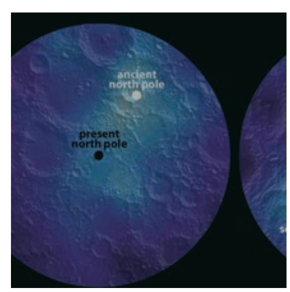


TABLE OF CONTENTS









FROM THE BRIDGE

We are delighted to present the NASA Solar System Exploration Research Virtual Institute (SSERVI) 2018 Annual Report. Each year brings its own new scientific discoveries and technological breakthroughs, and this year we're pleased to share some particularly exciting results. As the nation's premiere institute for Exploration Science, SSERVI continues to advance NASA's science and exploration goals, with field expeditions, laboratory experiments, instrument development, and theoretical models that probe our origins and evolution and provide important insights for NASA's human exploration enterprise.

In little more than a decade, our view of the Moon has been dramatically altered after a series of missions showed that the Moon is a host to valuable resources, such as water. This new view of the Moon has allowed us to ask fundamental questions and target specific sites for more detailed investigations. As our closest neighbor, the Moon's proximity to Earth makes it especially valuable as a proving ground for deeper space exploration. As we look back to the Apollo program with enormous gratitude for its historic and world-changing achievements, SSERVI is already contributing to NASA's next ambitious goal: to land the first woman and next man on the south pole of the Moon by 2024. We are doing this by both helping to resolve key science issues for a human return to the Moon, and pointing toward the next important scientific steps enabled by this ambitious program.

Reflecting on the past year's discoveries and advancements serves as a potent reminder that there is still a great deal to learn about NASA's human exploration destinations. SSERVI is working to close key knowledge gaps that will allow humans and robots to safely conduct lunar and interplanetary missions to establish a permanent, sustained human presence. SSERVI teams have conducted studies on rover tele-operation and conditions that affect rover trafficability, on cargo and crew lander dust-pluming effects, the interaction of robotic and human systems on the lunar environment (and vice versa), and on the geology of the south pole to identify an integrated set of science & exploration targets.

Adding to efforts already underway across the country, SSERVI teams are providing key technologies and advancing scientific payloads needed for the lunar surface. In 2018, SSERVI produced a white paper on "Transformative Lunar Science" at the request of the NASA Science Mission Directorate Associate Administrator, detailing key exciting lunar science efforts in the future. Field research in analog environments have demonstrated innovative new ways to access, sample, measure, visualize, and assess NASA's target destinations. SSERVI also supported the "Science of the Deep Space Gateway" workshop to consider how the Lunar Orbital Platform-Gateway in the Moon's orbit can facilitate new scientific discoveries in a breadth of fields. This workshop, with ~300 attendees, led to a better understanding of what resources would be required to conduct a variety of science investigations in cislunar space using the gateway. In partnership with the Lunar Exploration Analysis Group (LEAG), SSERVI held the "Lunar Science for Landed Missions" workshop, which produced a set of high-priority targets for near-term landed missions on the Moon, primarily, but not exclusively, from commercial exploration firms. This along with other efforts SSERVI is involved in or leading, will contribute to NASA's Commercial Lunar Payload Services (CLPS) program, an effort to land a wide variety of experiments on the Moon in the near term.

With the ramping up of NASA's human space exploration efforts, the agency is planning a major role for international partners in the renewed exploration of the Moon. SSERVI's International Partnerships Program provides collaboration opportunities for researchers around the globe within the planetary science and human exploration communities. Our network of 10 International teams leverage government, academia, and industry to advance science and engineering technologies on a no-exchange-of-funds basis. This year the 6th European Lunar Symposium in Toulouse, France (14-16 May, 2018) was held under the umbrella of SSERVI's European teams. This meeting brought together the European scientific community interested in various aspects of lunar exploration, along with lunar experts from countries engaged in launching lunar missions.

As the year 2018 closed, we celebrated the Apollo 8 anniversary--the first look back at our home planet from the vantage point of the Moon--with an eye toward the future. One of the most important elements of laying the foundation for this future is engaging and inspiring the next generation. In the report that follows you will find an overview of outreach activities, leadership activities of the SSERVI Central Office, reports prepared by the U.S. teams, and achievements from several of the SSERVI international partners. These are exciting times! Follow along by visiting our website, sservi.nasa.gov, and by subscribing to our Twitter feed and other social media sites. 2019 is going to be a wild ride; fasten your seatbelts!

On a personal note, I was deeply honored to assume the helm at SSERVI in 2018, clearly standing on the shoulders of the great achievements of my predecessors Dr. Yvonne Pendleton and Dr. David Morrison. I will be forever grateful to each of them for all they did to move the institute forward--in particular to David for his founding of NLSI, and to Yvonne for her capable transitioning of NLSI to SSERVI. I look forward to working with each of you in the coming years to continue the high quality science and technology that's such a hallmark of this institute, and to increase SSERVI's impact in the science and exploration communities. I also look forward to increasing our efforts to bring more women and underrepresented groups into our field; in so doing, we will not only be doing the right thing but we will improve our efforts through the inclusion of diverse views and approaches.

To the Moon and beyond!

Greg

Greg Schmidt

SSERVI Director

SSERVI.NASA.GOV

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THE SSERVI CENTRAL OFFICE

Recognizing that science and human exploration are mutually enabling, NASA created the Solar System Exploration Research Virtual Institute (SSERVI) to address basic and applied scientific questions fundamental to understanding the Moon, Near Earth Asteroids, the Martian moons Phobos and Deimos, and the near-space environments of these target bodies.

Overview

The integration of basic research and development with industry and academic partnerships, plus leveraging rapidly evolving technologies, has opened a scientific window into human exploration. SSERVI sponsorship by the NASA Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) continues to enable the exchange of insights between the human exploration and space science communities, paving a clearer path for future space exploration.

SSERVI provides a unique environment for scientists and engineers to interact within multidisciplinary research teams regardless of their physical location. As a virtual institute, the best teaming arrangements can be made irrespective of the geographical location of individuals or laboratory facilities. The interdisciplinary science that ensues from virtual and in-person interactions, both within the teams and across team lines, provides answers to questions that many times cannot be foreseen. Much of this research would not be accomplished except for the catalyzing, collaborative environment enabled by SSERVI.

SSERVI consists of 13 U.S. teams and 10 international partnerships. SSERVI's domestic teams compete for five-year funding opportunities through proposals to a Cooperative Agreement Notice (CAN) released by NASA every few years. Having overlapping CANs allows SSERVI to be more responsive to any change in direction NASA might experience, while providing operational continuity for the institute. Allowing new teams to blend with the more seasoned teams preserves corporate knowledge and expands the realm of collaborative possibilities.

Understanding that human and robotic exploration is an international endeavor, SSERVI is pleased to have a thriving community of ten international partnerships. International partners collaborate with SSERVI domestic teams on a no-exchange of funds basis, but interact in a number of ways, including sharing students, scientific insights, and access to facilities.

The SSERVI Central Office, located at NASA Ames Research Center in Silicon Valley, CA, provides the leadership, guidance and technical support that steers the virtual institute. The Central Office forms the organizational, administrative and collaborative hub for the domestic and international teams, and is responsible for advocacy and ensuring the long-term health and relevance of the Institute. SSERVI has increased the cross-talk between NASA's space and human exploration programs, which is one of our primary goals. A key component of SSERVI's mission is to grow and maintain an integrated research community focused on questions related to the Moon, Near-Earth asteroids, and the moons of Mars. The team and international partnership reports contain summaries of 2018 research accomplishments. Here we present the 2018 accomplishments by the SSERVI Central Office.

Supporting Our Teams

The SSERVI Central Office supports our teams and their research goals in a number of important ways. First, we ensure the timely distribution of their funds, for both NASA led and non-NASA led teams. This includes augmentations to their agreements for new tasks. Second, SSERVI Central provides virtual environments for a wide range of activities, from the monthly executive committee to the support of on-line classes conducted and organized by SSERVI teams. Third, SSERVI Central provides an important interface to NASA HQ for establishing new strategic directions and providing input to NASA. This is applicable to both human exploration and planetary science. The general structure of the institute provides long-term, stable research environments, with the flexibility to allow new research directions as directed by both NASA HQ and SSERVI Central.

The SSERVI Central Office is responsible for advocacy of the Institute and ensuring the long-term health and relevance of the Institute. This takes many forms, including: solicitation of new teams, community development, representation at major conferences, reporting to NASA Headquarters (and beyond), public engagement, and providing the technical competence required to connect all of the represented teams, communities and agencies.

Cooperative Agreement Notice (CAN-3)

As the SSERVI CAN-1 teams came to the end of their 5-year cooperative agreements, SSERVI released a call for new teams with proposals that were due in December 2018. Proposals to be an institute team must clearly articulate a broad, innovative research program addressing basic and/or applied research fundamental to understanding the nature of the Moon, Near Earth Asteroids (NEAs), the martian moons Phobos and Deimos, and the near space environments of these bodies, to enable eventual human exploration of these destinations. Approximately 25 step-1 proposals were submitted and new teams are expected to be selected in mid 2019.

Integrating SSERVI Science within NASA

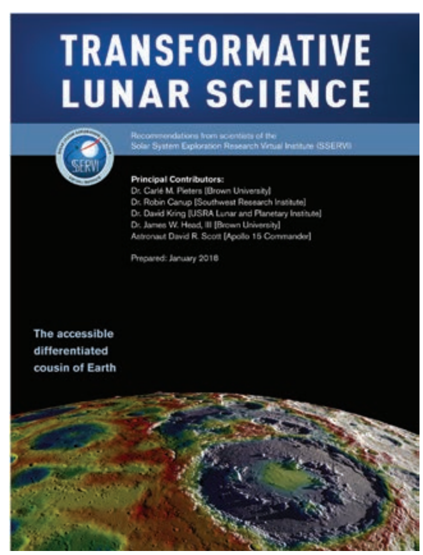
The SSERVI Central Office regularly reports team accomplishments to both SMD and HEOMD at NASA Headquarters (HQ), and also provides visibility of team progress through the SSERVI Headquarters seminar series. Periodically, a team Principal Investigator (PI), or representative, is identified by the SSERVI senior leadership to present a seminar at NASA Headquarters based on strategic assessments of topics most relevant to HQ, including a Transformative Lunar Science Lecture.

Transformative Lunar Science

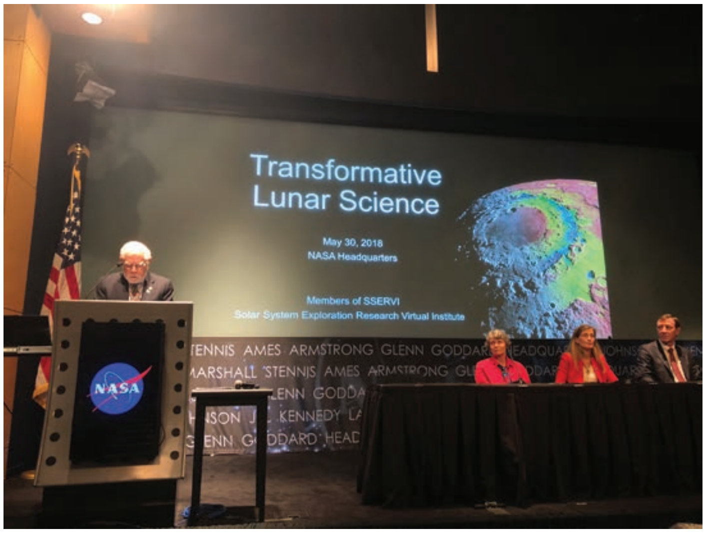
In late 2017, SSERVI was requested by the SMD Associate Administrator to produce a white paper on key areas of lunar science in the new era of lunar exploration. Senior lunar scientist and SSERVI PI Dr. Carle Pieters (Brown University) led the writing team with experience over a wide range of lunar science dating back to the Apollo era. The team included Dr. James W. Head III (Brown University), an Apollo-era lunar scientist, Dr. Robin Canup (Southwest Research Institute), a National Academy member, Dr. David Kring (USRA Lunar and Planetary Institute), another SSERVI PI, and Apollo 15 astronaut Dave Scott. The white paper, released in January 2018, provides a response to the question “What transformative lunar science issues can be addressed in the currently evolving space science era?” It explicitly addressed human exploration relevance in areas such as:

- Understanding water cycles
- Characterizing the lunar interior, and Evaluating plasma interactions with surfaces
- Using accessible vantage from lunar far side to view the universe
- Providing an absolute chronology for Solar System events, and establishing the period of giant planet migration

Additional focus was given to sustaining global leadership in lunar exploration, establishing lunar exploration infrastructure, coordinating planning & implementation of human/robotic partnerships, and optimizing commercial involvement. Dr. James Green, NASA Chief Scientist, used the report when asked to present Transformative Lunar Science concepts to Congress in Q2 2019.



On May 30, 2018, NASA held the “Transformative Lunar Science” talks in the James Webb auditorium at NASA Headquarters. Hosted by Dr. James Green, the talks discussed cutting-edge science that is transforming



our understanding of the Moon, and what we can still learn from our nearest neighbor.

Three of the team who wrote the “Transformative Lunar Science” paper presented short talks on some of the outstanding questions that scientific investigations of the Moon can answer, followed by a Q&A and panel discussion on the future of lunar science and exploration. Dr. Carlé M. Pieters spoke about the lunar water cycle; Dr. Robin Canup, talked about the origin of the Earth-Moon system; and Dr. David Kring, spoke about how the Moon can reveal the chronology of the Solar System. A question and answer session was moderated by Dr. James W. Head III. The talks included a panel discussion with Mr. David Schurr, Deputy Director of NASA’s Planetary Science Division, and Dr. Jason Crusan, Director of the Advanced Exploration Systems Division.

For more information, read the full Transformative Lunar Science white paper: https://sservi.nasa.gov/wp-content/uploads/2018/05/TLS_whitepaper_5-31.pdf

Seminar Series

A SSERVI-sponsored Graduate Seminar on “The Origin and Evolution of the Moon” was offered for the 2018 fall term at Brown University (September – December). The goal of the course was to investigate major outstanding questions and identify science/exploration goals related to robotic and human exploration of the Earth’s Moon.

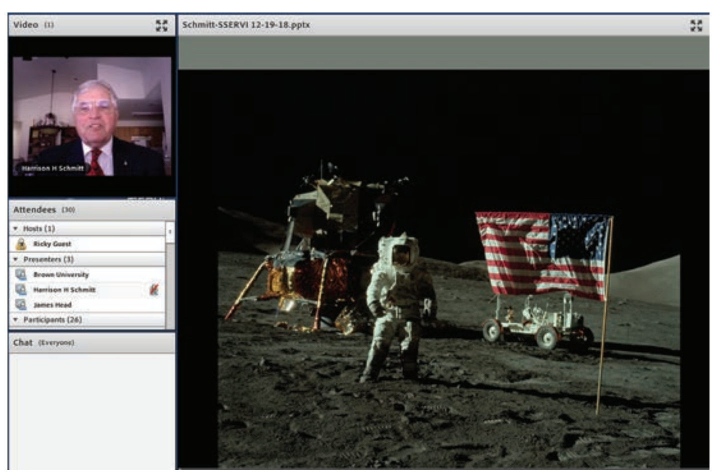
The seminars were jointly organized and led by the SSERVI Evolution and Environment of Exploration Destinations (SEEED) team and the Lunar and Planetary Institute

Jim Bridenstine, NASA Administrator, gave a lecture as part of “The Origin and Evolution of the Moon” Seminar Series on November 7th, 2018. In attendance (from Left to Right): SSERVI Director Greg Schmidt, NASA Administrator Jim Bridenstine, NASA Program Scientists Sarah Noble, and NASA Chief Scientist Jim Green.

Center for Lunar Science and Exploration (CLSE) team, with many SSERVI-affiliated institutions participating. 14 weekly sessions featured lectures given by leaders in the field. The format also provided an opportunity for questions and discussion. The SSERVI Central office broadcast the lectures and subsequent discussion to the entire Solar System community, and made them available in a recorded format for future use. As with other SSERVI-sponsored events, all the recordings are available on the SSERVI website:

https://sservi.nasa.gov/event/the-origin-and-evolution-of-the-moon-introduction/

SSERVI Central also supported the CLASS Asteroid Sample Return Seminar Series and CLASS Florida Space Institute (FSI) Seminar Series. Throughout the spring 2018 academic semester, CLASS, in partnership with



Apollo 17 astronaut Harrison “Jack” Schmitt gave the closing talk of the series, shown here in the on-demand video recording playback feature.

the FSI, held 13 Asteroid Sample Return Seminars and 4 seminars for the remaining CLASS/FSI speaker series. The series was open to UCF researchers, administrators, and students, NASA-KSC personnel, FSI member institutions and FSI employees. Seminars lasted 50 minutes with 30 minutes for discussion.

Community Building

SSERVI has a broader responsibility to support and grow the community even beyond its direct support of its own team members and partners. The wider community brought together through virtual and in-person events sponsored by the SSERVI Central Office and its teams includes scientists and engineers who focus on the Moon and other airless bodies. Recognizing that space exploration is a global enterprise, the SSERVI Central Office also focuses on the development and maintenance of its international partnership programs. The SSERVI domestic teams have significant collaborations with our international partners. For more information on our global endeavors, see the Summary of International Activities section of this report.

Some of the measures SSERVI takes to build and support the wider community include supporting focus groups, sponsoring the annual NASA Exploration Science Forum and smaller workshops, hosting community-wide virtual events, developing websites and opening SSERVI-developed research facilities to the community.

NASA Exploration Science Forum

The SSERVI Central Office organizes and sponsors the annual NASA Exploration Science Forum (NESF), which brings together several hundred researchers to discuss topics ranging from modeling to mission science. The NESF is a forum where new ideas and innovation are fostered through networking between basic and applied researchers. To date, the NESF is the largest conference dedicated to promoting the intersection of science and exploration. The format of the NESF is flexible with special sessions, talks, panels, exhibitions, and discussions that reflect the direction of the Agency and the community.

The 2018 NESF featured 55 scientific discussions about exploration targets of interest such as the Moon, near-Earth asteroids and the moons of Mars. Dedicated side conferences for students and young professionals, focus groups, and public engagement discussions, were interwoven among science topics. This year's forum included a special recorded introductory address by NASA Administrator Jim Bridenstine to welcome attendees and discuss the importance of SSERVI's work. In addition, a closing talk was given by Steve Clarke, the

Apollo 17 astronaut Harrison "Jack" Schmitt addresses recommendations for Transformative Lunar Science.

The fifth annual NASA Exploration Science Forum (NESF), held June 26-28, 2018 at NASA Ames Research Center, Moffett Field, CA, featured scientific discussions regarding human exploration targets of interest (the Moon, near-Earth asteroids, and the moons of Mars). Science sessions reported on recent mission results and in-depth analyses of new data. Dedicated parallel conferences for graduate students and young professionals coincided with the NESF

Deputy Associate Administrator for Exploration in NASA's Science Mission Directorate, who serves as the agency's interface between the NASA mission directorates, the scientific community, and other external stakeholders in developing a strategy to enable an integrated approach for robotic and human exploration within NASA's Exploration Campaign. The Forum also showcased a keynote talk by Apollo 17 astronaut Harrison "Jack" Schmitt, real-time updates from our Japanese colleagues as the Hayabusa2 spacecraft arrived at its target asteroid, Bennu, and a free movie night featuring the film "*Chesley Bonestell: a Brush with the Future*.

The SSERVI Central Office technology team seamlessly integrates virtual presenters and online attendees. The 2018 NESF was attended by 181 people (in-person) and had strong virtual participation (518 live-stream views and 2,106 on-demand views). These virtual metrics were the highest ever recorded for SSERVI, and represent strong global participation by the science and exploration communities. The recorded talks are archived for viewing at: nesf2018.arc.nasa.gov/program.

NASA Exploration Science Forum Awards

At the NESF, SSERVI presents awards as a means of honoring key individuals in the community: The Eugene Shoemaker Medal for lifetime scientific achievement, the Michael J. Wargo Award for outstanding achievement in Exploration Science, the Susan Mahan Niebur award for early career achievement, and the Angioletta Coradini Mid-Career Award.

The SSERVI awards are open to the entire research community and are presented with invited talks at the NESF. Nominations are welcome at any time at: [https://lunarscience.arc.nasa.gov/awards/submit] but must be submitted in early March for consideration in that calendar year. Recipients need not reside in the U.S. nor be a U.S. citizen. Winners are formally presented with the awards at the annual NASA Exploration Science Forum each summer. More information on these awards and all recipients can be found at: http://sservi.nasa.gov/awards.

Eugene Shoemaker Medal

SSERVI's 2018 Eugene Shoemaker Distinguished Scientist Medal, named after American geologist and one of the founders of planetary science, Eugene Shoemaker (1928-1997), was awarded to Dr. M. Darby Dyar of the Planetary Science Institute and Mt. Holyoke College for her significant scientific contributions throughout the course of her career. The award includes a certificate and medal with the Shakespearian quote "And he will make the face of heaven so fine, that all the world will be in love with night."

Dr. Dyar has had a distinguished career spanning more than 30 years in which she authored 242 peer reviewed publications. Darby's areas of expertise include optical mineralogy, crystal chemistry, and the perfection of numerous spectroscopic techniques. In recent years she has also revolutionized the use of machine learning techniques in the analysis and interpretation of X-ray absorption spectra. The careful laboratory work and model development that she has conducted throughout her career have enabled the development of countless other papers that have utilized the data generated by her efforts. In the opinion of many, her work will prove to be substantially more important than any single mission. Our understanding of planetary processes and the interpretation of various mission data have been made far richer through the tireless work of Dr. Dyar over the past 3 decades.

Michael J. Wargo Award

The Michael J. Wargo Exploration Science Award is an annual SSERVI award given to a scientist or engineer

Former SSERVI Director, Yvonne Pendleton, Shoemaker Award winner Darby Dyar, and SSERVI Director, Greg Schmidt at the NESF 2018 award presentation.

who has significantly contributed to the integration of exploration and planetary science throughout his or her career. Dr. Michael Wargo (1951-2013) was Chief Exploration Scientist for NASA's Human Exploration and Operations Mission Directorate (HEOMD) and was a strong advocate for the integration of science, engineering and technology. The SSERVI 2018 Michael J. Wargo Exploration Science Award was given to Dr. David Kring at the Lunar and Planetary Institute in Houston, Texas.

Dr. Kring's research explores the origin of the solar nebula and its evolution into a geologically active planetary system; the geologic history of the Earth, Moon, Mars, and several smaller planetary bodies; impact cratering on the Earth, its effect on Earth's environment, and its possible role in the biological evolution of our planet; and the chemical and physical properties of meteorites. He is currently integrating his field experience in impact-cratered terrains with his analytical experience of Apollo, Luna, and lunar meteorite sample collections from the Moon to lead the development of spacecraft missions in response to the President's lunar exploration initiative.

Angioletta Coradini Mid-Career Award

The 2018 Angioletta Coradini Mid-Career Award is given annually to a mid-career scientist for broad, lasting accomplishments related to SSERVI fields of interest. Angioletta Coradini (1946-2011) was an Italian planetary scientist who has inspired astronomers around the world. The 2018 Angioletta Coradini Mid-Career Award was given to Dr. Barbara Cohen at NASA Goddard Space Flight

Former SSERVI Director, Yvonne Pendleton, Wargo Award winner David Kring, and SSERVI Director, Greg Schmidt at the NESF 2018 award presentation.

Former SSERVI Director, Yvonne Pendleton, Coradini Award winner Barbara Cohen, and SSERVI Director, Greg Schmidt at the NESF 2018 award presentation.

Center.

Dr. Cohen's main scientific interests are in geochronology and geochemistry of planetary samples from the Moon, Mars and asteroids. She is a Principal Investigator on multiple NASA research projects, a member of the Mars Exploration Rover mission team operating the Opportunity rover until it became nonoperational, and the principal investigator for Lunar Flashlight, a lunar cubesat mission that will be launched in 2018. She has participated in the Antarctic Search for Meteorites (ANSMET) over three seasons, where she helped recovered more than a thousand pristine samples for the US collection, and asteroid 6186 Barbcohen is named for her.

Susan Mahan Niebur Early Career Award

The 2018 Susan Mahan Niebur Early Career Award is an annual award given to an early career scientist who has made significant contributions to the science or exploration communities. Recipients of the Susan M. Niebur Early Career Award are researchers who are no more than ten years from receiving their PhD, who have shown excellence in their field and demonstrated meaningful contributions to the science or exploration communities. Susan Mahan Niebur (1978-2012) was a former Discovery Program Scientist at NASA who initiated the first NASA Early Career Fellowship and established the annual NASA Early Career Workshop to help new planetary scientists break into the field. This year the prize

Former SSERVI Director, Yvonne Pendleton, Niebur Award winner Rachel Klima, and SSERVI Director, Greg Schmidt at the NESF 2018 award presentation.

was presented to Dr. Rachel Klima at the Johns Hopkins University Applied Physics Laboratory.

Dr. Klima is one of the premiere airless body spectroscopists of her generation, with published papers about the Moon, Mercury, Vesta, and other asteroids. Her general expertise in spectroscopy and lunar data has led her to lead and participate in studies of other materials as well, most notably lunar water and hydroxyl. Outside of published papers, her knowledge has put her in great demand—she has been sought after to play important roles in proposed missions. Currently she serves as a member of the project science team for the Europa Clipper mission. She has won a Carl Sagan Early Career Fellowship from NASA, showing that her promise has been widely recognized.

Student Poster Competition and Lightning Round Talks

The annual student poster competition at the NESF provides motivation, encouragement, and recognition to young researchers. Students competing for the awards are encouraged to give a one-minute lightning talk during special sessions at the NESF to briefly summarize their research and poster. Their presentations and posters are evaluated by a committee of senior researchers. Selection criteria include the originality of the research, quality and clarity of the presentation (including accessibility to the non-expert), and impact to science and exploration.

The 2018 NASA Exploration Science Forum Student Poster Competition winners were:

1. First place was awarded to Macey Sandford for the poster “Standoff Time-Resolved Raman and Fluorescence Spectrometer for a Lunar Lander.”
2. Second place was awarded to Zach Ulibarri for the poster “On the generation and detectability of organic chemistry in hypervelocity impact ice spectra.”
3. Third place was awarded to Marina Gemma for the poster “Visible-Near-Infrared Reflectance Spectroscopy of Ordinary Chondrite Meteorites Under Simulated Asteroid Surface Conditions.”
4. Honorable mention was awarded to Mount Horeb High School for the poster “Volcanic Contribution of Water at Lunar Silicic Domes.”

Lunar Grad Conference

The Lunar Grad Conference or LunGradCon is held each year adjacent to the NASA Exploration Science Forum and provides opportunities for networking with fellow grad students and postdocs, as well as senior members of SSERVI. The conference is completely organized and run by graduate students, and the talks are presented to their peers. It is an excellent opportunity to get feedback on their presentation style and content in a supportive environment. More information can be found at: lunarscience.arc.nasa.gov/articles/lungradcon.

Former SSERVI Director, Yvonne Pendleton, and SSERVI Deputy Director, Brad Bailey with several student poster winners at the 2018 NESF award presentation.

Focus Groups

SSERVI's Focus Groups are open to the entire community. Each addresses a topical area of particular community interest and are a way of sharing and coordinating research objectives in the broad community. Focus Groups provide venues for developing research areas across the broad exploration science community, stimulating new areas of research, promoting long-distance collaborations, and contributing to space mission concepts and instrumentation. SSERVI supports Focus Groups in several ways, including hosting online meetings, workshops, field trips, and/or other activities that support the Group's objectives. Since 2009, SSERVI has coordinated and supported 9 focus groups, yielding a multitude of white papers as well as specific studies and reports that have been helpful in informing NASA on key strategic objectives and establishing new directions.

Other Key Workshops and Conferences

SSERVI senior leadership and other central office staff members host and/or attend sessions at many of the top scientific meetings (e.g. COSPAR, LPSC, AAS, AGU, LEAG, JpGU, EPSC, etc.) in support of the science and exploration communities, providing public lectures, video and hyperwall talks, exhibits, as well as 3D and augmented reality/virtual reality (AR/VR) demonstrations. The international section of this report covers details for SSERVI's key International meetings.

Lunar Science for Landed Mission Workshop

SSERVI and the Lunar Exploration Analysis Group (LEAG) jointly hosted the "Lunar Science for Landed Missions Workshop," January 10-12, 2018, at NASA Ames Research Center. This workshop produced a set of priority targets for near-term landed missions on the Moon, primarily from commercial lunar exploration firms. Abstracts were solicited describing target areas on the Moon for near-term in-situ science, network science, and sample return missions. This workshop stimulated discussion about specific targets, and resulted in a report presented to NASA Headquarters as an initial community consensus of priority landed targets, with the potential of future solicitations for science-focused payloads at targeted sites. This workshop also resulted in a peer-reviewed publication in *Earth and Space Science* and is playing a key role in the future landing site selection for upcoming commercial landers. Read the full report at: https://lunar-landing.arc.nasa.gov/downloads/LunarLandedScience_Publication.pdf

Virtual technology tools enhance communication and eliminate geographical constraints, enabling selection of the best investigations, teams and resources to address NASA's current goals, regardless of where team members or infrastructure reside. By sharing students, facilities and resources, and by reducing travel, the virtual institute model reduces cost and can provide substantial savings to the Federal government.

Lunar Polar Volatiles Meeting

Understanding the importance that lunar polar volatiles will play in future human exploration of the Moon, SSERVI's DREAM2 team (PI Farrell) and VORTICES team (PI Rivkin) organized a special Lunar Polar Volatiles meeting with the Lunar Reconnaissance Orbiter (LRO) team August 7–9, 2018 at Johns Hopkins University, Applied Physics Laboratory, in Maryland. Experts in the areas of data analysis, modeling, instrumentation, and laboratory research from SSERVI and LRO came together with experts outside these communities to discuss the state of knowledge on volatiles in the lunar polar regions.

Carbon in the Solar System

SSERVI presented a series of community-wide virtual workshops on Carbon in the Solar System, led by Dr. Amanda Hendrix and Dr. Faith Vilas of the SSERVI TREX team. The first workshop was held on April 25-27, 2018.

Recent investigations within our Solar System, including the Pluto system, the Saturn system, Mercury, and nearly all points in between, made this the right time to hold a workshop to discuss and synthesize these results as we focus on the role of carbon in the Solar System. The workshop included invited and contributed talks on observational, lab and modeling work related to carbon and carbonaceous species on Solar System bodies. In addition to the scheduled talks, the workshop provided ample discussion time for the community to participate through the use of the Adobe Connect chat feature. This was the first of two SSERVI workshops on this topic. Subsequent in-person meetings responded to questions that arose during the virtual workshop, especially those that could elucidate research areas where collaborative efforts would enable further progress. Subsequent meetings took place at DPS and AGU meetings and were open to the entire research community.

Supporting the Next Generation

Developing the next generation of scientists and engineers to carry on the important work of bridging science and human exploration is a critical facet of SSERVI's work and has been supported strongly since the institute's inception in 2008. As we approach the 50th anniversary of the Apollo 11 landing, it is clear that bringing in a new, robust workforce will not only ensure a bright future for SSERVI but will also serve to preserve the knowledge gained by earlier generations. SSERVI has long been a strong supporter of activities which provide opportunities to graduate students, postdoctoral fellows and early-career scientists and engineers, ranging from providing student travel and important roles in workshops to establishing a graduate student conference (LunGradCon), direct funding of postdoctoral fellows and supporting university-led research.

In 2018, SSERVI co-hosted two major workshops for the community: Lunar Science for Landed Missions, and Survive and Operate through the Lunar Night Workshops. Each workshop came with the opportunity to work with the Next Gen Lunar Scientists and Engineers (NGLSE) group to identify some of the top young professionals in the field to lead the development of the final reports, present the workshop findings at major scientific and engineering conferences, and to be the interface between the community and the workshop stakeholders. In the case of the Lunar Science for Landed Missions report, the workshop resulted in a prominent peer-reviewed publication with the young professionals as first authors.

SSERVI supports several student travel awards that allow early career researchers an opportunity to experience other research laboratories, field campaigns, or to present their work at conferences. In 2018, SSERVI supported 3 students' travel to the annual Lunar Exploration & Analysis Group (LEAG) meeting through the B. Ray Hawke travel scholarship. SSERVI also awarded 4 $1,000 travel scholarships to the winners of the 2018 Exploration Science Forum Student Poster Competition and an international student to attend Lunar Grad Con, and supported early career travel to both the European Lunar Symposium and the Women in Planetary Science and Exploration Conference.

In 2018 SSERVI released a call for proposals by university student-led research teams to investigate augmented and virtual reality tools for integration of field data into science visualization tools and con-ops. Our end goal is to allow for ease of use of remote robotic handling as well as robotic/human interactions in a field campaign setting. This work is scheduled to begin at the end of CY19.

The 2018 Exploration Science Forum marked the 8th year of hosting the LunGradCon, a conference planned, organized, and completed by and for graduate students. More than 200 students have participated in the LunGradCon since its inception and this year ~28 students presented their research and discussed ideas for new lines of investigation, instrumentation, and mission concepts. Zachary Ulibarri from the IMPACT team led this year's effort.

NASA Postdoctoral Program (NPP)

To further enable cross-team interactions and support the next generation of researchers, the SSERVI Central Office established a NASA post-doctoral fellowship position to be shared between two or more teams. In 2018, the SSERVI Central Office posted the opportunity and received several applications for appointments in 2019. The SSERVI NPP fellows are expected to work within multiple disciplines on scientific topics that push the boundaries of what is currently known. SSERVI NPP fellowships are two-year awards with a potential third year based on performance. SSERVI currently has one NASA Postdoctoral Fellow, Dr. Micah Schiable, located at Georgia Tech as a part of the REVEALS team. Dr. Schiable is focused on the chemical effects caused by electrostatically charged regolith dust grains on lung tissue and function. This work specifically brings together expertise and research from the REVEALS, DREAM2, IMPACT, and RIS4E teams to further understand the reactivity and toxicity of charged regolith grains and the ultimate impact on human exploration activities.

Public Engagement

The SSERVI Central Office and SSERVI teams conduct extensive public engagement activities throughout the year. SSERVI reaches out to inspire tomorrow's explorers, to engage the general public and to include members of the public who are in underserved populations. The SSERVI Central Office activities for 2018 are discussed in this section, with the PI team reports listing individual team activities.

As NASA takes on the monumental challenges of going forward to the Moon and establishing a sustained human presence, looks forward to Mars, and carries out campaigns of exploration across the Solar System, SSERVI Central shares in NASA's appreciation for the essential role of inspiring the public and next generation of explorers, and in winning the hearts and minds of the public in conducting these campaigns. SSERVI Central's Public Outreach efforts can be divided into several areas.

Local Outreach – SSERVI Central staff regularly make presentations to schools, community organizations, etc. These presentations are intended to increase understanding of and appreciation for SSERVI, Ames and NASA as a valued resource within the very tough, competitive environment in Silicon Valley. Throughout the course of the year, these ranged from events as small as presentations in individual classrooms to being the agency's prime organizer of a NASA Night with over 10,000 guests.

SSERVI Research Team Support – SSERVI Central staff work to facilitate collaboration between teams

The Make-a-Wish Foundation grants life changing wishes for children with critical illnesses. 8-year-old Madison spent a day at NASA Ames learning about the different careers at NASA and creating artwork and inventions of her own. Astronaut Dr. Yvonne Cagle and SSERVI graphic designer Jennifer Baer showed Madison the rewarding work they do. Jennifer also read from her children's book, "Yes, I Work at NASA. No, I'm Not an Astronaut."

in outreach as well as in science. Central staff acts as liaison between SSERVI teams' outreach programs and SMD's STEM engagement SciAct Collective, making sure the efforts of our SSERVI teams are value-added to SciAct. We also provide resources including rocks, stickers, pins and printed materials to teams.

Ongoing Stakeholder Support – It is essential that SSERVI integrates with and brings critical extra value and expertise to stakeholder outreach programs. SSERVI's Solar System Treks Project (SSTP) continues to serve as designated infrastructure for SMD's SciAct Collective, producing and providing data visualizations for SciAct CAN awardees. SSERVI Central staff continue to conduct Apollo Lunar Sample and Meteorite certification workshops in partnership with the Astromaterials Research and Exploration Science Division headquartered at JSC, developing enhancements to the workshops and sharing these enhancements with other certifiers across the agency. This year, SSERVI SSTP conducted seminars supporting and augmenting a number of HQ engagement programs including NASA Solar System Ambassadors, NASA Museum Alliance, NASA Night Sky Network, and the NASA Community College Aerospace Scholars.

Brian Day discussing space exploration with students on a classroom visit during Journey Through the Universe.

Key Partnerships – SSERVI Central staff has identified existing highly-successful programs with which we can partner, benefitting from their penetration, reach, and contacts, and providing them with value that enhances their programs with end results of benefiting the broader community, extending the agency's reach, and enhancing the brand value of SSERVI. SSERVI maintains an ongoing collaboration with Gemini Observatory and their partnership with other observatories of Mauna Kea (including Subaru, Keck, Canada-France-Hawaii Telescope (CFHT), Thirty-Meter Telescope (TMT), and NASA Infrared Telescope Facility (IRTF) in their Journey Through the Universe Program. SSERVI Central also continued its ongoing relationship with the California Academy of Sciences, filling in for Apollo astronaut Rusty Schweickart at the academy's Dean Lecture this year, and collaborating in the production of a new planetarium show about lunar exploration and supporting the 50th anniversary of Apollo.

Special Opportunities – It is essential that SSERVI is responsive to "big ticket" events identified by HQ, providing unique resources and expertise available from SSERVI Central and its teams. In 2018, we exemplified this by playing a leading role in coordinating efforts with NASA's Planetary Missions Program Office, the InSIGHT mission, and Allan Hancock College for the public program for the Mars InSIGHT launch at Hancock's Santa Maria Campus near the Vandenberg AFB launch site. Approximately 5,000 people attended the event over the two days prior to launch. Six months later, SSERVI returned to Hancock to present to the public and the media at their InSIGHT landing public event.

General – In 2018, SSERVI Central continued to provide additional value across all of the above areas through development work on exhibits, providing materials (such as facilitating production of the Braille books and sharing 3D print files and prints of Tranquility Base), and developing online resources. One of our greatest successes was the development of touchable Moon and Mars rock exhibits using meteoritic lunar and Martian samples. These exhibits were exceptionally popular among many thousands of people at the InSight launch, NASA Night at a Fresno Grizzlies baseball game, Journey through the Universe, AGU, and more.

Journey Through the Universe

During the week of March 5-9, 2018, SSERVI Central Office staff brought their passion for science into local Hawai'i Island classrooms as a part of Gemini Observatory's flagship annual outreach program, Journey Through the Universe. Thanks to combined efforts, the Journey program was able to reach about 8,000 students in both the Hilo-Waiākea district and Honoka'a Schools, and several hundred more in various community events; of these, the SSERVI team alone talked with roughly 1,000 students.

NASA Lunar and Meteorite Sample Certification Workshop

Participants in the 2018 NASA Lunar and Meteorite Sample Certification Workshop pose with SSERVI instructors Joe Minafra and Brian Day at the SSERVI Central Office.

NASA directly benefits from Robotic Competitions. The innovative concepts students develop result in clever ideas and solutions which can be applied to actual excavation devices and payloads on ISRU missions.

Two SSERVI Central Office staff held a certification workshop that enables teachers to borrow lunar and meteorite samples from the historic Apollo missions and share them with their students. Teachers attending this workshop also learned how to use NASA online tools to explore and visualize the surfaces of the Moon, asteroids, and Mars as seen through the eyes of many different instruments aboard a great range of spacecrafts.

Robotics Competitions

The SSERVI Central Office participated with over 50 countries in RoboRAVE and RoboTex, which sponsor international robotics competitions for K-12 students and supports STEM, robotic exploration, and planetary science. SSERVI Central Office Staff participated in the Robotics Academy, part of RoboRAVE International, helping teachers integrate robotics into their curriculum.

NASA Centennial Challenges have been engaging the public in the process of advanced technology development since 2005. These exciting challenges have triggered an outpouring of creative solutions from academia, citizen inventors and small businesses for technologies such as lunar landers, space elevators, fuel-efficient aircraft and astronaut gloves. One of the Centennial Challenges, the Annual NASA Robotic Mining Competition (NASA RMC) was a spin-off established in 2010 as a way for university students to build a mining robot designed to navigate on the Lunar/Martian Surface. As a co-founding participant, SSERVI staff served as a Mining, Communications and Competition Timing Judge and consulted on the 9th Regolith Mechanics Award given to the team with the best innovation for solving a specific regolith mechanics problem (like the way soil flows around grousers, or identifying an angle of repose that is too high for a dump bucket, etc.).

SSERVI Central's Joe Minafra gave the Keynote address at RoboTex in Estonia.


Team Zopherus of Rogers, Arkansas, was the first-place winner in NASA's 3D-Printed Habitat Challenge, Phase 3: Level 1 competition.

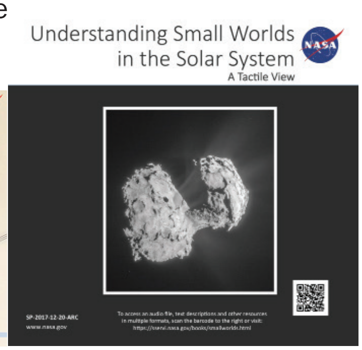
NASA's 3D-Printed Habitat Challenge, seeks to foster development of new technologies to additively manufacture a habitat using local indigenous materials with, or without, recyclable materials, in space and on Earth. The 3D-Printed Habitat Challenge, which began in 2014, is structured in phases: three construction levels and two virtual levels. In 2018, SSERVI participated in judging the Virtual Modeling Stage of NASA's 3D-Printed Habitat Competition. The construction levels challenge the teams to autonomously 3D-print elements of the habitat, culminating with a one-third-scale printed habitat for the final level to be completed in 2019 with a $2 million prize. SSERVI staff will serve as a Judge for all phases of this challenge.

Reaching Underserved Communities

SSERVI Central staff participate in workshops for the Minority University Research and Education Project (MUREP). Through MUREP, NASA provides financial assistance via competitive awards to Minority Serving Institutions, or MSIs, including Historically Black Colleges and Universities, Hispanic Serving Institutions, Asian American and Native American Pacific Islander Serving Institutions, Tribal Colleges and Universities, other minority-serving institutions, and eligible community colleges, as required by the MSI-focused Executive Orders. These institutions recruit and retain underrepresented and underserved students, including women and girls, and persons with disabilities, into STEM fields. In 2018, SSERVI supported NASA Ames MUREP workshops. SSERVI's Brian Day was an invited speaker and provided an overview of Solar System research and an introduction on how to use NASA Solar System Treks.

Books for the Blind

For over ten years, SSERVI has supported the development of books for the blind in partnership with the Director of NASA's Science Engagement and Partnerships Division within NASA's Science Mission Directorate. Several SSERVI teams were involved in developing specific content for this series of books for the blind. The first three books in the series were: 1. "*Getting a Feel for Lunar Craters*;" 2. "*Mars Exploration*"; 3. "*Getting a Feel for Solar Eclipses.*" 5000 copies of each book have been distributed to libraries across the country that support the blind community. A fourth book, "*Understanding Small Bodies in the Solar System, a Tactile View*" was published in 2018 as a follow-on book in the series. SSERVI also secured funding to produce



Sight Impaired students investigate SSERVI Braille books with Dr. Cass Runyan at special events around the country.

two additional books: 1) an updated version of "*Getting a Feel for Lunar Craters*" which includes Apollo Landing sites, and 2) "*Getting a Feel for Solar Eclipses: South America*" which is in production for the upcoming eclipses in 2019.

Journey Through the Universe

As part of our Journey Through the Universe program we visit and support presentations in Hawaiian homeland schools, providing valuable service to the underserved native Hawaiian population. With Journey's recent expansion into the Puna district, we have extended our outreach into the community that was devastated by the recent volcanic eruption.

Engaging the General Public

Citizen Science

SSERVI's Central Office provides a representative to the NASA Citizen Science Forum run by the Office of the Chief Scientist at NASA Headquarters. SSERVI's primary citizen science focus in 2018 was to promote the Fireballs in the Sky program of the Desert Fireball Network (DFN) run by SSERVI's Australian partner, Curtin University. Fireballs in the Sky engages citizen scientists through an app, allowing them to report bright meteors which are then

For decades, space exploration has brought excitement and inspiration to people of all ages. This is especially true now, with new opportunities for students and citizen scientists to directly participate in expanding our knowledge of the Solar System. Amateur astronomers and students with wide ranges of equipment and expertise are making valuable contributions to better understanding the Solar System. Learn how you can become part of the adventure: https://sservi.nasa.gov/citizen-science/

SSERVI's outreach exhibit table presented by Joe Minafra at the Annual Space Festival in Novato, CA, on August 5, 2018. Six astronauts and over 7000 attendees participated in the event.

put into the DFN database. SSERVI presented Fireballs in the Sky at a number of conferences, and showcased the program at the new citizen science office at NASA HQ. The institute also began discussions with its Canadian node (PI Gordon Ozinski), to investigate how Mars Trek could potentially reenable iMars to help citizen scientists interpret the Martian surface.

International Observe the Moon Night

SSERVI is a proud founding sponsor and organizer of a worldwide, public celebration of lunar science and exploration held annually since 2010. One day each year, everyone on Earth is invited to observe and learn about the Moon together, and to celebrate the cultural and personal connections we all have with Earth's nearest neighbor. Each year, thousands of people participate in InOMN at museums, planetaria, schools, universities, observatories, parks, businesses, and backyards around the world. The ninth annual International Observe the Moon Night was held on October 20, 2018. The Coordinating Committee is led by NASA's Lunar Reconnaissance Orbiter Education and Communications Team, with representatives from NASA's Solar System Exploration Research Virtual Institute, the Lunar and Planetary Institute, the Planetary Science Institute, the Astronomical Society of the Pacific, and CosmoQuest.

SSERVI Central conducts outreach activities in accordance with NASA PSD's directive to engage the public in NASA Science and Exploration. SSERVI representatives serve on the steering committee for International Observe the Moon Night, which helps to organize hundreds of events around the world. In 2018, SSERVI partnered with the Peninsula Astronomical Society to conduct a Bay Area event at Foothill College Observatory, gave a remote presentation at the SSERVI UK partner's event, and prepared graphic materials with a lunar map used at events around the world.

Virtual Events and Web

The SSERVI Central Office technology team has a wide array of communication and collaboration tools that have helped build and continue to strengthen SSERVI's teams and the broad community. Technologies including high-definition video-conferencing, real-time meeting and communication platforms, websites and web applications, online communities, social networks, shared databases, data visualization applications, and mobile devices are seamlessly integrated to produce virtual seminars and workshops, and to support numerous groups such as LEAG and SBAG. SSERVI is pleased to use its core skills to facilitate effective communication and to enable collaborative research and data sharing in support of not only its own teams and partners but the community as well. SSERVI is recognized for proficiency in this area, and our technology team is requested throughout the year to assist with non-SSERVI events for other parts of NASA and the broader community.

Information Technology and the digital delivery of content remains an increasingly significant component to not only the Virtual Institute model at the Agency but equally so to SSERVI's community. SSERVI continued in 2018 to make strides in effectively empowering and facilitating technology and modern tools to enable its teams and community members to easily access and share various types of content.

Event Production

In 2018, SSERVI Central's Technical Team led the production and delivery of over 400 presentations from 24 major workshops, conferences and seminar series, that were broadcasted live and made available for on-demand playback. This valuable service makes important information widely available to the community, with over 5,800 live-stream views and more than 8,400 views of recorded sessions. Of these events, 188 were in direct support of SSERVI's Domestic Teams while 226 supported SSERVI affiliated organizations both within and outside of NASA. SSERVI's annual Exploration Science Forum presentations saw a significant on-demand playback with 2106 views. Additionally, community members have expressed growing praise of SSERVI's content delivery and event production capabilities; all of the recordings are captioned for hearing impared viewers, and the ease and intuitive nature of online playback has greatly broadened the reach of these events.

Some of the top events included:

1. The 2018 NASA Exploration Science Forum, which produced 73 recorded presentations with 518 live views and 2106 on-demand playback views.

Behind the scene with SSERVI Central's Technical Team as Ricky Guest monitors a virtual event.

2. The Lunar Science for Landed Missions Workshop, with 28 presentations recorded over 3 days, 1199 live views, and 2508 views of the recorded content. The most popular session was the Commercial Landing Opportunities Panel which received 568 on-demand playback views.
3. SSERVI produced the live broadcast and streaming of the 18th and 19th Meetings of the NASA Small Bodies Assessment Group. The two multi-day events accrued a total of 2311 live views and 621 on-demand playback views.
4. There were 13 CLASS Asteroid Sample Return Seminars totaling 96 live and 144 on-demand views and an additional 4 CLASS/FSI Seminars with 27 live and 46 on-demand playback views.
5. The Origin and Evolution of the Moon class/seminar series had 14 sessions with 413 live and 1216 on-demand playback views.
6. The Carbon in the Solar System Workshop was viewed by 865 live and 994 on-demand playback views.
7. The Lunar Polar Volatiles workshop produced 43 recordings which were viewed 33 times.
8. The 2018 Annual Meeting of the Lunar Exploration Analysis Group recorded 28 presentations that totaled 186 on-demand playback views.

9. Survive and Operate Through the Lunar Night Workshop had 11 recordings with 212 on-demand views.

10. The International Asteroid Warning Network (IAWN) Meeting Support had 4 recordings with 52 live and 8 on-demand playback views.

11. Space Mission Planning Advisory Group Meeting had 68 live views.

12. SSERVI supported 6 virtual Executive Council meetings.

13. Other support included: 14 different (NASA Earth and Space Science Fellowship (NESSF) Panel Reviews; Planetary Defense Coordination Office (PDCO) "Forecasting the "Hard Rian" Workshop; ATAP Seminar on "Observing Small Asteroid Atmospheric Entries"; "Tunguska Impact" Workshop, and a Zoom Meeting with SSERVI/Mexico lecture on Mars Trek.

Unified Communications & Collaboration

Enabling collaboration and communication across multifaceted teams and community members remains at the forefront of SSERVI's Information Technology priorities. The technology industry is constantly updated with new hardware and software platforms and the SSERVI Central Technical Team regularly evaluates, integrates, and builds tools and capabilities that extend effective communication, often utilizing SSERVI Central's location in the heart of Silicon Valley to good advantage. In 2018, new hardware and software systems were explored that will serve as the foundation for stronger virtual collaboration across the SSERVI community. Moreover, SSERVI provided insight and guidance to numerous Agency organizations and teams to increase the effectiveness of collaboration system deployments.

Web & Infrastructure

To effectively convey the multi-disciplinary science and technological tools that SSERVI teams and affiliates frequently release, the sservi.nasa.gov website is updated regularly with science highlights and stories, and auxiliary websites and web applications are developed and maintained for relevant events and community members. For example, in 2018 SSERVI Central teamed with our European partners to create their "European

Website	Description	URL
SSERVI	Defining the Institute while highlighting SSERVI research, related science, events/activities, and resources to the community.	sservi.nasa.gov
NASA Exploration Science Forum	Home of the annual NASA Exploration Science Forum (NESF) where users find information on logistics, registration, abstract submissions, and on-demand playback of all presentations.	nesf2018.arc.nasa.gov nesf2019.arc.nasa.gov
SSERVI Awards	The SSERVI Awards website highlights past winners of the distinguished Shoemaker Medal, and the Wargo, Niebur, and Coradini Awards, while allowing the community to nominate candidates for the yearly distributed awards.	sservi.nasa.gov/awards
SSERVI Books	The SSERVI Books website was created to highlight the Institute's literary efforts, including books for the blind such as "Getting a Feel for Lunar Craters" and "Getting a Feel for Eclipses"	sservi.nasa.gov/books
European Lunar Symposium	The European Lunar Symposium (ELS) website provides users with logistics, registration, and abstract information related to this annual event.	els2018.arc.nasa.gov els2019.arc.nasa.gov
Centaur Exploration Workshop	A workshop addressing the scientific importance and space exploration relevance of active centaurs, with a specific focus on mapping knowledge gaps and paths forward. CEW website provides users with logistics, registration, and abstract information.	cew2019.arc.nasa.gov
Lunar Science for Landed Missions Workshop	The Lunar Science for Landed Missions Workshop produced a set of priority targets for near-term landed missions on the Moon; all logistics, registration, abstract submissions, and on-demand playback of presentations are available on the website.	lunar-landing.arc.nasa.gov
Carbon in the Solar System Workshop	The Carbon in the Solar System Workshop focused on the community's understanding of carbon's role in the Solar System. All logistics, registration, abstract submissions, and on-demand playback of presentations for this workshop are available on the website.	carbon-workshop.arc.nasa.gov
Ames Collaboration Team	SSERVI has provided the Ames Collaboration Team with an event scheduler application which records all events to a database while also automatically scheduling the events to a central calendar.	For Internal Use Only
URL Shortener	SSERVI continued to support a tailor-made URL shortener with analytics that has been used across the agency.	For Internal Use Only

Websites developed and managed by SSERVI Central.

Lunar Symposium" website, along with creating websites for specific events such as the "Lunar Science for Landed Missions" and "Carbon in the Solar System" workshops. SSERVI Central's Technical/Web Team accomplishes a significant amount of work in maintaining and updating these websites, while continuing to develop and deploy dynamic websites and web applications using modern tools and technologies.

Shared Tools and Facilities Open to the Community

SSERVI has developed and continues to support a wide array of cutting-edge facilities available not only to SSERVI researchers but also to the broader community. Here we report on NASA's Solar System Treks Project (SSTP) managed by the Institute's Central Office and briefly describe 2018 activities in the SSERVI Central-supported Regolith Testbed located at NASA Ames. In addition is a list of Team Facilities; interested parties should engage the facility POC to discuss scheduling time at the facility, along with any potential associated costs. 2018 research activities that took place using team-supported facilities can be found in the individual team reports.

Solar System Treks Project

SSTP Overview

NASA's Solar System Treks Project (SSTP) is a SSERVI project managed through the Institute's Central Office and developed and operated by the project's team at the NASA Jet Propulsion Laboratory (JPL). SSTP is the successor to the Lunar Mapping and Modeling Portal (LMMP), originally developed as a key landing site selection tool for the Constellation program. At the request of SSERVI stakeholders at NASA HQ, the SSTP has extended the scope and advanced technologies of its platform to move beyond the Moon to a variety of other planetary bodies, making it more user-friendly and more relevant to the planetary science community and a broad suite of missions. Along with the retirement and replacement of the original LMMP has come this new, more appropriate name for the overall project.

SSTP provides a growing family of web-based portals and suites of interactive visualization and analysis tools enabling mission planners, lunar and planetary scientists, engineers, students, and the public to access mapped data products from many different instruments aboard past and current lunar and planetary missions. During the past year, the project enhanced the technologies used in SSTP's existing portals for the Moon, Mars, and Vesta; extended these technologies additional planetary bodies; partnered with existing and future missions in mission planning, data visualization, and analytics; and played key roles in NASA's efforts in STEM engagement to learners of all ages. The project is supporting NASA partnerships with JAXA (Japan), ESA (Europe), KARI (S. Korea), INFN (Italy), and IRAP (France). It is an integral participant in NASA's Mars Human Landing Site Selection process and has been tasked with providing detailed visualization and analysis capabilities for proposed future human and robotic landing sites on the Moon, for which it was originally developed.

LMMP, the SSTP predecessor, was noted for the "vast" amount of lunar data that it was able to serve in its day; this totaled to something under 2TB. Today, the product generation pipeline of the vastly-expanded SSTP portals handles some 50TB of data per day, with an expected increase to 75TB in FY19.

It is worth noting that SSTP was also selected by JPL's Chief Technologist to be one of the featured projects in JPL's 2018 Technology Highlights report: https://scienceandtechnology.jpl.nasa.gov/sites/default/files/documents/JPL_2018_Technology_Highlights.pdf

SSTP Management

Program Office-level management of SSTP is provided through SSERVI Central, with development and operations provided by the team at JPL. The project is jointly funded by the Advanced Exploration Systems (AES) division within HEOMD, the Planetary Science Division (PSD) of SMD, and the Science Engagement and Partnerships Division (SEPD) of SMD. Brian Day at NASA SSERVI Central serves as SSERVI Program Office

SSTP Project Manager and Science Lead for the project. Emily Law at JPL serves as Development Team Project Manager and Engineering Lead. The SSTP task plan defines five specific areas of effort for the project.

1. Planetary Science efforts include working with SSERVI teams specifically and the lunar and planetary science community in general to identify and integrate appropriate mapped data products and analysis tool algorithms, and create new portals for a variety of other planetary bodies for which data is readily available, providing a context of comparative planetology for ongoing planetary studies.

2. Mission Support efforts include providing data products and tools to support mission planning and operations activities.

3. Education and Outreach efforts focus on serving as a key infrastructure component for SMD's STEM Activation program. SSTP will also support NASA outreach and communications efforts such as exhibiting in the NASA booth at designated conferences and at key public events such as launches as directed by our stakeholders.

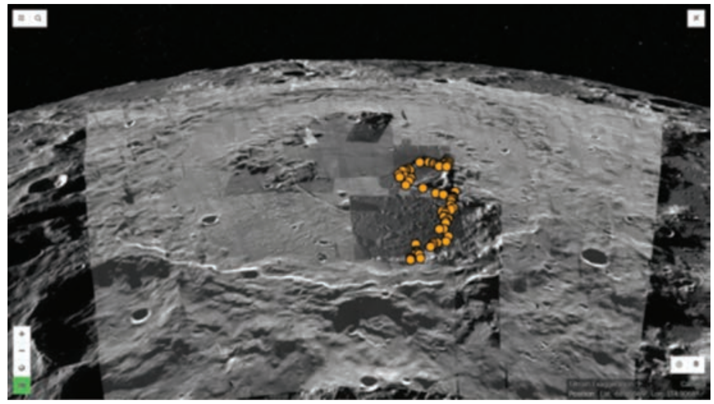
4. Recurring Engineering efforts represent recurring annual procurements including system administration, IT security, hardware maintenance, Amazon Cloud expenses, and user support.

These efforts also include upgrading the back-end infrastructure to handle the significantly increasing data and the number of users served, costs to participate in recurring meetings and conferences, and researching and implementing new technologies.

5. Support for NASA External Partnerships entails working with foreign partners as directed and approved by NASA HQ, making our tools' capabilities available to them in planning specific missions they are undertaking, as well as encouraging and facilitating the inclusion of data returned by their missions into our system.

Updates to Existing Portals

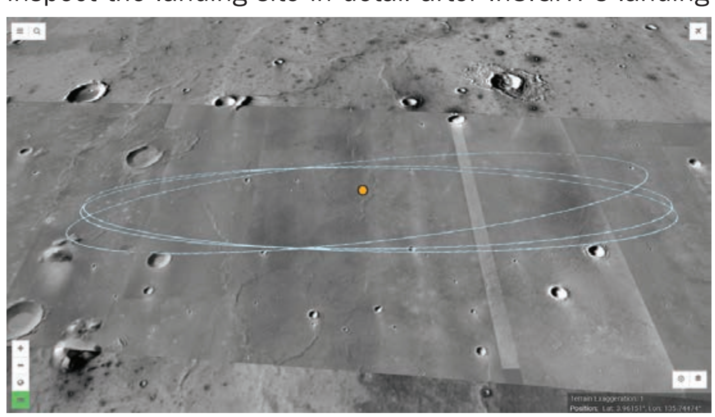
In 2018, the project's original portal was retired and was formally replaced by its successor, Moon Trek (https://moontrek.jpl.nasa.gov). Moon Trek features many



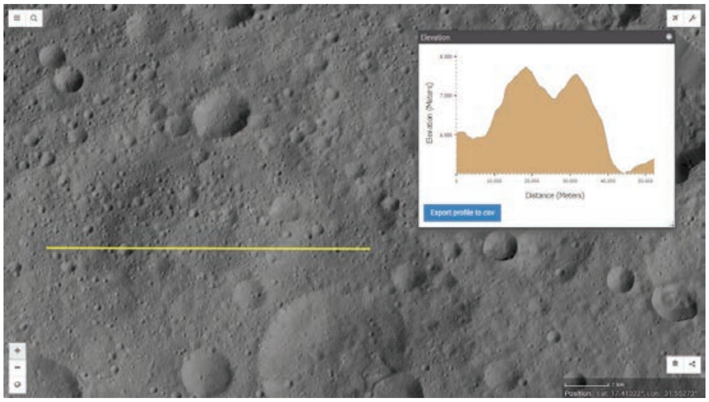
Traverse planning in Schrodinger Crater with Moon Trek

improvements including enhanced navigation, search, and 3D visualization, as well as utilizing a new user interface that is the standard across all Trek portals. During the course of the year Moon Trek specifically received a number of enhancements including addition of new data layers such as polar and global mineralogy. Working with LPI, new data layers including NAC mosaics and notional rover paths were developed and ingested for traverse planning within Schrodinger Crater. Working with SSERVI's Italian international partners, a prototype Laser Retroreflector study planning tool was deployed and tested.

SSTP's Mars Trek portal (https://marstrek.jpl.nasa.gov) also received specific enhancements in the form of Context Camera (CTX) mosaics for candidate Human Exploration Zones. Working with the SETI Institute, new data layers were produced and ingested for Human Landing Site (HLS2) traverse planning. A new bookmark was added featuring landing ellipses for the Mars InSIGHT mission in conjunction with the InSIGHT launch. This bookmark will be updated to include the ability to inspect the landing site in detail after InSIGHT's landing



InSIGHT landing site ellipses in Mars Trek



Ceres Trek visualization and elevation profile of relic cryovolcano in Begbalel Crater

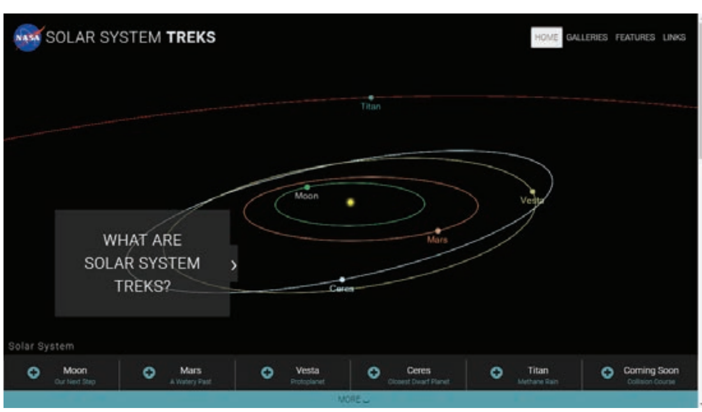
and the return of high-resolution imagery of the site from the Mars Reconnaissance Orbiter (MRO).

NASA's Dawn mission commissioned an upgrade to SSTP's Vesta Trek portal, adding new data products and upgrading the user interface to the new Trek standard.

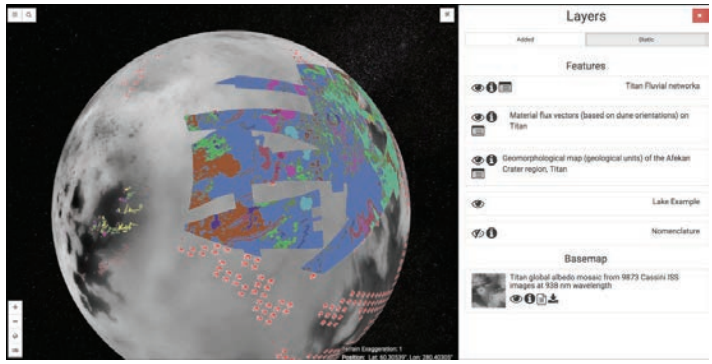
Other SSTP enhancements were generally applicable across all portals. A new geospatial data pipeline will greatly enhance the producing of high-resolution mosaics and DEMs. The new Experience TrekVR tool allows users to draw any path they want across surfaces displayed in the portals and then fly those paths in VR using their smart phones and inexpensive Cardboard-compatible goggles. Enhancements were made to our machine-learning-based crater and rock detection tools.

New Additions to SSTP

In addition to commissioning an update to the existing Vesta Trek portal, NASA's Dawn mission commissioned a new portal for Ceres, which was released in October, 2018. As it was being prepared for release, an article by a team led by Michael Sori at the University of Arizona



Solar System Treks Home Site



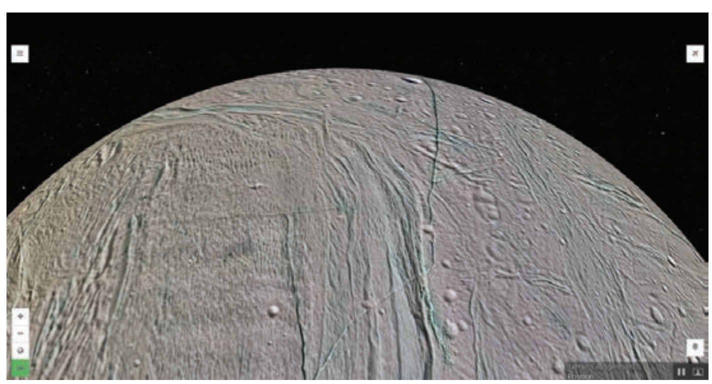
Fluvial network, material flux vectors, and geomorphological map in Titan Trek

announced the identification of relic cryovolcanoes on Ceres with topographies obscured by viscous relaxation. These proved to be an excellent test for the new portal, with Ceres Trek able to clearly visualize and measure these newly-discovered features. SSTP shared our results, and Sori enthusiastically reported his intentions to use Ceres Trek for future presentations about their discovery.

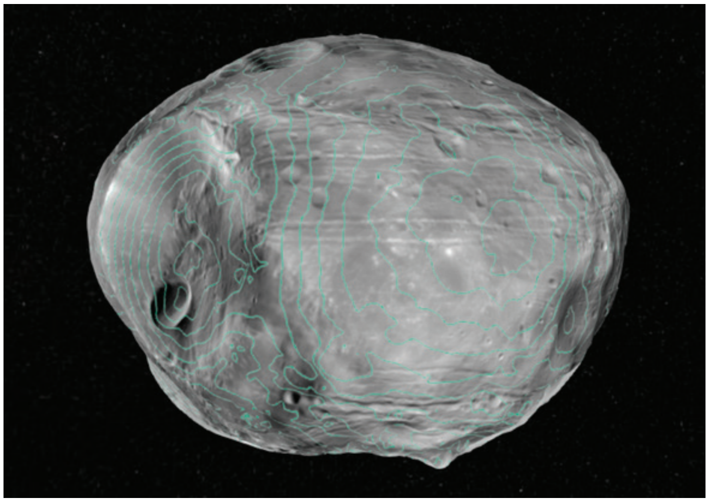
With the continuing growth of the number of portals in the SSTP suite, a new project home site was developed providing a single point of access to all of the project's portals as well as a number of supporting resources including galleries, videos, Feature of the Month articles and more. The new Solar System Treks Home Site is available at https://trek.nasa.gov.

New Portals Under Construction

The Cassini Mission commissioned SSTP to assist with data visualization, dissemination, and analytics for its observations of a number of Saturn's moons. They provided their data for us to include in two new portals, Titan Trek and IcyMoons Trek. Titan Trek has over 130,000 data products acquired during many individual encounters between Cassini and Titan, and incorporates



Enceladus in IcyMoons Trek



Phobos with gravity contours in Phobos Trek prototype

a new catalog design to greatly improve and facilitate searches. This will be extended across the Trek family of portals in the coming year. IcyMoons Trek features Cassini data from Saturn's moons Enceladus, Dione, Iapetus, Mimas, Phoebe, Rhea, and Tethys. Prototypes for both portals were developed in 2018 for review by the Cassini mission prior to public release of both portals in the first quarter of CY19.

At the request of NASA HQ and the Institute of Space and Astronautical Science (ISAS) we are collaborating with the Japanese space agency (JAXA), to support mission planning for their upcoming Martian Moons eXplorer (MMX) mission to Phobos and Deimos. Our work this year has included producing an initial Phobos portal prototype, working to integrate a new catalog of surface features, and participating in international working groups planning the data and tools that will be necessary for this mission and further exploration of Mars' moons.

The Science Visualization Working Group was formed this year as a new working group established under Kristen Erickson, Director for NASA's Science Engagement and Partnerships Division. Emily Law has assumed the lead position for this working group, working with disciplines across the agency--and communities of practice outside the agency--to guarantee NASA maintains a high bar for data visualization.

SSTP STEM Engagement

SSTP's primary efforts in STEM engagement and public engagement center on its participation in NASA SMD's SciAct Collaborative, led by Kristen Erickson and NASA SMD's Science Engagement and Partnerships Division. SSTP is an infrastructure component for this program, providing content, visualizations, and interactive experiences to meet the needs of the participant teams in the collective. Our many partnerships with teams in this program include working with the American Museum of Natural History, WGBH public television, the Challenger centers, Arizona State University, the USGS, NASA's Astromaterials Curation Office, and many more.

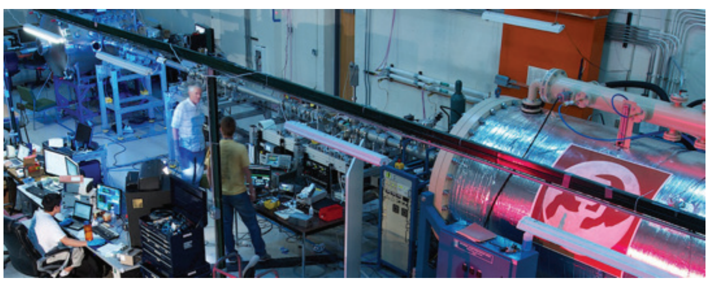
Our additional outreach activities throughout the year directly engaged thousands of learners in diverse environments. SSTP was featured at NASA Night of the Fresno Grizzlies minor league baseball team, showcasing our new virtual reality capabilities (Experience TrekVR) with SSTP flyovers of planetary terrains shown on the JumboTron. Over 10,000 guests enjoyed virtual reality flyovers of the surfaces of the Moon and Mars, and many personally examined a variety of meteorites including lunar and Martian samples. SSTP also helped organize and was featured at the public launch event for the Mars InSIGHT mission at Alan Hancock College next to Vandenberg Air Force Base in May, 2018; SSTP returned in November to support the InSIGHT landing event. We conducted special presentations for the NASA Community College Aerospace Scholars, the NASA Minority University Research and Education Project Educator Institute, the Astronomical Society of the Pacific's Summer Institute, the Keck Observatories Lecture Series, LPI's Palooza educational event at LPSC, and two Moon Night public events at Henry Cowell Redwoods State Park in California. Through SSERVI Central, SSTP partnered with Gemini

SSTP Experience Trek VR being demonstrated at Fresno Grizzlies baseball game

Observatory and their Journey through the Universe program. SSERVI Central has integrated the Trek portals into the Apollo Lunar Sample and NASA Meteorite Sample certification workshop that SSERVI conducts. High school astronomy students in Palo Alto served as beta testers for our Phobos portal prototype. The ongoing program of having computer science majors at Cal State University Los Angeles assume development tasks for the project as senior projects resulted in significant development being accomplished for a movie generator tool for the portals. Team members worked directly with summer interns at LPI and SETI doing traverse planning activities for the Moon and Mars. SSTP is an active participant in various anniversary planning groups planned for the Apollo 50th and NASA 60th anniversaries and is working to integrate detailed Apollo landing site bookmarks into Moon Trek that will allow users to explore these sites in detail. This is a representative, though not exhaustive list.

SSERVI Team Facilities

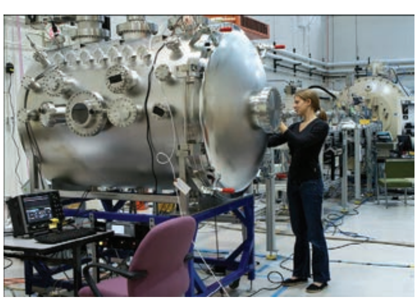
Dust Accelerator Laboratory (DAL) (U. of Colorado



A 3 MV linear electrostatic dust accelerator, the largest dust accelerator in the world, is used for a variety of impact research activities as well as calibrating dust instruments for space application. The 3 MV Pelletron generator is capable of accelerating micron and submicron particles of various materials to velocities approaching 100 km/s.

Contact: http://impact.colorado.edu/facilities.html

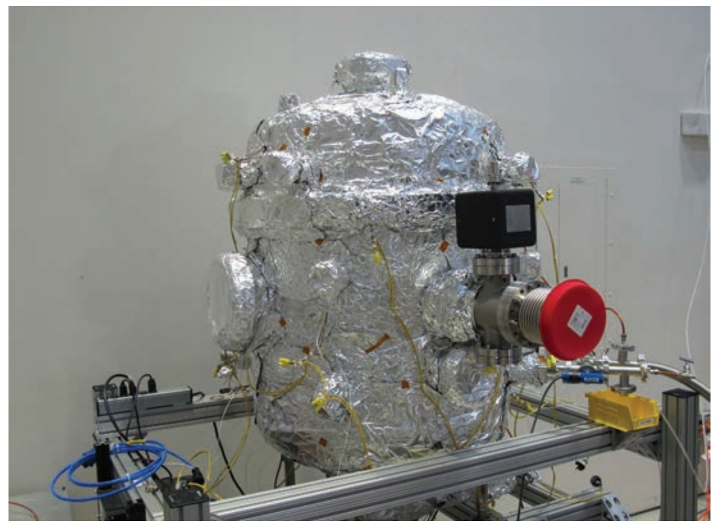
Large Experimental (LEIL) Chamber



The LEIL chamber is 1.22 m in diameter, 1.52 m long, and has a volume of 2 m^3. An externally-controlled moving translation stage is installed in the chamber which allows control over the impact position in one dimensions (transverse to the beam line) without breaking vacuum. All ports are standard ConFlat, of various sizes, and a variety of different viewports and electrical feedthroughs are available.

Contact: http://impact.colorado.edu/facilities.html

Ultra High Vacuum (UHV) & Ice and Gas Target Chambers (U. of Colorado)



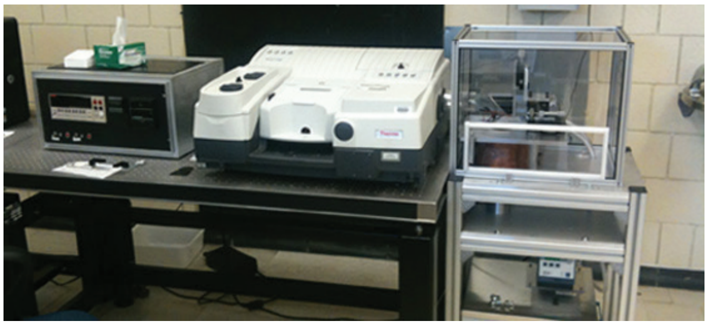
The Ultra High Vacuum and Gas Target chambers are dedicated chambers that are directly connected to the Dust Accelerator Laboratory for impact experiments requiring very clean conditions with exceptionally low background gas pressure, extreme cold temps, or various atmospheric gas pressures. Contact: http://impact.colorado.edu/facilities.html

Reflectance Experiment Lab (RELAB) (Brown University)

The Reflectance Experiment Lab (RELAB) supports obtaining spectroscopic data to analyze compositional information relevant to planetary surfaces. High precision, high spectral resolution, bidirectional reflectance spectra of Earth and planetary materials can be obtained using RELAB.

Contact: http://www.planetary.brown.edu/relab/

Vibrational Spectroscopy Lab (Stony Brook University)



The Vibrational Spectroscopy Lab has spectroscopic tools allowing examination of geologic materials similar to those that are present on Mars, the Moon, or other solar system bodies for better interpretations of remote sensing data.

Contact: http://aram.ess.sunysb.edu/tglotch/

Physical Properties Lab (U. Central Florida)

Planetary simulants: The Exolith lab is the world leader in the development and preparation of high-fidelity planetary regolith simulants. Equipment includes a large inventory of regolith minerals including olivine, pyroxene, magnetite, serpentines, organics, anorthosite, basalt, and glass. The equipment includes a range of rock graders and crushers, high-capacity sieves, mixing equipment, a Cilas 1190 particle size analyzer, various furnaces, freezers, and vacuum chambers for simulant processing.

Density and Porosity: the lab includes a Quantachrome ULTRAPYC 1200e gas pycnometer for precise grain volume measurements; A Konica Minolta Vivid 9i laser camera for precise bulk volume measurements; and custom-built pycnometer for larger samples. A special insert for thin slabs (up to ¼ in.). Both pycnometers have uncertainties of better than 0.5%.

Materials properties: The lab also includes a number of direct physical properties measurement and preparation facilities. Hardness testing, material flow and angle of repose testing, a PM100 planetary ball mill for colloidal grinding, compaction testing, ZH Instruments SM-30 magnetic susceptibility meter, and a fieldspec reflectance spectrometer with a wavelength range of 0.4-2.5 microns. The UCF Materials Characterization Facility includes facilities for X-ray diffraction, X-ray fluorescence, electron microscopy, MTS Criterion 43 instrument for compressive strength measurements, and milling/coating facilities.

Contact: britt@physics.ucf.edu

GSFC Radiation Facility (NASA GSFC)

The GSFC Radiation Facility includes a new dedicated 1 MeV proton beam line used to create radiation-stimulated defects in materials to help determine low energy H retention effects.

Contact: william.m.farrell@nasa.gov

Microgravity Drop Tower (U. Central Florida)

The microgravity drop tower provides a mcirogravity experience with 0.7sec of freefall. An LED backlight helps track individual ejecta particles. Images are recorded with a high-resolution camera at 500 frames/second, which allows tracking of individual particles.

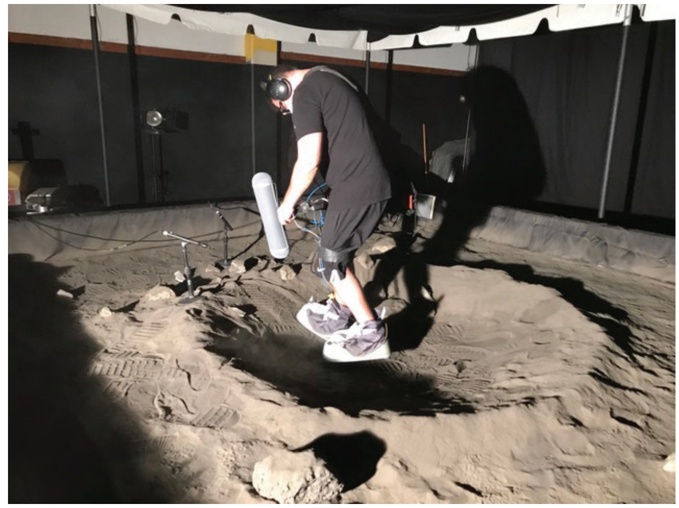
Contact: josh@ucf.edu

Regolith Testbeds

The 4m x 4m x 0.5m Regolith testbed at NASA Ames is filled with 8 tons of JSC-1A regolith simulant, the largest single quantity of this simulant in the world. It is excellent for investigations in resource prospecting and regolith manipulation due to its relatively large size.

Contact: joseph.minafra@nasa.gov

The SSERVI Central Office maintains the Regolith Testbed Facility at NASA Ames Research Center--a sandbox filled with 8 tons of JSC-1A lunar regolith simulant. In 2018, SSERVI worked with UCF and the KSC Swamp-works soil mechanics lab to add new simulants for new research in the testbed/LunarLab. SSERVI introduced Universal



Universal Studio's sound research in the Regolith Testbed at NASA Ames for *First Man* movie.

Studios "First Man on the Moon" movie producers and studio engineers to Apollo hardware collectors and engineers who helped them record realistic audio of switches, pumps, space suits and regolith. Apollo 15 astronaut Al Worden met with audio engineers recording the sounds from the Apollo mission, and Universal Studios recorded audio and video in the testbed for a behind the scenes making of the *First Man* film.

Acknowledgments

We gratefully acknowledge the enormous support we received in 2018 from our NASA Headquarters supporters and stakeholders: Lori Glaze, Sarah Noble and Shoshana Weider from the Planetary Science Division of the Science Mission Directorate (SMD), Paul Hertz from the Astrophysics Division of SMD, Kristen Erickson from the Science Engagement and Partnerships Division of SMD, Jason Crusan, John Guidi, Ben Bussey and Bette Siegel from the Human Exploration and Operations Mission Directorate, and James Green, NASA Chief Scientist. We also are grateful for the continued support from NASA Ames Research Center Senior Management: Eugene Tu, Carol Carroll, David Korsmeyer and Michael Bicay, as well as ARC grant specialists Barrie Caldwell and Beatrice Morales, resource specialists Ben Varnell and Michael Baumgarten, and many from Ames mission support services. We also thank the SSERVI teams, international partners, and the broader research community that interacts with SSERVI in many capacities throughout the year.

SSERVI U.S. Team Reports

Executive Summaries of Team Reports

The executive summaries of the 2018 team reports provide a high level look at some of the team accomplishments enabled by SSERVI. These selected highlights briefly touch upon some of the important topics covered in the team reports, but they give a flavor of the activities and impact of each individual team. Cross-team collaborations, international partnerships, student involvement, and mission experience are topics covered in much greater detail in the full reports that follow.

CAN 1 Teams (2014-2019)

The Center for Lunar and Asteroid Surface Science (CLASS) team led by Prof. Dan Britt at the University of Central Florida studies the interaction between the surfaces of airless bodies and the space environment. Our goal is to support robotic and human exploration, resource assessment and exploitation, and the commercial development of space with the best possible science in order to explore smarter. Our research focus is on topics that directly affect the exploration community to provide solid answers to exploration, ISRU, and resource questions: (1) The physics of plume interactions with airless surfaces. (2) The physical and thermal properties of lunar and asteroid regoliths. (3) The behavior of regoliths in lunar and microgravity. (4) The cohesive and interparticle forces acting in lunar and asteroidal regoliths. This includes a successful program of experiments on suborbital launches, on ISS, and UCF-built cubesats. (5) The charging environment on airless bodies including the effects of dust lofting on the lunar surface. (6) The chemical and physical challenges in use of regolith as a resource for construction, fuel and life support. (7) The chemical reactions and reaction products that are part of space weathering and understanding the effects of weathering to aid in the remote characterization of lunar and asteroid resources. (8) Observations of mineralogy of primitive asteroids and assessments of their resource potential. (9) Combined radar and optical characterization of asteroid surfaces. (10) Analysis of the strength properties of meteorites, asteroids and bolides to assess the mining and physical properties of asteroid resources. CLASS has several team-wide initiatives: (A) On-line advanced planetary science education with 5 graduate-level seminar courses recorded for community access. Topics are designed to bring the best science to the exploration community and include “The Science and Technology of ISRU” and “The Exploration of Phobos and Deimos”. (B) The CLASS Exolith Laboratory which is the world leader in the development and production of lunar and asteroid regolith simulants. (C) The CLASS Landing Team which brings together the world’s experts in plume physics and dynamics with the leaders of the growing commercial landing industry. (D) An innovative public engagement program that includes a unique program to bring the wonder and excitement of planetary science to underserved Blind/Visually Impaired students. (E) Partnership with NASA KSC in their annual Robotic Mining Competition. CLASS is fundamentally an organization to bring the best science into the service of lunar and asteroid exploration.

The Center for Lunar Science and Exploration (CLSE) team led by Dr. David Kring at the USRA Lunar and Planetary Institute and NASA Johnson Space Center studies impact history and processes, geochemistry of regoliths, including volatile components, and ages of regolith materials on the Moon and other airless bodies. In 2018, a large fraction of the team’s work focused on the distribution of metallic core and mantle silicate materials during collisions in the final phases of accretion which, in turn, affect estimates of how volatile-bearing material accreted to the Earth-Moon system and other planetary bodies, such as Mars. While examining some of the products of late heavy bombardment, the team discovered a unique rock specimen in an Apollo 14 sample that may have been derived from Earth during that period of bombardment. The team also examined the processing and release of volatiles at the lunar surface where they may have been transported to polar regions for storage. Studies of lunar landing site and traverse options, cis-lunar communication requirements, ConOps for tele-operated lunar surface assets, and trafficability of surface assets in ISRU-rich areas were conducted.

A large fraction of CLSE work is focused on the training of young investigators in sample science and the geologic and astrophysical processes that affect surface samples that might be collected in the future. This year, the CLSE team guided ten high school teams from across the nation with novel research projects, including one that was presented at the SSERVI-hosted NASA Exploration Science Forum. The CLSE team also trained 10 graduate students in an integrated lunar science and engineering exploration program in Houston, plus 31 graduate students and postdocs in exploration strategies at the Sudbury impact structure.

The Dynamic Response of Environments at Asteroids, the Moon, and Moons of Mars (DREAM2) team led by Dr. Bill Farrell at Goddard Space Flight Center (GSFC) examines the complex three-way interaction between the harsh space environment, the exposed surfaces of airless bodies, and human systems near these affected surfaces. During its fifth program year the team produced/published over 25 papers on the space environment at airless bodies, including the Moon. The team also was recently awarded the prestigious Robert H. Goddard Award for excellence in science, being specifically cited "For excellence in the application of space environmental science to exploration applications." In the area of surface interactions, the team presented a new model of the solar wind implantation, OH creation, H diffusion and exospheric H_2 creation that fits the current surface and exospheric observational sets. They also performed new laboratory experiments in the GSFC Radiation Facility of proton implantation and hydroxyl creation in mineral samples and lunar samples, demonstrating the development of the 3 micron OH feature in the more complex lunar sample mineralogy. In the area of exospheric research, the team published a generalized model of exosphere creation that examines the potential development of a bounded surface exosphere across all body sizes. They also modeled exospheric water liberated at the lunar surface by impacts in support of LADEE mission results. In the area of space plasma, team members used ARTEMIS data to detect the tenuous lunar ionosphere around the Moon. In radiation research, the team continues to monitor galactic cosmic ray flux and allowable astronaut flight days during this unusual period of weakening solar cycles. They also published a review paper on space weathering from deep dielectric discharge (DDD) that can occur at cold regions at the Moon. DDD is an impulsive discharge that can occur in insulating surfaces due to excessive charge build-up from solar energetic particles – and cold lunar soils act as such an insulator. In an intermural effort, team members performed research in support of the now-canceled Resource Prospector (RP) mission, including modeling the landing plume and its effect on the near-rover volatile environment, the effect of Earthshine on polar volatiles, and rover charging in shadowed regions near the poles. Many of these studies were presented at the SSERVI Forum in mid-summer of 2018 and apply not just to RP but to any rover mission to the lunar polar regions. To assist in enabling this array of exciting research, DREAM2 continues to support an outstanding intern program—with many students from a Howard University-DREAM2 collaboration established in 2013. The team continues to integrate many post-doctoral fellows and graduate students at Goddard and at partnering institutions. DREAM2 also works in close coordination with our SSERVI partnering teams (eg. VORTICES, IMPACTS and REVEALS), especially in the areas of surface interactions and exospheric research. The expertise is intimately connected across teams triggering many new joint research projects.

FINESSE (**Field Investigations to Enable Solar System Science and Exploration**) is an interdisciplinary team of scientists, technologists, and mission operations specialists conducting field-based research to understand geologic processes on the Moon, asteroids, and Phobos & Deimos while simultaneously preparing for future human and robotic exploration. FINESSE is led by Principal Investigator (PI) Dr. Jennifer Heldmann and Deputy PIs Drs. Darlene Lim and Anthony Colaprete of NASA Ames Research Center. We operate under the philosophy that "science enables exploration and exploration enables science."

FINESSE fieldwork at the West Clearwater Impact Structure (WCIS) in northern Canada has focused on age-dating the impact structures. For WCIS, U/Pb analysis of impact-related zircons by thermal ionization mass spectrometry (TIMS) yielded the most precise age currently available for this impact structure at 286.55 ± 0.33 Ma. Thorough assessment of WCIS samples has demonstrated that the combination of low and high precision chronometric data from a variety of techniques can improve overall confidence in age assignments for impact craters.

FINESSE fieldwork has also been conducted in the volcanic fields of Idaho, Hawaii, and Iceland as lunar analogs. We have investigated the formation of sinuous rilles on the Moon, such as the Hadley Rille visited during Apollo 15, by analyzing the rheology of lunar analog materials. We have studied heat transport which plays a crucial role in the thermal evolution of high-temperature, magmatic regimes on Earth and other planets. Our studies of intrinsic geochemical variability in volcanic rift zones and use of terrestrial analogs for magma evolution in sill and dike networks on the Moon have shown that geochemical diversity within analog systems enables an improved understanding of expected magmatic complexities in lunar floor-fractured craters, dike-related linear rilles, and silic domes on the Moon.

We have also focused on developing new technologies to optimize exploration of SSERVI target bodies. Field instrumentation is critical for enabling both robust science and understanding the concepts of operations and capabilities required for robotic and human exploration of SSERVI target bodies. The FINESSE project has also used terrestrial field data of lava tubes and volcanic surface landforms to render these sites in virtual and augmented reality platforms. New analysis tools have been developed within the VR/AR framework to enable scientific measurements of these features, with extensibility to future exploration scenarios for SSERVI target bodies.

The Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT) Team led by Prof. Mihaly Horanyi at the University of Colorado Boulder continues to be dedicated to: a) studying the effects of hypervelocity dust impacts into refractory, icy, and gaseous targets; b) developing new laboratory experiments to address the effects of UV radiation and plasma exposure of the surfaces of airless planetary objects; c) developing new instrumentation for future missions to make in situ dust and dusty plasma measurements in space; and d) providing theoretical and computer simulation support for the analysis and interpretation of laboratory and space-based observations. Two of IMPACT's initial instrument development ideas matured and received independent funding. The Double Hemispherical Plasma Probe (DHP) is now supported by NASA's PICASSO and the Electrostatic Lunar Dust Analyzer (ELDA) instrument is now supported by NASA's DALI program. Both of these are continuing their engineering development for early payload opportunities using NASA or commercial lunar landers. IMPACT provides access to its facilities to the space physics community and works with a large number of undergraduate and graduate students, and two high school students. IMPACT continues to support a number of NASA missions, including Cassini, New Horizons, Solar Probe Plus, and the Europa Clipper for follow up testing and calibration of dust instruments, to help assessing dust impact damages on thin films used in particle detectors, and to evaluate the degradation of optical instruments. IMPACT continued to have extensive collaborations with international partners from Germany, Norway, Canada, and Japan. We have been selected for 2018/9 funding by the Partnership Program with North America, Norway, that pays all travel and living expenses of IMPACT students visiting Oslo, and the Norwegian students visiting us. IMPACT remains the 'center of gravity' for cosmic dust and dusty plasma research within SSERVI with ongoing complementary research projects with several of SERVI's other teams.

The Institute for the Science of Exploration Targets (ISET) Team led by Dr. Bill Bottke at the Southwest Research Institute uses state-of-the art modeling, combined with interpretation of spacecraft data, to reveal what the Moon, Phobos and Deimos, and asteroids tell us about the origin and evolution of the inner Solar System. The ISET team does this over four main themes. In Theme 1, "Formation of the Inner Solar System and the Asteroid Belt," we explored how "viscously stirred pebble accretion" and collisional fragmentation affected planet formation. Pebble accretion describes how the accretion of objects ranging from centimeters up to meters in diameter onto planetesimals can be enhanced by aerodynamic drag within a protoplanetary disk. We also examined how an instability taking place among the orbits of the giant planets, and subsequent giant planet migration, may have dynamically excited the asteroid belt. In Theme 2, "Origin of the Moon and Phobos/Deimos," we showed how Phobos/Deimos could form from a debris disk produced by a Vesta-to-Ceres sized impactor striking Mars. We also examined how late accretion could be constrained by the addition of highly siderophile elements, defined as metals like Re, Os, Ir, Ru, Pt, Rh, Pd, Au that are likely to go to the core of the Earth during the formation of its core. For the Moon, we conducted the first simulations of moonlet assembly from lower-mass protolunar disks produced in a multiple-impact model, and examined the chemistry of those protolunar disk. In Theme 3, "The History of NEAs and Lunar Bombardment," we examined the survival of a large binary with the Trojan asteroid population. Trojans are a large group of asteroids that share the planet Jupiter's orbit around the Sun, residing in stable regions that are located 60° ahead and 60° behind Jupiter's position. It is believed this binary was captured during giant planet migration from a large disk of comet-like planetesimals originally located just beyond the initial orbit of Neptune. Our work showed this binary could only survive if the planetesimal disk was minimally collisionally evolved, and that in turn implies the giant planets migrated early in their history. This work indicates another source is needed for the so-called Late Heavy Bombardment. We also showed the flux of asteroid striking the Earth and Moon increased by a factor of 2-3 roughly 300 Myr ago. In Theme 4, "NEAs: Properties, Populations, New Destinations," we continued our research on the effects and implications of non-gravitational forces and weak cohesive bonds within primitive solar system bodies, with implications for the nature of Bennu, a body currently being visited by the OSIRIS-REx spacecraft.

The Remote, In-Situ, and Synchrotron Studies for Science and Exploration (RIS4E) team led by Dr. Tim Glotch at Stony Brook University uses advanced field, laboratory, modeling, and remote sensing techniques to enable the safe and efficient exploration of the Solar System and to maximize the science return from missions to airless bodies in the Solar System. In the last year, RIS4E team members have conducted a number of activities that fall within or span across the four key themes of our team: (1) Preparation for Exploration: Enabling Quantitative Remote Geochemical Analysis of Airless Bodies, (2) Maximizing Exploration Opportunities: Development of Field Methods for Human Exploration, (3) Protecting our Explorers: Understanding how Planetary Surface Environments Impact Human Health, and (4) Maximizing Science from Returned Samples: Advanced Synchrotron and STEM Analysis of Lunar and Primitive Materials. As part of Theme 1, we have characterized the effects of a simulated airless body environment on infrared spectroscopic measurements. These measurements clearly demonstrate the need to account for environmental factors when interpreting thermal infrared spectra of airless bodies. We have also continued to refine and improve light scattering models, with a new focus on the visible/near-infrared portion of the electromagnetic spectrum. Our work in this area is setting new constraints on how space weathering should be accounted for using such models. As part of Theme 2, we conducted field work in a planetary analog volcanic terrain while continuing to refine procedures for the use of portable and handheld instruments by astronauts. This work included the preliminary development of a new tool designed to place field measurements in a spatial and chronological context for easy review. As part of Theme 3, we demonstrated that experimentally space-weathered lunar regolith simulants are substantially more toxic and reactive than unweathered materials. These results are leading to additional experiments designed to test the effects of composition and maturity on toxicity. Finally, as part of Theme 4, we have demonstrated new techniques for nano-scale analyses of planetary materials including future returned samples. We pioneered the use of monochromated electron energy loss spectroscopy to collect infrared spectra of individual interplanetary dust particles, and demonstrated for the first time the ability to use synchrotron nano-IR techniques to characterize the 3 μm H_2O band in mineral spectra.

The SSERVI Evolution and Environment of Exploration Destinations (SEEED) team is hosted at Brown University with key participants from five other centers and collaborators from seven countries. The diverse SEEED team investigates topics related to the chemical and thermal evolution of planetary bodies, the origin and evolution of volatiles, several regolith issues for airless environments, and science and engineering synergism. Highlights from 2018 peer-reviewed publications and our widely circulated 'white paper' include: models of lunar mantle complexity that result from the timing of crystallization and density-driven overturn; systematic characterization of lunar basalt eruption phases with gas-release and recognition of small features that appear to represent the last phase and exhibit highly porous deposits; estimation of the thickness and volume of ice in the shadowed poles of Mercury (with implications for the Moon); unambiguous detection of water ice/frost across the shadowed lunar poles; high precision isotopic measurements achieved for volatile and weakly volatile lunar elements allowing new issues to be addressed with lunar samples; evaluation of lunar soil samples through decades of investigations proving no significant degradation from storage in terrestrial facilities; application of advanced image analysis techniques with M3 data to subdue unfortunate detector variability effects and improve compositional mapping, visualization and testing of a viable hypothesis for formation of the global grooves on Phobos, and preparation and dissemination of Transformative Lunar Science topics. The SEEED team demonstrates dedication to leading, supporting, and participating in a variety of community, international, cross-team, academic and public engagement activities related to SSERVI goals, exemplified by planning the upcoming Microsympoium 60 – "Forward to the Moon to Stay: Undertaking Transformative Lunar Science with Commercial Partners."

The Volatiles, Regolith and Thermal Investigations Consortium for Exploration and Science (VORTICES) team, led by PI Andrew Rivkin and Deputy PIs Rachel Klima and Jeff Plescia at the Johns Hopkins University Applied Physics Laboratory, has been carrying out research since 2014 on four broad themes: "Volatiles: Sources, Processes, Sinks;" "Regolith Origin and Evolution;" "Resource Identification;" and "Strategic Knowledge Gap Analysis." During 2018, work by the VORTICES team spanned a broad range of topics. Indirect measurements showed that micrometeorite impactors liberate more water than they deliver to the lunar surface, while direct measurements of lunar hydrogen via a new resolution-improving technique shows a correlation between high amounts of hydroxyl and thorium anomalies. An estimate of the number of volatile-bearing near-Earth asteroids shows that dozens to hundreds may be easier to reach than the Moon (depending on the desired size), while photometric work is ongoing to determine whether a variation in lunar hydration that is seen could be a photometric effect rather than a change in volatile amount. Modeling of rock breakdown by thermal cycling finds that there are optimal block sizes at which the process occurs most efficiently, while a look at the properties of lunar regolith finds that the accepted overturn rate is far short of what is necessary to explain its properties.

CAN 2 Teams (2017-2022)

In mid-2017 NASA selected four new research teams to join the existing nine teams in SSERVI to address scientific questions about the moon, near-Earth asteroids, the Martian moons Phobos and Deimos, and their near space environments, in cooperation with international partners. The new teams were selected from a pool of 22 proposals based on competitive peer-review evaluation.

The Project for Exploration Science Pathfinder Research for Enhancing Solar System Observations (Project ESPRESSO) team led by Dr. Alex Parker at the Southwest Research Institute in Boulder, Colorado, is conducting a suite of investigations into new techniques and technologies for improving the safety and efficiency of human and robotic exploration of the inner Solar System. In 2018, their work included a test of a novel asteroid regolith sampling approach onboard a reduced-gravity research aircraft, field tests of handheld laser-induced breakdown spectrometers, maturation of a compact standoff Raman spectrometer for lunar exploration, and maturation of laboratory and analytical techniques for building a comprehensive database of optical constants for lunar and asteroid analog minerals.

Project ESPRESSO team members worked closely with the ISET and RIS4E nodes on analyses of the lunar and terrestrial cratering records and analog fieldwork data, respectively. In collaboration with ISET, powerful new Bayesian statistical techniques developed by ESPRESSO team members demonstrated that there is strong evidence that the impact flux in the inner Solar System has increased substantially in the last 290 million years. These new methods show promise for advancing the statistical basis of many areas solar system science. Handheld laser-induced breakdown spectroscopy data was collected at an analog field site in collaboration with RIS4E, and these data are now under analysis to determine how similar instruments may guide astronauts' efforts on the surface of the Moon. A new collaboration with the CLSE team on dynamical modeling of the transient lunar atmosphere was also begun in 2018.

Project ESPRESSO team members at JHU have begun collecting laboratory for measuring optical constants of lunar and asteroid analog minerals for retrieving quantitative composition measurements from future remote sensing observations, and a new SwRI spectroscopic laboratory is under construction that will substantially increase Project ESPRESSO's optical constant measurement throughput. Novel analytical techniques were also pioneered by team members in 2018 that will enable faster and simpler data collection and conversion into optical constants.

Project ESPRESSO has been active with its international partners, including the Canadian NRC-CNRC Flight Research Laboratory on implementation of the Airborne Space Environment Chamber for conducting tests of lunar and asteroid exploration hardware in relevant gravity, vacuum, and regolith environments. A demonstration flight aboard their Falcon 20 reduced gravity aircraft carried a reduced-scale experiment to test regolith and vacuum handling procedures, and this experiment also conducted the first demonstration of using nano-landers with magnetic grapples to safely and simply collect asteroid regolith for sample return. A new international partnership was initiated with a team from ISAS/JAXA to further mature related nano-lander technologies for exploration of the lunar poles.

The Network for Exploration and Space Science (NESS) team led by prof. Jack Burns at the University of Colorado Boulder, is an interdisciplinary effort that investigates the deployment of low frequency radio antennas in the lunar/ cis-lunar environment using surface telerobotics, for the purpose of cosmological measurements of exotic physics at the end of the Dark Ages, astrophysical measurements of the first luminous objects during Cosmic Dawn, radio emission from the Sun, and extrasolar space weather. NESS is developing instrumentation and a data analysis pipeline for the study of departures from standard cosmology in the early Universe and the first stars, galaxies and black holes, using radio telescopes shielded by the Moon on its farside. The design of an array of radio antennas at the lunar farside to investigate Cosmic Dawn, Heliophysics, and Extrasolar Space Weather is a core activity within NESS, as well as the continuous research of theoretical and observational aspects of these subjects. NESS is developing designs and operational techniques for teleoperation of rovers on the lunar surface facilitated by the planned Lunar Gateway in cis-lunar orbit. New experiments, using rover + robotic arms and Virtual/ Augmented Reality simulations, are underway to guide the development of deployment strategies for low frequency antennas via telerobotics.

The Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS) team lead by Dr. Thomas Orlando at the Georgia Institute of Technology investigates the condensed matter physics, materials chemistry and applied aspects associated with radiation-induced processes in regolith and man-made composite materials relevant to the exploration of near-Earth destinations. In 2018, the team improved a model to describe the solar wind formation of water on the Moon. The atomistic model was improved and expanded to address formation, diffusion, transport and eventual polar trapping of water on the Moon and Mercury. The model is applicable to other airless solar system bodies and, for the case of Mercury, it presents a new source of water that does not require nor invoke cometary impact events. A laser-based micrometeorite accelerator has been constructed and tested for future SSERVI-wide use. The system will initially be used to examine impact induced space weathering and chemical transformations of both highland and mare Apollo samples. The chemical transformations include but are not limited to water and methane formation via associative or recombinative desorption (RD). The water formation mechanisms, loss channels, and diffusion coefficients are all being measured directly on highland and mare Apollo samples and surrogates. The program also involves an applied component of solar-based in-situ resource utilization and printing of regolith-based building and shielding materials. In addition, novel polymer composites and two-dimensional meta-materials are being developed and tested as novel flexible materials and real-time passive radiation detectors. The materials and active dosimetry will be integrated into spacesuits and hardware for extra-vehicular and surface exploration activities. Overall, the REVEALS effort is addressing a number of SMD and HEOMD objectives to help understand and minimize risks associated with radiation exposure during human exploration.

The Toolbox for Research and Exploration (TREX) team, led by Dr. Amanda Hendrix at the Planetary Science Institute (PSI), aims to provide science-driven tools to ensure successful planetary surface exploration. TREX studies place a particular emphasis on fine grains (<10 μm), which cover the surfaces of the Moon, Phobos, Deimos and near-Earth asteroids. Such fine grains can present hazards to future human explorers and their equipment, and also harbor volatiles that can be useful for future in-situ space resources (ISRU) programs. TREX also places an emphasis on ultraviolet measurements, in addition to more traditional visible and infrared studies, for thorough compositional analyses considering unique and diagnostic UV spectral capabilities. TREX studies are organized into four Themes (laboratory studies, Moon studies, small bodies studies, and field work). In 2018, the TREX team made substantial progress on building the TREX spectral library, with work focused on preparing and measuring terrestrial samples in our five laboratories, and well as preparing for field work and performing analyses of lunar and small bodies surfaces using datasets from the Lunar Reconnaissance Orbiter, Hayabusa2, the International Ultraviolet Explorer, ground-based observatories, the Dawn spacecraft, and other facilities. Members of the TREX team also organized and participated in a series of successful SSERVI-sponsored Carbon in the Solar System workshops..

TEAM REPORTS

The SSERVI teams are supported through multiple year cooperative agreements with NASA (issued every 2-3 years) for long duration awards (5 yrs) that provide continuity and overlap between Institute teams. Each team is comprised of a number of elements and multiple institutions, all managed by a Principal Investigator.

CAN-1 TEAMS

Center for Lunar and Asteroid Surface Science (CLASS)
Daniel Britt, University of Central Florida

Center for Lunar Science and Exploration (CLSE)
David Kring, Lunar and Planetary Institute, Houston, TX

Dynamic Response of Environments at Asteroids, the Moon, and Moons of Mars (DREAM2)
William Farrell, NASA Goddard Space Flight Center, Greenbelt, MD

Field Investigations to Enable Solar System Science and Exploration (FINESSE)
Jennifer Heldmann, NASA Ames Research Center

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)
Mihaly Horanyi, University of Colorado, Boulder, CO

Institute for the Science of Exploration Targets (ISET)
William Bottke, Southwest Research Institute, Boulder, CO

Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS4E)
Timothy Glotch, Stony Brook University

SSERVI Evolution and Environment of Exploration Destinations (SEEED)
Carle Pieters, Brown University, Providence, RI

Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES)
Andy Rivkin, Johns Hopkins University/ Applied Physics Lab, Laurel, MD

CAN-2 TEAMS

Exploration Science Pathfinder Research for Enhancing SS Observations (ESPRESSO)
Alex Parker, Southwest Research Institute in Boulder, CO

Network for Exploration and Space Science (NESS)
Jack Burns, University of Colorado in Boulder, CO

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)
Thomas Orlando, Georgia Institute of Technology in Atlanta, GA

Toolbox for Research and Exploration (TREX)
Amanda Hendrix, Planetary Science Institute in Tucson, AZ

Daniel Britt

University of Central Florida, Orlando, FL

Center for Lunar and Asteroid Surface Science (CLASS)

CAN 1 Team

1. Center for Lunar and Asteroid Surface Science (CLASS) Team Project Report

Dan Britt: CLASS PI: UCF

- Established the CLASS Landing Team to bring together experts from NASA, academic, and commercial groups to address plume and debris hazards from landing on the regoliths of airless bodies. The team includes 14 NASA, 12 academic, and 10 commercial members.
- Sponsored and lead a CLASS/SSERVI Graduate Seminar on "The Science and Technology of Asteroid Sample Return" at UCF. It is one of 5 CLASS advanced planetary science classes available at https://sciences.ucf.edu/class/graduate-seminars/
- Graduate student Leos Pohl, working with Chris Bennett (UCF), Sudipta Seal (UCF), Kennedy Space Center, and Thom Orlando (REVEALS), we have been measuring the dehydration, mineralogical changes and spectral changes in hydrated minerals exposed to different temperatures to characterize space weathering on NEAs.
- CLASS partner Florida Space Institute took over the management of the Arecibo Observatory for the National Science Foundation. CLASS already had a close working relationship with the lunar and asteroid radar observations at Arecibo and the new management has strengthened the links between CLASS and Arecibo. CLASS Co-I Dr. Yan Fernandez is now the chief scientist for the Arecibo Observatory.

Addie Dove: Deputy PI: UCF

- Built, delivered, and launched (Sept 15, 2018) SurfSat,

CLASS Established the Exolith Laboratory to develop and produce high-mineralogical fidelity regolith simulants for lunar and asteroid science and exploration. The Exolith Lab has become the defacto standard for simulants world-wide and has shipped materials to over 220 customers.

Built, delivered, and launched (Sept 15, 2018) SurfSat, a 2U CubeSat that will study spacecraft charging in the ionosphere.

a 2U CubeSat that will study spacecraft charging in the ionosphere. Continuing plasma-chamber testing of custom electronics and instrumentation to use for interpretation of on-orbit data. Working on proposals for similar instrumentation on more complex ionospheric missions.

- Built and delivered experiment hardware for the first set of Hermes experiments. These are follow-ups to the Strata-1 experiments. Data analysis from Strata-1 is ongoing (presented early results at LPSC).

Chris Bennett: Deputy PI: UCF

- Commissioned a new EasyDIFF FTIR spectrometer which can take bidirectional diffuse reflection measurements over 350 nm to 25 μm. We have also set-up a vacuum KBr pellet maker (CrushIR; PIKE) capable of making high-quality 13mm KBr pellets for analysis of their spectral features. *These facilities are available for general use, and we will be using them to analyze minerals and carbonaceous meteorites both as pristine samples as well as after exposure to various weathering agents.*

- Using correlated analytical techniques (visible, near-IR and infrared spectroscopy, Raman hyperspectral mapping, nanoIR hyperspectral mapping, SEM-EDS, TEM-EDS, ToF-SIMS, and novel multimodal X-ray techniques) to understand the evolution of organic molecules (particularly amino acids and peptides) within meteorites. This work has led to several successful collaborations involving the Advanced Light Source (ALS; Berkeley) and UCLA and the University of Lille (France).

- Using hyperspectral Raman mapping to diagnose the temperature variations and degree of carbon degradation at sub-micron resolutions in meteorites to understand space weathering processes on volatile-rich asteroids.

Rob Mueller Co-I: NASA Kennedy Space Center, Swamp Works, Granular Mechanics & Regolith Operations (GMRO) Lab

- Developed new In-Situ Resource Utilization (ISRU) materials for 3D Printing with regolith resources including Iron Silicon (FeSi) feedstocks extracted from lunar regolith via Molten Regolith Electrolysis (MRE). The MRE process has been demonstrated to produce raw feedstock materials and oxygen at high yield with lunar materials under KSC leadership.

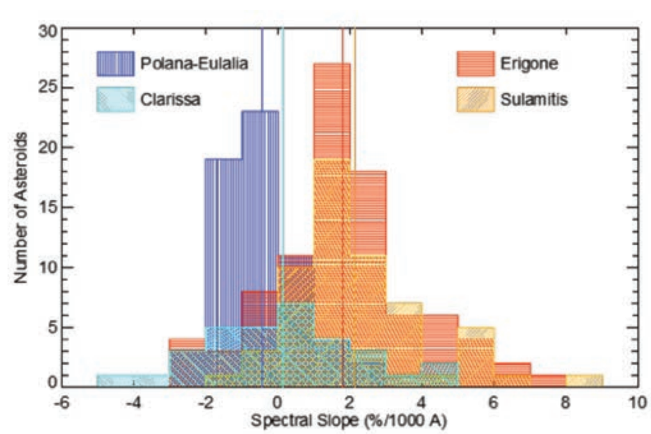
- Swampworks and KSC hosted the annual NASA Robotic Competition with assistance from CLASS.

- Developed Polymer Composite Concrete (PCC) with indigenous regolith aggregates (70%) as part of feedstocks for 3D printing with regolith materials.

Humberto Campins: Co-I: UCF

- Carried out observations with 3 major ground-based telescopes and analyzed data from Spitzer Space Telescope and the Dawn mission. Data show spectral diversity among inner-belt primitive families, with at least two and possibly more distinct groups: hydrated and spectrally diverse (Erigone-like) or no 0.7-μm hydration feature and spectrally homogeneous (Polana-like). These data are shown in the figure (right) and supported by laboratory simulations of space weathering (Lantz et al. 2015, 2017). This result has testable implications for Bennu and Ryugu (older terrains would be expected to be bluer than younger surfaces).

- Applied a novel clustering method to color images of Ceres to identify clusters associated to different albedo and spectral shapes, which correlated with morphological structures. We also detected a 700-nm absorption band associated with hydration in outer parts of the Occator crater.

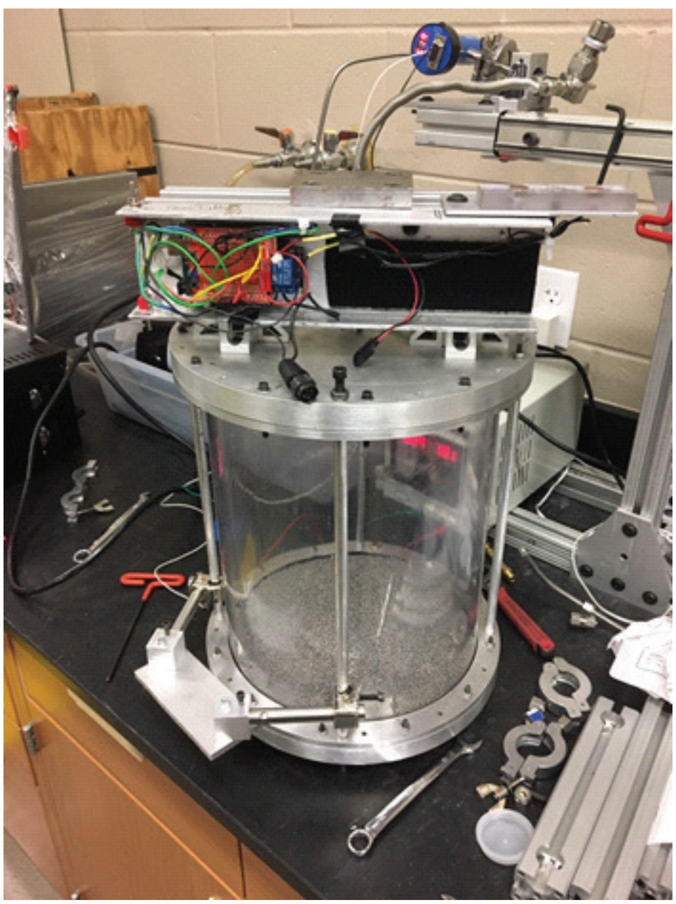


Josh Colwell: Co-I: UCF

- Parabolic flight experiments using asteroid regolith simulant were carried out to study the cohesive and adhesive properties of asteroid regolith in microgravity when subjected to low-velocity impacts (< 50 cm/s). Results indicate that regolith with grain sizes less than 1 mm agglomerate into cm-scale clumps and that impacts at less than ~30 cm/s do not produce significant ejecta even in microgravity for fine-grained regolith.

- Parabolic flight experiments using asteroid simulant were carried out to study the response of regolith to flexible boring or drilling probes in microgravity in collaboration with Dr. Karen Daniels, North Carolina State University.

- A drop tower experiment to study the response of regolith in microgravity to rocket exhaust plumes ("GRIT") was developed and has undergone initial testing at the UCF CMR. The GRIT vacuum chamber has been constructed and tested on the drop tower to check electronics, solenoid function, and prove the experiment concept. Initial results are promising and show a range of behavior dependent on plume conditions and particles.



vacuum chamber for study of regolith plumes from rocket exhaust impact on small asteroids.

- CubeSat "Q-PACE" to study collisions among chondrules and early stages of asteroid accretion progressed toward a 2019 launch.

- The COLLIDE regolith experiment flew aboard the first Virgin Galactic SpaceShipTwo suborbital flight to space. Experiments observe low-velocity regolith interactions relevant to lunar and asteroidal surfaces.

Dan Durda: Co-I: SWRI

- Participated in planning and hardware development for the ISS HERMES experiments.

- Flew several boxes of CI regolith simulant on a Zero-G flight to examine the accretion/clumping behavior in microgravity (planetary accretion experiment).

Yan Fernandez: Co-I: UCF

- We investigate the thermal and scattering properties of the regolith of NEA (433) Eros using an extensive set of near-IR spectra obtained at NASA/IRTF that simultaneously measure both the thermal emission of and the reflected sunlight from the regolith. By using Eros's known shape, we can correlate thermal properties with specific topographic regions.

- We are collaborating with researchers in the world-wide planetary radar group to obtain near-IR spectra of objects that are observed also with radar at Arecibo Observatory. The characterization of the NEAs in the infrared enhances the interpretation of the radar echoes and the scattering properties.

- Studies of the interstellar asteroid 1I/`Oumuamua using CCD imaging to obtain visible-wavelength colors and a rotational lightcurve. We also participated in a study of `Oumuamua with the Spitzer Space Telescope, which allowed the team to constrain the object's albedo and gas production rates despite only having upper limits to the photometry.

Chris Herd: Co-I: University of Alberta

- The active use of the cold curation facility continues – primarily for the development of curation methods for returned samples, funded for the next 3 years by the Canadian Space Agency.
- Provided Tagish Lake samples that were used in the study by Glotch et al. (2018) assessing the origin of the martian moons.
- Member of the Global Fireball Observatory led by Phil Bland (Curtin U); actively working on establishment of the Western Canada arm of the Observatory.

Robert Macke: Co-I: Vatican Observatory

> The work of Leos Pohl (grad student UCF) has shown that the parent asteroids of CM carbonaceous chondrites dehydrate and spectrally alter at temperatures 200 C lower than other volatile-rich asteroids. This has major implications for asteroid resource prospecting and mining.

- Constraining the size-porosity relation of intact stones from large meteorite falls. As a meteoroid enters the atmosphere, it often breaks up into many fragments. More porous parts of the object will be weaker, and thus tend to break into smaller fragments than less porous sections. This past year we measured porosities for approximately 70 fully intact stones from the Kosice meteorite, and observed this size-porosity relationship in stones ranging from <1 cm^3 to several hundred cm^3.
- Hosted the first Workshop on the Curation of Meteorites and Extraterrestrial Samples. This meeting brought together thirty curators and collections managers from institutional scientific collections of meteorites and extraterrestrial samples around the world. Topics discussed included best practices for curation, tracking laws of meteorite ownership, allocation of specimens for research, acquisition and evolution of collections, and record-keeping and sharing information between institutions.
- Serving the scientific community by characterizing physical properties in conjunction with high-precision, non-destructive and non-contaminating equipment at the Vatican Observatory; this has become a valuable resource for the scientific community.

Philip Metzger: Co-I: UCF

- Developed mathematical methodology to characterize asteroid simulants. The methodology is based on NASA's Figure of Merit system developed for lunar soil simulants, but it is expanded to the additional needs of asteroid simulant.
- Supported the NASA Robotic Mining Competition at KSC. CLASS sponsors one of the trophies. We have been analyzing the results of the mining competitions and identified a trend overall toward increasing mobility as teams learn from experience and competition pushes designs to greater performance.
- Working on lunar landing plume effects, including

> Phil Metzger is leading the CLASS Planetary Landing Team, which brings together experts from NASA, academic, and commercial groups to address plume and debris hazards from landing on the regoliths of airless bodies. The team includes 14 NASA, 12 academic, and 10 commercial members. https://sciences.ucf.edu/class/landing-team/

establishing the CLASS Planetary Landing Team and creating an information website that explains the physics, phenomena, modeling, and mitigation of planetary landing plume effects. https://sciences.ucf.edu/class/landing-team/

Cyril Opeil: Co-I: Boston College

- Ongoing study of low-temperature heat capacities of meteorites in conjunction with Bob Macke. This study is to better characterize low-temperature heat capacities of chondrites to improve models of the thermal behavior of their parent bodies. This involves measurement of heat capacities of large numbers of hand-sized stones (ca. 15-40 g), high-precision measurements of Cp(T) on small (a few mm^3) meteorite fragments, and development of composition-based models for Cp(T) at low temperatures.
- Study of the thermal and mechanical properties of meteorites including elastic constants, Young's Modulus, thermal inertia, thermal conductivity, heat capacity, resonant ultrasound spectroscopy, and thermal expansion/dilatometry. Current measurements are focused on iron meteorites and carbonaceous chondrites.

Dan Scheeres: Co-I: University of Colorado

- CLASS supported Dan Scheeres and Senior Research Scientist Paul Sanchez involvement in the ISS STRATA-1 experiment to participate in the development and analysis of the experiment results, including developing the paper describing the experiment. The CU team remains involved with the Hermes experiment, the next phase of this activity.
- Investigating the fundamental mechanical properties of cohesive regolith on small body surfaces has resulted in publications and presentations, with a range of results that include proposed methods to determine the cohesive strength of a regolith surface based on observing a cratering experiment of known strength. These results can be applied to the Hayabusa2 impact experiment scheduled for this year, and will provide a direct means to determine the strength of the surface of Ryugu.

Cass Runyon Co-I: College of Charleston

Finalizing "*The World Ender*," a problem-based learning packet for grades 5 - 8. Developed with a core team of dynamic science educators, authors, artists and storytellers from around the country, the curriculum is an engaging inquiry-based set of hands-on activities using SSERVI data and resources. We field tested it with a group of middle school science teachers at the 2018 National Science Teachers Association (NSTA) annual conference. A revised and updated packet will be shared during a

Students who are Blind/Visually Impaired from across Austria and southern Germany are shown here attending the inaugural 'Inspiring Stars' showcase and presentations at the International Astronomical Union meeting. CLASS Co-I Cass Runyon is leading the distribution over 3,000 copies of "Understanding Small Worlds in Our Solar System: A Tactile Guide" and 1,500 copies of the recently updated tactile book, "Getting a Feel for Lunar Craters" to Schools for the Blind, State libraries, Museums and Science Centers and the Library of Congress here in the US. Additionally, the tactile books are being used by students who are Blind/Visually Impaired at schools in Italy, Poland, France, England, South Africa, Ethiopia, Chile, Argentina, Australia, China, Japan and more, and have been highlighted at several national and international conferences. The books were showcased at the 2018 Vis-U Summer Camp at Space Center Houston (a science and engineering camp for students who are Blind/Visually Impaired) and the inauguration of 'Inspiring Stars' at the International Astronomical Union meeting in Vienna, Austria. The books are being translated into Spanish and are being signed. These accessible versions of the text are available online using the 'QR' code on the front of the books: https://lunarscience.arc.nasa.gov/books short-course at the upcoming 2019 NSTA conference in St. Louis.

- We are currently in press for Abre tus Sentidos a los Eclipses: Sud America. This tactile book covering the upcoming 2019 and 2020 solar eclipses in Chile and Argentina, respectively, will be printed in Spanish, including Braille. English and Spanish translations of the text will be available online.

Faith Vilas: Co-I: PSI

- Continued work on the compositional properties of the irregular outer Jovian satellites, and the weathering processes on primitive (C-complex) asteroids in the UV/blue.
- Amanda Hendrix (SSERVI TREX) and Vilas organized and supported the SSERVI Carbon in the Solar System series with the original workshop-without-walls and two additional panel sessions at major scientific meetings (DPS for 50 attendees and fall AGU with 150 attendees).

Peter Brown Collaborator: Western University

- Collaborator Peter Brown is working on the idea that Tunguska may have been a Beta Taurid. There may be a linkage between “lumpy” meteor streams like the Beta Taurid complex (normally active from June 5 to July 18) and significant concentrations of Tunguska-sized fragments that are too small to be observed unless in the vicinity of the Earth.

2. CLASS Inter-team/International Collaborations

SSERVI Central and NASA

- Provided UCF regolith simulants to the following planetary researchers: TransAstra (Joel Sercel) for their NIAC project in collaboration with the Colorado School of Mines (Chris Dreyer). Delivered 400 kg total. NASA ARC’s SSERVI Lunar Lab (Joe Minafra) to provide asteroid regolith simulants CI and CR, and the BP-1 lunar simulant for optical reflectance studies. Delivered 220 kg total. JSC (Roy Christoffersen and John Gruener) to provide UCF asteroid regolith simulants C2, CI and CM for their studies involving impact experiments into asteroid regoliths. Delivered 15 kg total. University of Delaware, (Maria Katzanova, Graduate Student) to provide lunar regolith simulant in order to support NASA funded work. Provided 1 kg of Black Point -1 and 1 kg of JSC-1A lunar regolith simulants. Also provided 1,000 kg of Black Point 1 lunar regolith simulant for geotechnical and robotic trafficability testing at JSC.
- Kevin Grossman (NASA KSC Pathways Intern) interacted with CLASS research students to analyze samples that were provided to him to perform TGA testing and mechanical strength testing of the samples at KSC.

REVEALS

- Chris Bennett, Dan Britt and Leos Pohl collaborated with Thom Orlando on Thermo Gravimetric Analysis (TGA) of volatile-rich asteroidal regolith materials.

FINESSE

- Rob Mueller Collaborated with Mike Downs on aerial surveying using drones and specifically, remote sampling technologies using drone mounted sampling systems.

TREX

- Humberto Campins worked with Amanda Hendrix at PSI to co-author the chapter on Compositional Diversity Among Primitive Asteroids.

ESPRESSO

- Dan Durda worked with Alex Parker to adapt the magnetic grappling hardware that he recently flight tested on a parabolic flight in October to perform with the regolith simulant in the BORE experiment.

VORTICES

- Yan Fernandez collaborates with Ron Vervack (JHU/APL), Ellen Howell (U. Arizona), and Chris Magri (U. Maine) on the NEA thermal properties project.

RIS^{4}E

- Chris Herd provided Tagish Lake samples that were used in the study by Glotch et al. (2018) assessing the origin of the martian moons.
- Cass Runyon collaborated with RIS^{4}E on outreach.

ISET

- Dan Britt collaborated with Bill Bottke on the effects of space weathering on volatile rich NEAs. Bill is a member of Leos Pohl's graduate committee.
- Dan Scheeres worked extensively with the ISET team to study the mechanics of cohesive asteroids and probe themes of motion on the surfaces of small bodies.

IMPACT

- Addie Dove collaborated with IMPACT on dust charging research.
- Dan Britt collaborated with IMPACT on design of space weathering experiments.

CLSE

- Dan Britt and Bob Macke work with CLSE member Walter Kiefer on the density and porosity of lunar meteorites and Apollo samples.

International Collaborations

- The CLASS Exolith Lab has shipped lunar and asteroid regolith simulant to researchers in 20 countries. We are involved in proposals with researchers in 5 countries.
- Chris Bennett collaborated with Prof. Claire Pirim et al. University of Lille on ToF-SIMS experiments
- Humberto Campins collaborated with Drs. S. Fornasier, A. Barucci in Paris, with Drs. P. Tanga and J. Hanus in Nice, France, and with Drs. J. Licandro and J. de Leon in Spain.
- Dan Durda collaborated with Tatsuhiro Michikami (Hayabusa2) to re-fly SwRI's Box-of-Rocks Experiment (BORE) on another Blue Origin suborbital spaceflight to investigate the properties of Ryugu's regolith.
- Dan Britt and Chris Herd collaborated with Phil Bland (Curtin U, Australia) on the Global Fireball Observatory. Herd is actively working on establishment of the Western Canada arm of the Observatory.
- Robert Macke collaborated with Juraj Toth (Comenius University, Bratislava, Slovakia) and Tomas Kohout (U. of Helsinki, Finland) on the size-porosity trends in intact stones of the Kosice meteorite.
- Dan Britt collaborated with Phil Bland (Curtin U, Australia) on the analysis of a newly discovered iron meteorite that was found in northwestern Iowa.
- Dan Britt (along with Bill Bottke and Andy Rivkin) attended the MIAPP workshop on NEOs in Munich which brought together interdisciplinary researchers from 10 countries in an excellent collaborative environment.
- Cass Runyon is distributing tactile books to students who are Blind/Visually Impaired at schools in Italy, Poland, France, England, South Africa, Ethiopia, Chile, Argentina, Australia, China, Japan and more.
- Dan Britt attended the UNOOSA / Holy See Seminar: Exploration and Development of Space Opportunities and Issues in the Context of the Sustainable Development Goals

3. CLASS Public Engagement Report

Robert Mueller and Philip Metzger: NASA Robotic Mining Competition (RMC)

Competition is for university-level students to design and build a mining robot that can traverse the challenging simulated lunar terrain. The mining robot must then excavate the regolith simulant and/or the ice simulant (gravel) and return the excavated mass for deposit into the collector bin to simulate an off-world, in situ resource mining mission. The complexities of the challenge include the abrasive characteristics of the regolith simulant, the weight and size limitations of the mining robot and the ability to tele-operate it from a remote Mission Control

Center. In 2018 over 50 university teams from across the United competed at NASA's Kennedy Space Center. CLASS provided expertise, judging and sponsored one of the major trophies.

Robert Mueller NASA Centennial Challenge – 3D Printed Habitat Competition

NASA and its partners are holding a $3.15 million competition to build a 3D printed habitat for deep space exploration, including the agency's journey to the Moon and Mars. Participation in the Challenge provides an opportunity to support the commercialization of advanced technology. SERRVI CLASS provided expertise, judging and rules committee support.

Addie Dove

Dr. A. Dove gave nine public talks about the Moon, asteroids, and related science, and events including UCF Distinguished Speaker Series talk – "CubeSats: Big science in tiny spacecraft." Organized and hosted International Observe the Moon Night (InOMN) event at UCF with the UCF Astronomy Society and Robinson Observatory.

Humberto Campins

H. Campins gave a public lecture organized by the LEAD Scholars at the University of Central Florida on March 21, 2018. He was interviewed and quoted several times by US and international press outlets, including local WKMG TV (CBS; https://www.clickorlando.com/news/space-news/heres-whats-next-for-nasas-spacecraft-at-asteroid-bennu) and Cosmos magazine (https://cosmosmagazine.com/space/twist-in-the-tail-oumuamua-was-a-comet-not-an-asteroid).

Yan Fernandez

Fernandez and Graduate Student Mary Hinkle ran an extensive outreach program that included nine free, public events to which about 800 visitors were able to view the night sky through our telescopes. In particular, these events are almost always scheduled at favorable Moon phases to motivate and enhance discussion of the Moon with the public. In addition, we organized or participated in several one-off outreach events: (i) "International Observe the Moon Night" on October 20, (ii) a special Mars viewing event on August 24, and (iii) campus-wide "Space Game" festivities where UCF added a space and astronomy theme to the November 1 college-football home game.

Cass Runyon and the CLASS Public Engagement Program

See CLASS Public Engagement Summary in Table 3.1.

4. Student / Early Career Participation

Undergraduate Students

1. A University of Central Florida Aerospace Engineering Department Senior Design Project was sponsored by NASA KSC Swamp Works and SSERVI CLASS to create a scaled, cheaper functioning engineering model of a NASA regolith excavation robot called EZ-Regolith Advanced Surface Systems Operations Robot (EZ-RASSOR)Chris Britt, UCF Engineering CubeSat development and assembly
2. Chase Cox, UCF Engineering CubeSat development and assembly
3. Jacob Hambor, UCF Engineering CubeSat development and assembly
4. Alex Heise, UCF Engineering CubeSat development and assembly
5. Jonathan Kessluk, UCF Engineering CubeSat development and assembly
6. Jacob Kirstein, UCF Engineering CubeSat development and assembly

Event / Activity	Date	Location	# participants	Audience	Underserved*
Lady Cougars STEM Day	02.22.18	Charleston, SC	3,000	Gr 4 – 8	Yes
Charleston STEM Festival	02.10 2018	Charleston, SC	10,000	Public	Yes
NASA STEM Engagement Workshop	02.18-20.2018	Myrtle Beach, SC	60	In-service teachers	Yes
National Council of Space Grant Director's Meeting	03.02.2018	Washington, DC	150	NASA HQ, Space Grant Dir.	Yes
The World Ender Educator Short Course	03.16.2018	Atlanta, GA	20	Gr. 4 – 12	Yes
US Air & Space Expo	04.27–28.2018	North Charleston Air Force Base	85,000	Public	Yes
2018 Penn-Del AER Conference Workshop	04.25-27.2018	Harrisburg, PA	25	Educators & Parents	Yes
Career Exploration Lab MI Bureau of Services for Blind Persons	06.18-22.2018	Kalamazoo, MI	100	Public	Yes
International Planetarium Society Programs for those with Special Needs panel	07.01-05.2018	Toulouse, France	100+	Public	Yes
Vis-U Camp	08.07 –10. 2018	Houston, TX	24	Gr 6 - 12	Yes
International Astronomical Union Inspiring Stars Showcase Exhibition and presentation	08.20-24.2018	Vienna, Austria	200+	Public	Yes
NASA Expo in Charleston	08.29.2018	North Charleston, SC	1,500	Gr 6 – 12 Public	Yes
Apollo 50th Anniversary Workshop	08.29.2018	Washington, DC	60	NASA HQ	Yes
Great Lakes Planetarium Association Annual Conference	10.10-13.2018	East Lansing, MI	50	Public	Yes
Astronomical Society of the Pacific	11.09-11.2018	San Francisco, CA	200+	Public	Yes
USS Yorktown – Space Day	12.16.2018	Mt. Pleasant, SC	800	Public	Yes

Table 3.1: Public Engagement Summary

7. Anna Metke, UCF Physics and Business, Regolith simulant development and experiments
8. Thomas Miletich, UCF Engineering CubeSat development and assembly
9. Chance Reimer, UCF Engineering CubeSat development and assembly
10. Sean Shefferman, UCF Engineering CubeSat development and assembly
11. Benjamin Straw, UCF Engineering CubeSat development and assembly
12. Manuel Trujillo, UCF Engineering CubeSat development and assembly
13. Clayton White, UCF Engineering CubeSat development and assembly
14. Seamus Anderson, UCF Physics, Microgravity and suborbital flights
15. Jacob Anthony, UCF Engineering, Microgravity and suborbital flights
16. Ryan Boehmer, UCF Engineering, Microgravity and suborbital flights
17. Stefano Cattarini, UCF Engineering, Microgravity and suborbital flights
18. Tyler Cox, UCF Physics, Microgravity and suborbital flights
19. Emily D'Elia, UCF Engineering, Microgravity and suborbital flights
20. Michael Fraser, UCF Physics, Microgravity and suborbital flights
21. Gillian Gomer, UCF Physics, Microgravity and suborbital flights
22. Alex Hopkins, UCF Physics, Microgravity and suborbital flights
23. Trisha Joseph, UCF Physics, Microgravity and suborbital flights
24. Eric Markowitz, UCF Physics, Microgravity and suborbital flights
25. Taylor Mello, UCF Physics, Microgravity and suborbital flights
26. John Peterson, UCF Physics, Microgravity and suborbital flights
27. Cody Schultz, UCF Engineering, Microgravity and suborbital flights
28. Nicholas Spangler, UCF Physics, Microgravity and suborbital flights
29. Sean Touros, UCF Physics, Microgravity and suborbital flights
30. Madison Weinberg, UCF Physics, Microgravity and suborbital flights
31. Michael Wooley, UCF Engineering, Microgravity and suborbital flights
32. Alexandra Yates, UCF Engineering, Microgravity and suborbital flights
33. Brian Ferrari, UCF Physics, chemical processes in meteorites
34. Michael Cintron, UCF Physics, chemical processes in meteorites
35. Sarah Swiersz, UCF Physics, chemical processes in meteorites
36. Johnathan Sepulveda, UCF Physics, chemical processes in meteorites
37. Matthew Bonidie, Boston College, mechanical properties of iron meteorites
38. Luke Martin, Boston College, digital scanning calorimeter measurements of iron meteorites and ordinary chondrites
39. Drew Rasor, Boston College, designed and built an 8-inch slow-speed diamond saw to cut large meteoritesNick Gorman, Trident Technical College, STEM engagement

40. Christen Browder, College of Charleston, STEM engagement, assistant

Graduate Students

1. Beverly A. Watson, Florida Institute of Technology, interned at the NASA Kennedy Space Center Swamp Works, in the Granular Mechanics & Regolith Operations laboratory
2. Juergen Schleppi, Heriot-Watt University, Edinburgh, Scotland was hosted for 2 months in summer 2018 by SSERVI CLASS in Orlando, Florida and NASA Kennedy Space Center while working on a space resources research task
3. Keanna Jardine, UCF, Physics/Planetary Science, regolith properties research
4. Wesley Chambers, UCF, Physics/Planetary Science, landing plume dynamics
5. Isabel Rivera, UCF, Physics/Planetary Science, microgravity research
6. Stephanie Jarmak, UCF, Physics/Planetary Science, microgravity research
7. Leos Pohl, UCF, Physics/Planetary Science, asteroid surface processes
8. Amy LeBleu-DeBartola, UCF, Physics/Planetary Science, meteorite space weathering
9. Anicia Arredondo UCF, Physics/Planetary Science, observations of primitive asteroids
10. Vanessa Lowry, UCF, Physics/Planetary Science, observations of primitive asteroids
11. Mary Hinkle, UCF, Physics/Planetary Science, thermal modeling of asteroidsEbberly MacLagan, U Alberta Geology, impact melt in core from the Steen River impact structureJarret Hamilton, U Alberta Geology, identifying source craters for the martian meteorites
12. Alex Sheen, U Alberta Geology, martian meteorite geochronology
13. Caitlyn Nolby, Univ. North Dakota, Accessibility, aerospace & STEM education
14. Marissa Saad, Univ. North Dakota, Accessibility, aerospace & STEM education
15. Maria Royle, Stall High School, ESOL and Science teacher, Deaf
16. Jennifer Thompson, Berkeley County High School, STEM Coordinator and science teacher

Postdoctoral Fellows

1. Kevin D. Grossman, NASA KSC, Swamp Works. Regolith processes. Hired as a civil servant at KSC
2. Kevin Cannon, UCF, Regolith mineralogy and the CLASS Exolith Laboratory
3. Zoe Landsman, UCF, Observations of primitive asteroids
4. Jenna Crowell, UCF, postdoctoral researcher (Jan - Apr), thermal modeling of asteroids

5. Mission Involvement

Dan Britt

1. NASA New Horizons Mission Science Team, Interdisciplinary Scientist on Geology/Geophysics Investigation and Composition Investigation, Integration of geological surface processes and interior structure.
2. NASA Lucy Mission Science Team, Lead-Interior and Bulk Properties Working Group, Investigates bulk density and porosity of Lucy Trojan asteroid targets and surface processes/morphology.
3. STRATA-1 ISS, Hermes microgravity regolith dynamics experiment.

Humberto Campins

1. NASA OSIRIS-REx Mission Science Team, Interdisciplinary Scientist for asteroid composition and morphology.

2. CAESAR, comet nucleus sample return under consideration for New Frontiers 4, Co-I in the comet science working group.

Dan Scheeres

1. STRATA-1 ISS, Hermes microgravity regolith dynamics experiment.
2. JAXA Hayabusa2 Science Team, Microgravity dynamics, Astrodynamics, and the impact experiment scheduled for this year will provide a direct means to determine the strength of the surface of the asteroid Ryugu.
3. NASA OSIRIS-REx Mission Science Team, Microgravity dynamics, Radio Science Lead.

Rob Mueller

1. JAXA Martian Moon eXploration (MMX) mission, project manager for the Pneumatic Sampler being provided by NASA to JAXA.
2. Plume Surface Interaction Effects for lunar missions – The NASA KSC SSERVI CLASS team supported a NASA agency workshop at the NASA Marshall Space Flight Center (MSFC) to assess "state of the art" in analysis and data for future prediction and environments modeling. This effort will inform and coordinate future lunar mission design and analysis at NASA.

Addie Dove

1. SurfSat, CubeSat, PI, Built, delivered, and launched (Sept 15, 2018).
2. QPACE, CubeSat, Co-I.
3. STRATA-1 ISS, Hermes microgravity regolith dynamics experiment (Experiment PI).

Josh Colwell

1. SurfSat, CubeSat, Co-I, Built, delivered, and launched (Sept 15, 2018).
2. QPACE, CubeSat, PI.
3. Cassini, Co-I on UVS instrument.

Dan Durda

1. STRATA-1 ISS, Hermes microgravity regolith dynamics experiment.

Yan Fernandez

1. NEOWISE: collaborator in the mission's comet group led by James Bauer (U. Maryland) and Emily Kramer (Caltech/JPL).
2. CAESAR, comet nucleus sample return under consideration for New Frontiers 4, Co-I in the comet science working group.
3. NEOCam: Co-I and Investigation Team member, and the comet group lead.

Chris Herd

1. CAESAR, comet nucleus sample return under consideration for New Frontiers 4, Science Team Member, Cold Curation Expert.
2. Mars 2020, Returned Sample Science Board member (ended June 2018).

Robert Macke

1. LUCY Science Team, collaborator, Interior and Bulk Properties working group.

David Kring

Lunar and Planetary Institute, Houston, TX

Center for Lunar Science and Exploration (CLSE)

CAN 1 Team

1. LPI-JSC Center for Lunar Science & Exploration (CLSE)

1.1 Science

The science objectives of the *Center for Lunar Science and Exploration* (CLSE) involve the origin, collisional or impact delivery, and processing of planetary material, especially volatiles, on the Moon. The team's research includes analyses of lunar samples and, because the source of volatiles is dominated by asteroids, meteoritic samples of asteroids. In our parallel exploration studies (Section 1.2), we developed strategies for testing new ideas with future lunar missions and, in the case of volatiles, methods to prospect for, and recover, resources for a sustainable exploration program.

We began the year with a SSERVI-sponsored study, coordinated with other SSERVI teams, that describes *Transformative Lunar Science* that will be possible with NASA's evolving Lunar Exploration Campaign. That study, prompted by a request from SMD Associate Administrator Thomas Zurbuchen, was delivered January 29 and briefed at NASA Headquarters May 30 (Fig. 1). This document captures, at the highest level, the strategic implications of a lunar exploration campaign and the types of scientific outcomes that may be realized. Due to the integrated nature of SSERVI, the briefing provided a description of how science and exploration can function together (e.g., call out box) to maximize productivity and the accomplishments of a lunar exploration campaign. Sample return was recognized as a cornerstone of Apollo's success (Fig. 2) and will be a fundamentally important capability of the current lunar exploration campaign.

- Explore the unexplored: go to the lunar farside and poles.
- To make truly transformative scientific discoveries, we need sample return missions to high-priority landing sites.
- An integrated robotic and human exploration program, with international and commercial partners, will produce the greatest science and lead to the sustainable exploration program of SPD-1.

Those strategic assessments were augmented throughout the year with a series of focused scientific studies, some of which are briefly captured here.

We began by building on a previous CLSE finding: that mare eruptions could release so much vapor that a transient atmosphere may have surrounded the Moon (Needham and Kring, 2017). That atmosphere may have been responsible for a sizable fraction of the volatiles in polar permanently shadowed regions (PSRs) that may be suitable for in situ resource utilization (ISRU). This year, we augmented that study with an investigation of the abundance of water that might be released by crustal deformational processes, such as moonquakes and impact cratering events. Interestingly, the mass produced by those processes approaches that of solar wind production. We note that the previously identified mare source produced volatiles during specific intervals

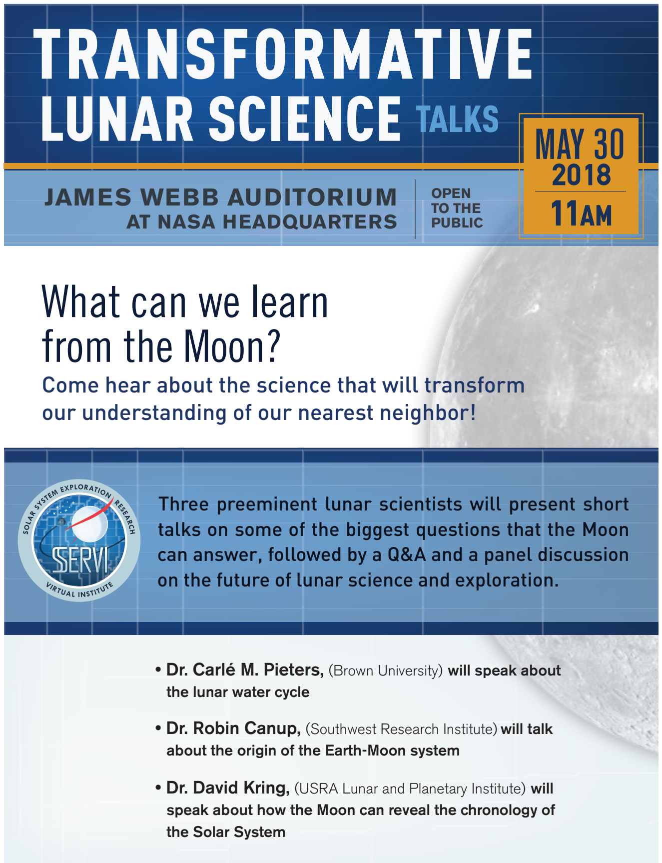


Fig. 1. NASA flyer announcing the public briefing of Transformative Lunar Science with an outline of the topics that were covered.

of time (e.g., 3.5 Ga), whereas the newly identified crustal source continued to operate long after mare eruptions diminished. Thus, it may be a relevant source for younger ice deposits. A preliminary analysis was presented (Taylor et al., 2018) at a SSERVI co-sponsored meeting about lunar volatiles hosted by the Applied Physics Laboratory.

We continued to measure water abundances in a variety of Apollo and lunar meteorite samples. At the same time, we looked forward to future missions that may further constrain lunar water abundances and better illuminate the lunar water cycle. We found that the existing sample collection does not allow us to sample the lunar water cycle in the same geographic region. For example, while we have samples from the Apollo 17 site that represent deep magmatic reservoirs (norites and troctolites) and surface extruded magmas (pyroclastic glasses), the norites and troctolites represent a completely different geographic region than the extruded magmas, because they were either ejected from the Serenitatis basin (a distance of 61 to 375 km) or the Imbrium basin (a distance of 1000 km or more). Thus, to properly sample a coherent lunar volatile cycle, future missions need to target a location, like the Schrödinger basin on the lunar farside, where deep magmatic reservoirs and surface extruded magmas from the same region can be collected (Kring and Robinson, 2018a,b).

In previous research, we developed methods to detect meteoritic fragments in lunar regolith samples (Joy et al., 2012; Fagan et al., 2015; Robinson et al., 2018). During the period of heavy bombardment circa 4 billion years ago, meteoritic fragments should have arrived from nearby Earth (Fig. 3). Thus, we began examining lunar regolith breccias for samples of that primitive terrestrial material. In sample 14321, recovered at the Apollo 14 landing site (Fig. 4), we found a surprisingly large clast, about 2 cm long, that had the chemical characteristics of Earth: (1) Presence of the mineral oxycalciobetafite, which indicates terrestrial oxidation conditions rather than lunar reducing conditions; (2) High concentration of Fe^{3+} and W^{6+} in oxycalciobetafite, which indicates

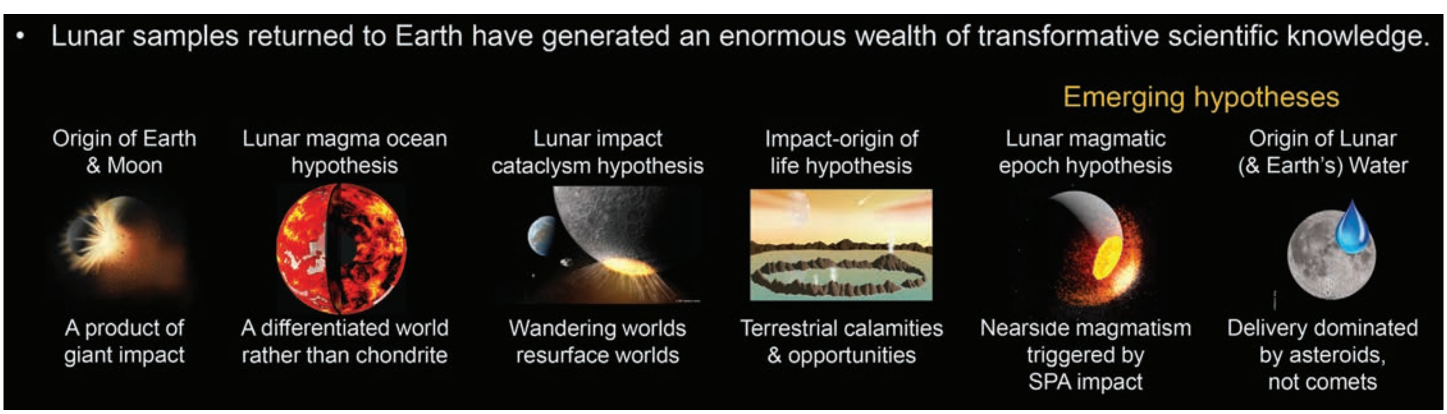


Fig. 2. Major scientific hypothesis prompted by Apollo sample return illustrates the type of transformative science that future sample return missions may generate.

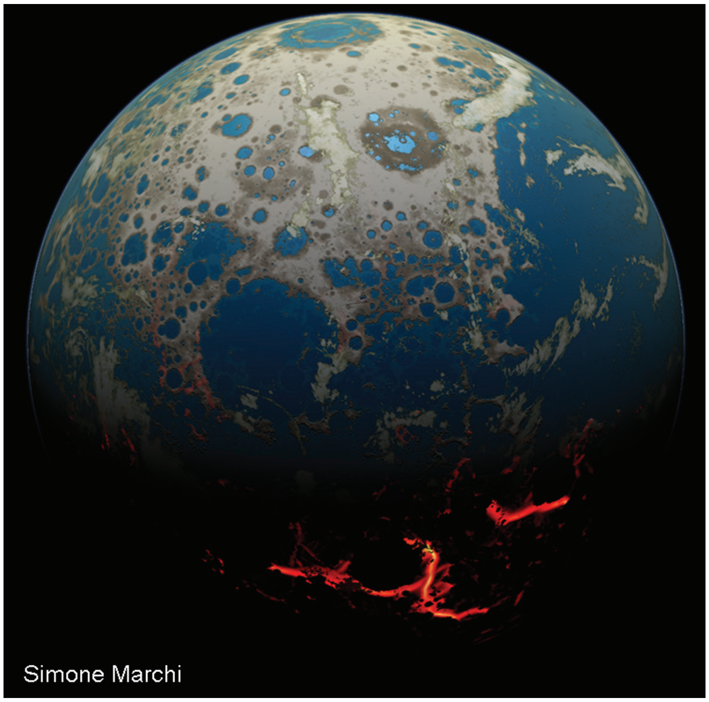


Fig. 3. Artistic rendering of the Hadean Earth, which may have been the source of a rock fragment found in the lunar regolith. Illustration credit: Simone Marchi.

terrestrial oxidation conditions rather than lunar reducing conditions; (3) High concentration of Nb^{5+} in ilmenite, which indicates terrestrial oxidation conditions rather than lunar reducing conditions; (4) Rare earth element concentrations in ilmenite that are more consistent with a terrestrial water-rich or F-rich fluid than a lunar magmatic fluid; (5) Positive Ce-anomaly in zircon, which indicates terrestrial oxidation conditions rather than lunar reducing conditions; (6) Ti abundance in zircon that is consistent with a terrestrial crystallization temperature rather than higher lunar crystallization temperatures; and (7) Ti abundance in quartz that is consistent with crystallization in Earth's crust at a depth of 20 km and completely inconsistent with a lunar crystallization depth of ~170 km where rocks should be composed of olivine and pyroxene rather than the observed quartz and feldspar. While we cannot prove the sample did not crystallize on the Moon, a lunar origin would require a completely different magmatic environment than has ever been detected on the Moon before. We, thus, suggested the sample may be a sample of early Earth (Bellucci et al., 2019). If true, the sample is one of the oldest Hadean Earth rocks ever recovered. This exciting discovery is shedding new light on Hadean Earth conditions and the bombardment that affected the Earth-Moon system when life was emerging.

We also continued to develop new isotopic methods for assessing the types of material that accreted to the Earth-Moon system and unravel the consequences such evidence has for the orbital evolution of planetary materials throughout the Solar System. Using Mo and R isotopes (e.g., Bermingham and Walker, 2018), we can

> An unique clast found in Apollo sample 14321 is an extraordinary find that helps paint a better picture of early Earth and the bombardment that modified our planet during the dawn of life.

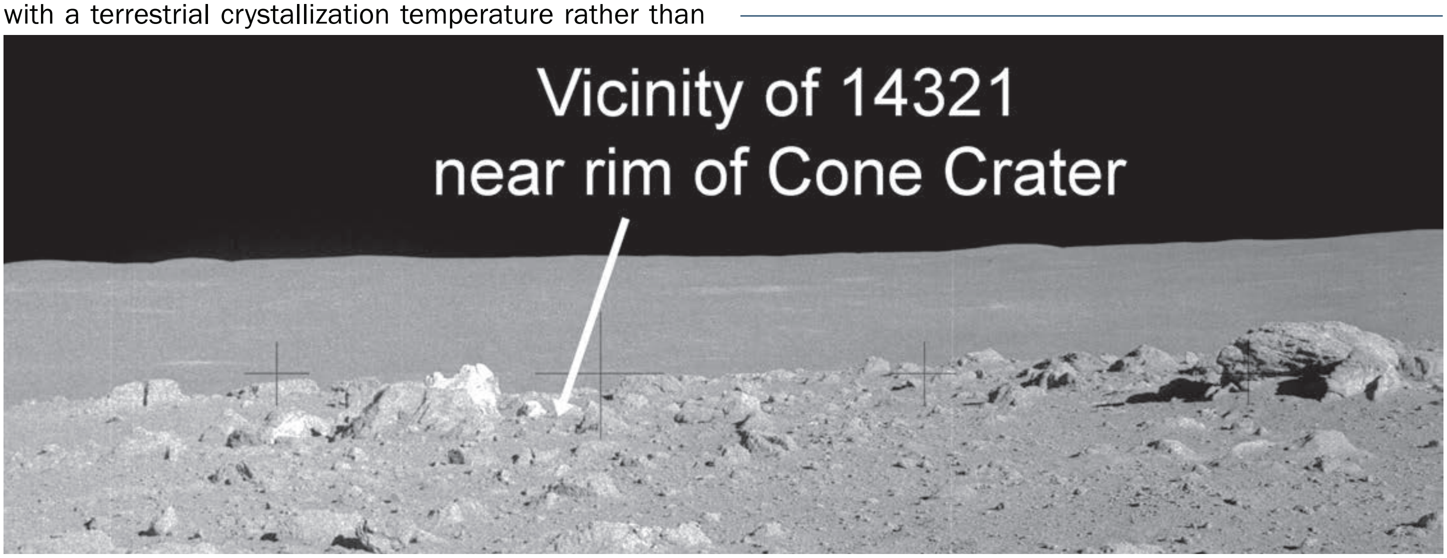


Fig. 4. Photograph of the Apollo 14 lunar surface site where sample 14321 was collected with a possible rock fragment of the Hadean Earth. Annotated detail of NASA photograph AS14-64-9100.

detect the nucleosynthetic fingerprints of impacting parent bodies and asteroid fragments of them that are derived from a reservoir related to carbonaceous chondrites or a reservoir not related to carbonaceous chondrites. Moreover, we can sometimes relate those fingerprints to specific meteorites and, thus, a specific type of parent body in the Solar System. These data can then be used to investigate the mixing of outer Solar System materials into the inner Solar System, including that of volatile-rich and volatile-poor reservoirs. These data can also be used to investigate the accretional and/or orbital processes that caused that mixing. Thus, the combination of meteoritic and lunar sample analyses being conducted here have broad implications for the evolution of the entire Solar System.

Some of the impacts with the Earth-Moon system involved enormous objects. In a study of Pluto-size collisions with the Earth, we – in collaboration with another SSERVI team – showed that metallic core materials and the silicate mantle of the impacting object may be separated (Marchi et al., 2018). Depending on impact angle and velocity, portions of the impactor core may merge with the core of the target (e.g., proto-Earth) or impactor core and mantle materials may be gravitationally lost from the system.

1.2 Exploration

Early in the year, we collated the results of cis-lunar communication studies that we conducted with another SSERVI team (that of Jack Burns at the University of Colorado) and our industrial partners at Lockheed Martin. We studied communication coverage of the farside from a variety of Orion and Gateway orbits. We also proposed a communication solution using an available NSTP-Sat. We developed ConOps for human-assisted tele-operation activities and their requirements (e.g., >1 Mbps) and began developing ConOps for human surface missions. Preliminary input was delivered to the Advanced Communications & Navigation Division (NASA HQ HEOMD) and GSFC, which were developing requirements for an optical communication system. Our – and broader community – input led to the addition of a communication requirement on the Gateway's Power and Propulsion Element (PPE).

We continued our analysis of human-assisted lunar surface tele-operations from Gateway with those same partners. A summary of that analysis was published in Acta Astronautica (Burns et al., 2019).

We envision the agency and agency-supported Commercial Lunar Payload Services (CLPS) missions will include instruments that can evaluate the ISRU potential of volatiles on the lunar surface. The CLSE team, working with the ISRU divisions at JSC and KSC, developed the WAVE+ instrument concept, which provides an analytical solution for three types of volatile deposits: ices in permanently shadowed regions (PSRs); FeO- and TiO_2-bearing basalts in volcanic regions suitable for water production via hydrogen reduction; and solar wind-implanted regolith. The integrated instrument is currently at a technical readiness level (TRL) of 4, although subsystems of it are at TRL 6.

The CLSE team completed its study (Allender et al., 2019) of five human landing sites and the traverses between them that were identified in the International Space Exploration Coordination Group's (ISECG's) design reference mission. The five landing sites were provided to ISECG by Ben Bussey, the HEOMD Chief Exploration Scientist, and our own team's Paul Spudis (who we tragically lost to cancer this year). The CLSE study demonstrate notable science can be achieved at each of the landing sites and, importantly, that the tele-robotic traverses of rovers between crew landing sites provide extraordinary opportunities to survey the polar regions (Fig. 5) for volatile ice deposits suitable for ISRU.

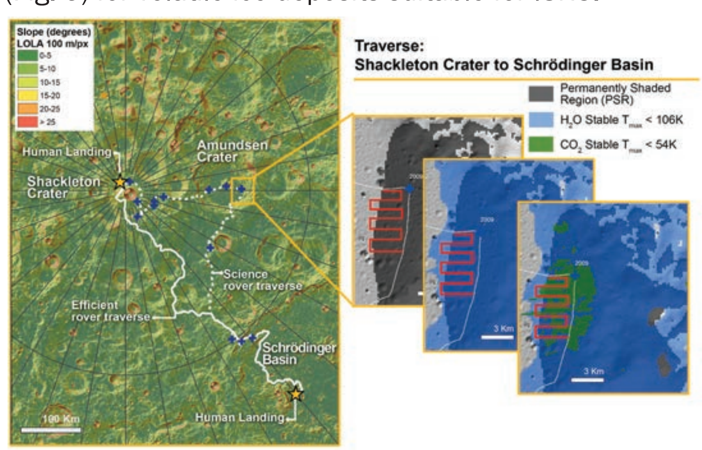


Fig. 5. Map of five human landing sites in an ISECG design reference mission concept and the traverses between those landing sites. Source: Allender et al. (2019).

Finally, we initiated a study of the trafficability of rovers in PSRs and pyroclastic deposits, two high-priority targets for ISRU. To assess the bearing capacity of regolith in those regions for rovers, we used high-resolution LROC images of boulder tracks through the regions. Qualitatively, we detected no variation in the regolith as a boulder crosses from a sunlit area into a PSR (Fig. 6). Preliminary analyses indicate the bearing capacities in those ISRU-related regions are quantitatively similar to that of the Apollo landing sites. This study has been immensely fruitful and will continue.

1.3 Training

Individual undergraduate students, graduate students, and postdoctoral researchers are engaged in all aspects of our science and exploration program. We also supported two additional training programs and a graduate student class.

Ten graduate students were trained in Houston through our *Exploration Science Summer Intern Program*. These students receive classroom and laboratory-style training about current lunar science and exploration topics (e.g., water in and on the Moon). They are also assigned research tasks. One team of five students led a study of a human-assisted tele-robotic traverse on the lunar surface using a previously designated landing site. Throughout that project, the student team worked closely with SSERVI's Moon Trek team as a beta-tester of the Moon Trek tool. Those students also used the latest spacecraft data to evaluate an alternative landing site for a human-assisted tele-robotic mission. A second team of five students led a study (described in Section 1.2) of the trafficability of PSRs and pyroclastic deposits. The students presented preliminary findings at AGU and have submitted a paper to the *Journal of Geophysical Research* that is currently under review.

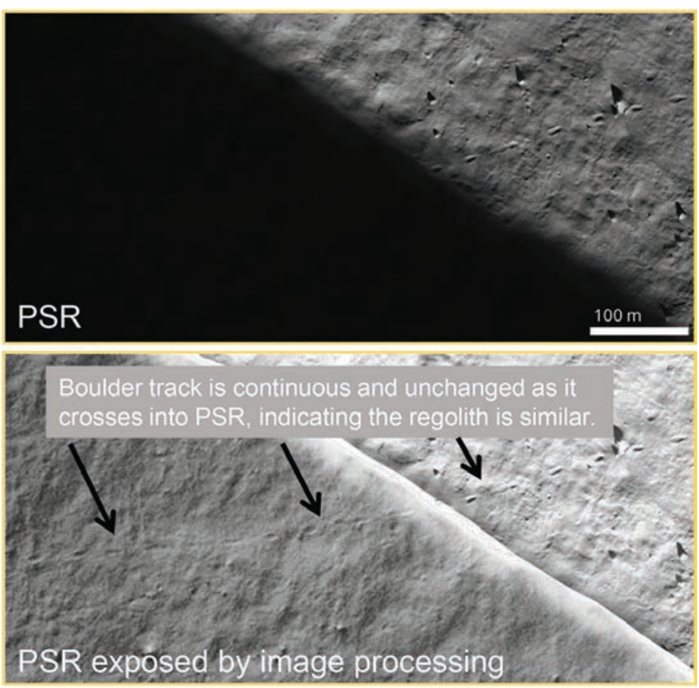


Fig. 6. Boulder track that crosses a sunlit region and then enters a permanently shadowed region. (top) Normally-processed LROC image showing both the sunlit and shadowed regions. (bottom) An enhanced-processed LROC image that reveals the boulder track in the PSR. Detail of LROC image M1178415678LE/RE.

Sixteen graduate students participated in CLSE's *Field Training and Research Program at Meteor Crater*. This intense, immersive, field-based program introduced students to the geology of impact-cratered surfaces. It also provided the students an opportunity for a research-grade field project. They successfully mapped the distribution of remnant fall-back breccia on the rim of Meteor Crater, which will be reported at the 50th *Lunar and Planetary Science Conference* in March 2019.

Finally, the CLSE SSERVI team assisted the Brown University SSERVI team with the design and implementation of a graduate-level course titled "*The Origin and Evolution of the Moon*." This course was supported by the IT staff at SSERVI Central, which made it possible to broadcast lectures and subsequent discussion to the entire Solar System community. The course had some extraordinary moments, such as when NASA Administrator Bridenstine spoke eloquently about Space Policy Directive-1. It was in incredibly illuminating presentation and, thanks to the assets of SSERVI Central, is available in a recorded format for future use.

2. Inter-team/International Collaborations

An essential ingredient in the success of SSERVI and our team's work is the rich collaborations that we have developed with other teams within SSERVI and its international partners. This year, those collaborations helped us address several different topics.

2.1 Inter-team Collaborations

We examined the consequences of large collisions during the accretional phase of Solar System evolution. CLSE

Co-I Rich Walker, with SSERVI partners at the Southwest Research Institute (SwRI), published an analysis of the distribution of metallic core and silicate mantle materials in those types of collisions, which affects the chemistry of rocks we analyze and, therefore, our estimates of the volatile inventory of planets, such as the Earth and Moon. The study involved Simone Marchi and Robin Canup, both of whom are members of Bill Bottke's SwRI team.

Prompted by the success of our study of lunar volatiles and the thin atmosphere it may have generated around the Moon, we continued a study with Alejandro Soto, who is a member of a second SwRI SSERVI team led by Alex Parker. Soto, expert with global circulation models and the properties of tenuous atmospheres, is investigating the special properties of that lunar atmosphere.

On the exploration side of our program, we are working with one of the SSERVI teams at the University of Colorado, led by Jack Burns, and the SSERVI team at NASA Ames Research Center, led by Jen Heldmann. With Burns, we have been exploring Orion and Deep Space Gateway operational issues, such as orbits and communication requirements. With both Burns and Heldmann, we have been exploring tele-robotic issues that may affect rover operations from Earth and the Deep Space Gateway.

As noted in Section 1.3 above, we also collaborated with the SEEED team, led by Carlé Pieters, in the development of a graduate student course about lunar science and exploration. That activity was led by Jim Head (Brown University) and CLSE team PI David Kring (LPI).

2.2 International Collaborations

One of this year's most exciting research results (Bellucci et al., 2019) is a grand example of how international collaborations enrich our work. This study was prompted by CLSE team PI David Kring, but the implementation was led by two of our international partners, Jeremy Bellucci and Alex Nemchin, of the Swedish Museum of Natural History and Australia's Curtin University. The project also involved collaborators from the United Kingdom's Imperial College London, The Netherland's Vrije Universiteit Amsterdam, and the Australian National University.

We also expanded our international partnerships this year to include Harald Hiesinger and Carolyn H. van der Bogert of Germany's *Westfälische Wilhelms-Universität Münster. They and their students immediately contributed several studies (e.g., van der Bogert et al., 2018; Williams et al., 2018; Ivanov et al., 2018) that will enhance our analysis of lunar landing sites being considered for both scientific and ISRU reasons.*

3. Public Engagement Report

A key component of our external activities is a high school research program titled *The Exploration of the Moon and Asteroids by Secondary Students* (ExMASS). It has been an immensely successful program. This year we hosted another suite of nationally-distributed teams. In addition, we published a formal peer-reviewed assessment of the program in *Acta Astronautica* (Shaner et al., 2018). That study demonstrated that ExMASS is a practical model of improving high school student attitudes towards science.

CLSE engaged the public with a broad range of formats designed to reach the broadest range of audiences. PI Kring spoke about lunar exploration at the Houston Museum of Natural Science as part of its Distinguished Lecture Series; (b) PI Kring and LPI's Andy Shaner joined JSC Associate Director Melanie Saunders and Rice University for an event called "*Space Day in Space City*" that involved several hundred middle school students from throughout the Houston region. Saunders and Kring spoke to the students about past, present, and future exploration. Shaner and several other LPI and JSC staff then provided a series of activities for the middle school students. LPI Co-I Taylor and Collaborator Martel published an on-line article featuring lunar science that is suitable for the public and students. Co-I Edgard Rivera-Valentin helped us produce a Spanish-language version of our library exhibit "Protecting Our Home" that is called "Protegendo nuestro planeta." These exhibits are used throughout the country, including underserved communities. PI Kring assisted the city of Flagstaff, Arizona, with its Lunar Legacy Project, which is a year-long educational opportunity that highlights the Apollo program and ongoing efforts to explore the Moon. Several team members supported the International Observe the Moon Night. Throughout the year, our team members also explained to the public the results of lunar exploration by promptly responding to queries from a variety of print, online, radio, and television productions. This summary is not an exhaustive list of our activities, but represents the diverse ways we engaged society.

4. Student/Early Career Participation

Undergraduate Students – Laboratory Researchers

1. Emma Hon (University of Hawaii at Manoa)
2. Hannah O'Brien (University of Notre Dame)
3. Laura Seifert (University of Arizona)

Graduate Students – Laboratory Researchers

1. Sky Beard (University of Arizona)
2. David Burney (University of Notre Dame)

Graduate Students – Exploration Science Summer Intern Program

1. Valentin Bickel *(Max Planck Institute, Germany)*
2. Ellen Czaplinski (*University of Arkansas, USA)*
3. Benjamin Farrant *(University of Manchester, UK)*
4. Elise Harrington *(University of Western Ontario, Canada)*
5. Casey Honniball *(University of Hawai'i, USA)*
6. Sabrina Martinez *(Tulane University, USA)*
7. Alexander Rogaski *(South Dakota School of Mines & Technology, USA)*
8. Hannah Sargeant *(The Open University, UK)*
9. Gavin Tolometti *(University of Western Ontario, Canada)*

Graduate Students – Field Training & Research Program at Meteor Crater

1. Lauren Angotti *(Case Western Reserve University)*
2. Michael Bouchard *(Washington University in St. Louis)*
3. Benjamin Byron *(University of Texas at San Antonio)*
4. Neeraja Chinchalkar *(Auburn University)*
5. Sietze De Graaff *(Vrije Universiteit Brussel)*
6. Thomas Déhais *(Vrije Universiteit Brussel)*
7. Lori Glaspie *(Northern Arizona University)*
8. Joshua Hedgepeth *(University of Western Ontario)*
9. Madison Hughes *(Washington University in St. Louis)*
10. Pim Kaskes *(Vrije Universiteit Brussel)*
11. Jane MacArthur *(University of Leicester)*
12. Maree McGregor *(University of New Brunswick)*
13. Catherine Ross *(University of Texas at Austin)*
14. Kaitlyn Stacey *(University of Texas at Dallas)*
15. Stephanie Suarez *(University of Houston)*
16. Christina Verhagen *(Rutgers University)*

Postdoctoral Fellows

1. Dr. Jeremy Bellucci (Swedish Museum of Natural History)
2. Dr. Katherine Bermingham (University of Maryland)
3. Dr. Katharine Robinson (USRA-LPI)
4. Dr. Martin Schmieder (USRA-LPI)
5. Dr. Joshua Snape (Swedish Museum of Natural History)
6. Dr. Timmons Erickson (USRA-LPI)

Note: We also support 10 high school research teams across the country.

5. Mission Involvement

1. CubeX, CubeSat X-ray Telescope, concept studied for SMD, Science team member David Kring
2. Hayabusa2, asteroid sample return mission, Science team member Mike Zolensky
3. Osiris-REx, asteroid sample return mission, Science team member Tim Swindle
4. WAVE+, a proposed lunar surface instrument, Principal Investigator David Kring

William Farrell

NASA Goddard Space Flight Center, Greenbelt, MD

Dynamic Response of Environments at Asteroids, the Moon, and Moons of Mars (DREAM2)

CAN 1 Team

1. DREAM2 Team Project Report

DREAM2 has 4 space environmental themes in the area of space plasma interactions at airless bodies (1.1), collisionless atmospheres or exospheres formed at airless bodies (1.2), radiation environment (1.3), and surface interactions (1.4). DREAM2 also has 2 derived themes: one being team intermural studies, like that recently performed in support of Resource Prospector (1.5) and the other being DREAM2's footprint into mission activities (5.0).

1.1 Plasma Environment

The DREAM2 plasma team conducted fundamental data analysis and theoretical investigations focused on the Earth's Moon and other small bodies. Highlights include fundamental investigations of the physics of the interaction of the solar wind protons with unmagnetized areas of lunar regolith, and the characteristics of the resulting scattered/reflected protons [Lue et al., 2018]. This work is a companion paper to the work by Poppe et al. [2017], which studied the reflection of protons from magnetized regions of the Moon. DREAM2 plasma team members also studied the effects of these reflected protons on the near-Moon plasma environment, with an oral presentation on this topic at AGU by Ms. Stephanie Howard. The DREAM2 team also studied the trailing wake downstream from the Moon, utilizing a novel technique to infer wake electric fields from electron measurements, and comparing to a theoretical treatment of an asymmetric wake. This work was presented by Dr. Shaosui Xu at AGU, and submitted to GRL. DREAM2 members were also active in planning the next steps in lunar exploration, participating in the Lunar Gateway workshop, making presentations on the use of the platform to study solar wind and geomagnetic tail plasma and the use of a patch plate onboard the platform to examine solar wind implantation, diffusion and hydroxylation.

Another highlight of the DREAM2 plasma team's 2018 research was a comprehensive investigation of the lunar ionosphere in the geomagnetic tail (Figure 1.1.1) [Halekas et al., 2018]. In the solar wind, ionized constituents of the Moon's exosphere do not comprise a significant portion of the charged particle density, and do not appreciably perturb the local plasma environment. However, in the tenuous environment of the Earth's magnetic tail, the Moon is often the dominant source of plasma, and this plasma can significantly affect the local environment. Halekas et al. [2018] used ARTEMIS measurements of electric field oscillations to probe this tenuous ionosphere and determine its properties and dynamics.

1.2 Exospheres at Airless Bodies

Exospheres, or collisionless atmospheres, form as a direct result of space weathering of the surfaces at airless bodies. Solar radiation, space plasmas, and meteor impacts all create outgassing in the form of thermal, photonic, and electron desorption, plasma sputtering and impact vaporization. Depending upon the species

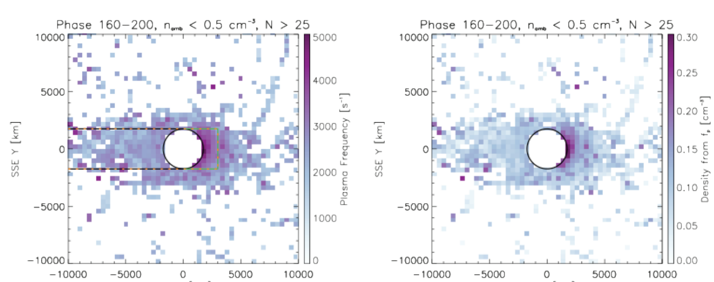


Figure 1.1.1. Frequency of narrowband plasma oscillations (left), and the resulting inferred ionospheric density (right) near the Moon in the lunar geomagnetic tail.

released, the ejection velocity, and the gravity of the body, the material can remain in the local space environment to form a surface bounded exosphere.

DREAM2 team members continue to contribute to knowledge of the lunar volatile and exosphere environment from observations, Monte Carlo models, and laboratory studies. Highlights include:

Hurley and Benna [2018] simulated lunar exospheric water events from meteoroid impacts. Their model calculates the probability of measuring any given density from the water vapor released, given a meteoroid impact mass distribution and water content. They calculate the mission profile required to measure the water released by meteoroid impacts on the Moon for >1% mass fraction of water. Figure 1.2.1 illustrates the model results of a 1 gram water release at 5000K at a time 30 seconds after impact.

Prem et al. [2018] performed Monte Carlo simulations of volatile transport on the Moon and other airless bodies with and without a surface roughness model. They conclude that small scale temperature variations and shadowing lead to a slight increase in cold trapping at the lunar poles accompanied by a slight decrease in photo-destruction.

Killen et al. continue to observe the lunar sodium exosphere remotely using their coronagraph situated at the Winer Observatory in Sonoita, Arizona. They reported

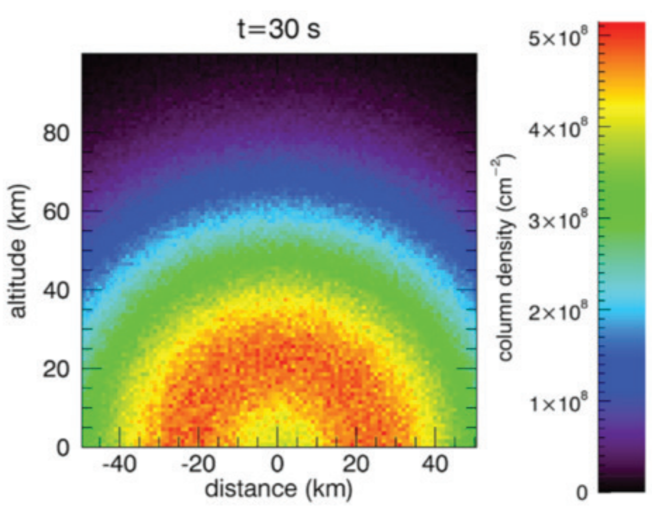


Figure 1.2.1 – The simulated water vapor cloud from a 1 g water release at 5000K (a temperature consistent with impact vaporization) [Hurley and Benna, 2018].

results featuring possible north/south asymmetries in the lunar sodium exosphere [Killen et al., paper under review, Icarus, 2019].

Sarantos provided modeling support for ground-based Fabry-Perot observations of the lunar sodium exosphere. They reported that the sodium effective temperature distribution of the sodium exosphere to be approximately a symmetric-function of lunar phase with respect to full Moon. Within magnetotail passage they found temperatures in the range of 2500 – 9000K [Kuruppuaratchi et al., 2018], consistent with the Killen et al. results.

Hodges [2018] performed a time-dependent simulation of the argon-40 exosphere of the Moon that spans 4 draconic years. He shows that the semiannual oscillation of argon identified by the neutral mass spectrometer on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft is consistent with adsorptive respiration in seasonal cold traps near the lunar poles. The magnitude of the oscillation requires that high energy adsorption sites on soil grain surfaces at polar latitudes be free of water contamination.

McLain and Keller continue to perform laboratory studies of gas sorption on regolith material at low temperatures to simulate the effects in lunar polar and nightside regions. These adsorption/desorption experiments are being performed in a separate UHV surface science chamber designed to measure laser-induced thermal desorption (LITD) from lunar soils. These LITD data indicate that the maturity of the lunar soil significantly increases the distribution of adsorption sites. Therefore, the temperature range at which volatiles like argon and carbon dioxide stick and desorb is significantly higher than that of less mature soils.

Killen and David Williams are continuing a study of the lunar exosphere using the recently archived LACE data from Apollo 17 [Killen et al., paper under review, Icarus, 2019]. In addition, Killen is collaborating with Prabal Saxena, Avi Mandell and Noah Petro on examining moderate volatile loss through lunar history [Saxena et al., paper under review, Nat. Geosci, 2019].

DREAM2 was the inspiration of two smallsat efforts funded under NASA's PSDS3 solicitation: Mike Collier led the PRISM (Phobos Regolith Ion Sample Mission) cubesat development and Tim Stubbs led the BOLAS (Bi-sat Observations of the Lunar Atmosphere above Swirls) tethered cubesat mission development.

1.3 Radiation Environment and Humans

The DREAM2 radiation team continued to explore the changing space radiation environment and how energetic charged particles affect the surface of the Moon. Unlike plasmas, which interact with the surfaces of airless bodies, galactic cosmic rays (GCRs) from outside the Solar System and solar energetic particles (SEPs) from solar flares and coronal mass ejections can penetrate regolith down to ~1 m. These penetrating particles can have significant effects on lunar regolith, and they create a radiation hazard for missions exploring the Moon, moons of Mars, and asteroids.

One highlight of this year's work is the continued investigation of how SEPs can cause dielectric breakdown in lunar regolith [Jordan et al., 2019]. Previously, the team showed that permanently shadowed regions (PSRs) are so cold that large SEP events can cause significant deep dielectric charging in the regolith; the charging can increase the subsurface electric field to the point of dielectric breakdown [Jordan et al., 2017]. The team also showed that breakdown could weather, (i.e., melt and vaporize), regolith in PSRs as much as meteoroid impacts. Building on this work, Jordan et al. [2019] found that the lunar nightside is also cold enough for breakdown to occur, and that breakdown weathering may have affected 3-10% of all gardened regolith on the Moon (Fig. 1.3.1). If so, breakdown-weathered material may be present in the Apollo samples—perhaps "masquerading" as the products of impact weathering. The team also conducted pilot experiments that lay the foundation for future laboratory explorations of how breakdown affects regolith grains.

Another highlight is the team's work showing that the space radiation environment in the inner Solar System is worsening more than predicted—something that was not expected when DREAM2 began [Schwadron et al., 2018].

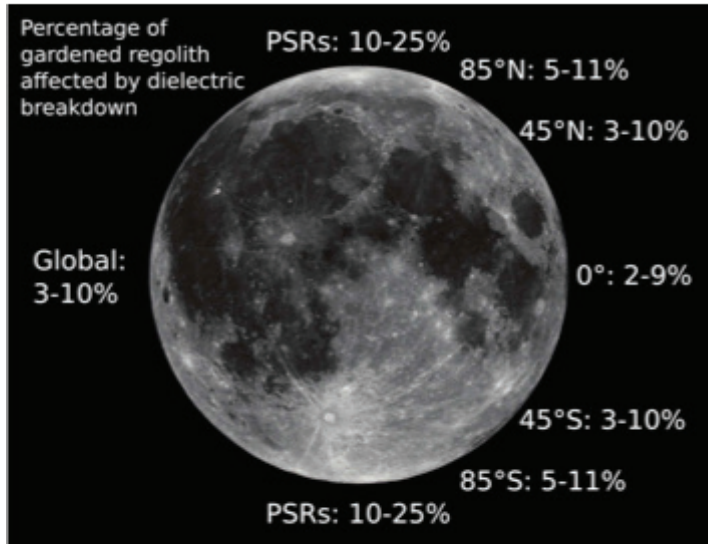


Fig. 1.3.1. Predictions for the percentage of gardened regolith that has been melted or vaporized by dielectric breakdown as a function of latitude and location. Breakdown-weathered material may be present in Apollo soil samples. (Figure from Jordan et al. [2019])

The solar minimum of cycle 23-24 was the longest in over 80 years, and cycle 24 continues to exhibit abnormally low activity. This enables GCRs to enter the inner Solar System more easily, and it has caused radiation dose rates on the lunar surface to be ~10% higher than the team had previously predicted [Schwadron et al., 2014]. This era of anomalously low solar activity suggests the Sun may be entering a new grand minimum, that is, an extended period of reduced activity. Yet although solar activity is low, large SEP events can occur with little warning: in September 2017, the largest event in almost a decade occurred after more than 1.5 years of quiet conditions. This work by the radiation team highlights the need to understand what the changing solar and radiation environment implies for the human and robotic exploration of the Moon, moons of Mars, and asteroids.

1.4 Surface Interactions

The harsh space environment—including impactors, energetic plasma, and radiation—creates damage within the regolith-rich surfaces at the Moon and other airless bodies. In PY 5, DREAM2 team members further examined the surface response to this environment.

Team members Tucker, Farrell, Killen, and Hurley [Tucker et al, 2019] published a new model of solar wind hydrogen implantation and expected surface hydroxylation, and

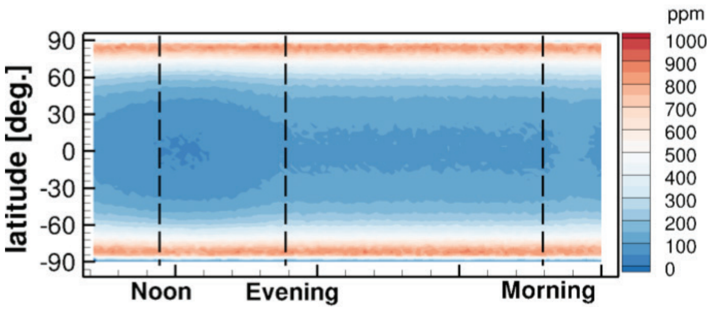


Figure 1.4.1: A new model of the hydrogen (in the form of metastable OH) buildup from solar wind proton implantation and subsequent Fink-like diffusion [from Tucker et al., 2019]. Surface loss of this hydrogen is via recombinative desorption of a pair of H atoms into exosphere H2 .

the formation of the H_2 exosphere (Fig.1.4.1). The model assumes that solar wind protons implant into exposed surface and diffuse out of the surface by hopping from O to O in the regolith oxygen to form surficial metastable OH. The model uses diffusion rates from Fink et al. [1995] and Farrell et al., [2017], and tests modifications of these rates by changing the activation energy of the H diffusion. The model predicted the amount of retained hydrogen at the Moon—including the effects of H atom diffusion in damaged, irradiated silica surfaces. The model then included hydrogen surface loss by recombinative desorption of two H atoms in the top surface to exospheric molecular hydrogen (H_2) via H + H = H2. The results suggest that the H_2 exosphere sensed by LRO/LAMP at 5000/cm^3 is controlled by the surface retention of H atoms – and a Fink-like diffusion is consistent with the H_2 exospheric values. If diffusion of H in the top surface was slower than the Fink et al. rates, the H_2 exosphere would be substantially less dense and the surface H content would be substantially higher. The model also predicts a lunation variation in OH content that was more recently confirmed in the IR observations.

McLain, Farrell, Keller, and Hudson continue their laboratory investigation of proton implantation and associated hydroxylation using the unique Goddard Radiation Facility. In PY5, they compared the ion implantation and OH creation of fused silica to that found in lunar samples. They found that for the complex mix of oxides (SiO_2, FeO, etc) in an actual lunar sample that the 3 micron feature appears different from pure silica – with the maximum depth of the OH feature upshifted in wavelength. This work was presented at the 2018 SSERVI Forum.

Team members Hartzell and Marshall published a paper on astronaut shaking as a means for removing adhered dust at small bodies like Phobos (see Section 1.6 also)– finding that shaking cannot remove small (<10 micron sized) grains due to the stronger cohesion forces. Team members Stubbs and Glenar have recently published a paper on the radiated power from sunlight reflected from the Earth (i.e., Earthshine) in support of the Lunar Prospector Mission (see Section 1.5).

1.5 DREAM2 Intramural Studies: the Space Environment Affected by Resource Prospector

During PY4 and 5, the team initiated a set of studies in support of the now-cancelled Resource Prospector (RP) mission. The rover mission was meant to examine the surface and sub-surface volatile environment in the polar regions, including roving into regions of permanent shadow. A drill was included as part of the package. DREAM2 Co-I Tony Colaprete was the instrument build lead of the RP Near IR and Visible sensing system (NIRVSS) and acted as a liaison between DREAM2 and the RP team.

Specifically, DREAM2 team members created models of RP rover wheel charging that define a limit to rover speeds in low plasma density PSR regions. If the wheel moves over the shadowed surface too fast, excess tribo-charging could occur in PSR regions (in the region of low plasma influx). Partial remedies include having any rover enter the PSR on the part of the crater facing into the solar wind inflow (or the wall facing into the sun) to ensure that deflected solar wind would continue to flow onto the rover to dissipate any charge build-up. In other words, the rover should stay in the electrical contact with the bulk plasma. This work was presented at the recent 2018 SSERVI Forum (Farrell and Colaprete, 2018, https://www.youtube.com/watch?v=HPJcp3oB0iU)

Prem and Hurley also examined the effect the landing craft exhaust plume has on the local volatile environment, especially near the RP rover. During the Chang'e-3 landing, over 100 kg of water was dumped onto the surface from the exhaust plume—in some locations possibly creating nearly a monolayer of water. This water was found to desorb and migrate over the surface. A similar exhaust plume from the RP lander could place a layer of volatiles adjacent to the survey site, which would also desorb and migrate poleward to contaminate the regions examined by RP. DREAM2 models can predict the impact of this process. Preliminary modeling of the landing plume gas merging collisional and collisionless models of the gas and the complex surface adsorption were presented at the recent SSERVI forum by Prem (Figure 1.5.1).

Stubbs and Glenar modeled Earthshine into polar regions where RP will rove and calculated the radiated power from an Earth-reflection to liberate volatiles. The reflected power was found to be relatively low. A paper on this Earthshine is in press in Icarus.

Jordan and Stubbs also have made some preliminary calculations of the possibility of active electrical events from radiation-induced deep dielectric discharge during solar energetic particle events and CME passes during the RP mission. The study was performed to consider whether RP's NIRVSS system would have the potential to directly observe the discharge event.

1.6 Space Environment at Mars' Moon Phobos

In late 2018, a set of four DREAM2 studies regarding the Phobos space environment were published in the journal Advances in Space Research (ASR). They are found in the ASR special issue on the 'Past, Present, and Future of Small Body Science and Exploration,' Volume 62 (15 October, 2018). The studies were part of the intramural DREAM2 team effort that ran from PY3-4 on the targeted

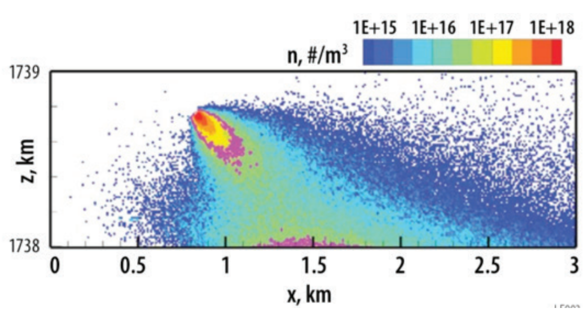


Figure 1.5.1 – A model by Prem et al., 2018 of a lunar lander exhaust plume including the collisional effects at the nozzle and surface. The release of the gas from the surface was modeled using a desorption model of the regolith. The desorbing and migrating plume volatiles represent a source contamination for any rover searching for surface volatiles.

study of the space environment at Phobos which produced a total of 6 published works and a number of conference presentations. The ASR special issue includes DREAM2 articles:

'The possible contribution of dielectric breakdown to space weathering on Phobos' by Jordan et al. https://www.sciencedirect.com/science/article/pii/S0273117718300759

"Anticipated electrical environment at Phobos: Nominal and solar storm conditions' by Farrell et al. https://www.sciencedirect.com/science/article/pii/S0273117717305847

"Shaking as a means to detach adhered regolith for manned Phobos exploration' by Hartzell et al. https://www.sciencedirect.com/science/article/pii/S0273117717306610

"Exospheric escape: A parameter study" by Killen et al. https://www.sciencedirect.com/science/article/pii/S0273117717304222

1.7 Conclusions

At any given time, there are many 10's of DREAM2 scientific and outreach activities occurring during PY5, and we highlight a few of these herein. DREAM2 continues to make great strides in understanding the space environment's effect on the surfaces of airless bodies, and the three-way interaction between the surface response, environmental drivers, and human systems. As noted in the RP study, any rover sent to prospect for resources has to contend with the rover's own contaminating effect on the fragile environment--which may directly impact the prospecting process. Given our vast assets, DREAM2 remains poised to assist the commercial lander groups in evaluating these lander-surface-environmental effects in aiding in the defining of payload and mission requirements.

2. DREAM2 Inter-team and International Collaborations

DREAM2 team members are in continual contact and collaboration with other SSERVI teams, science mission teams, and exploration architecture teams. Examples of DREAM2 interactions with other SSERVI teams include:

REVEALS: DREAM2 PI 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 an NASA Post-doc position via a SSERVI-Central slot that funds early career scientist Micah Schaible to perform lab work on the biochemistry and electrical passivity of irradiated surfaces.

NESS: DREAM2 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: DREAM2 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.

VORTICES: Our team shared strong collaborating work on solar wind/airless body interactions, volatile interactions, and Orion/asteroid interactions and lunar pits. Our strongest collaborations are with individuals Zimmerman, Hurley, Prem, & Hibbitts.

RIS^{4}E: DREAM2 shared strong collaborating work on lunar pits, with the RIS^{4}E field team providing lidar input to pit environment models shared by DREAM2 and VORTICES. We are working with RIS^{4}E team to pursue opportunities to architect, design and build future exploration-oriented field instrumentation for astronaut use. DREAM2 team members also are collaborators on irradiated grain reactive chemistry that feeds into RIS^{4}E's grain cell survivability work.

IMPACT: DREAM2 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 DREAM2 team member. Currently, Anthony Rasca, a former CU grad student, is now a DREAM2 postdoc at GSFC. DREAM2 modelers (Poppe, Zimmerman) are working with IMPACT team members (Daca, Wang) on magnetic anomaly and grain-grain surface charging studies.

FINESSE: DREAM2 share Co-Is Colaprete and Elphic, who under FINESSE perform field studies for the RP mission, while DREAM2 provides support with modeling studies on wheel-regolith interactions and volatile transport modeling (see Section 1.5).

International Partners

Sweden: DREAM2 team members continue close interactions with investigators at the Swedish Institute of Space Physics in Kiruna Sweden. DREAM2 Co-I Mike Collier took a 3-month NASA fellowship (sabbatical) to study with Mats Holmstrom, Stas Barabash, and Martin Wieser in Kiruna in 2012-2013. DREAM2 Co-I Shahab Fatemi relocated from UCB to Kiruna and is working closely with DREAM2 team members in modeling the plasma environment at asteroids, like 16 Psyche and the plasma flow about the Moon in the geomagnetic tail.

3. Public Engagement Report

3.1 Undergraduate Internship Program

Summer 2018 marked a fifth successful DREAM2 Undergraduate Internship Program. Team members at GSFC (W. Farrell, R. Killen, M. Sarantos, M. Collier, J. Cooper, N. Whelley, P. Misra) hosted five students from DREAM2 Co-I institution, Howard University. Students gained experience in both doing and communicating science by participating in DREAM2 team meetings and by preparing and delivering poster and oral presentations attended by the greater GSFC community. Their families were also invited to attend the oral presentations.

Funding for five of the students was leveraged through a NASA Minority University Research and Education Project (MUREP) funding award to Howard University. The project pairs Howard students with GSFC mentors and engages them in cutting-edge Earth and Space Science research throughout their undergraduate tenure. The project takes a multi-faceted approach, with each year of the program specifically tailored to each student's strengths and addressing their weaknesses, so that they experience a wide array of enriching research and professional development activities that help them grow both academically and professionally. During the academic year, the students are at Howard taking a full load of courses towards satisfying their degree requirements and engaging in research with their GSFC mentors via regular telecons, e-mail exchanges, video chats and at least one visit per semester to GSFC for an in-person meeting with their mentor. The students extend their research with full-time summer internships at GSFC, culminating in a Capstone Project and Senior Thesis. As a result, these Early Opportunities Program students, who have undergone rigorous training in the Earth and Space Sciences, are expected to be well prepared to enter the NASA workforce.

3.2 DREAM2 Support for Solar System Exploration Public Engagement Institute

The DREAM2 Education and Public Engagement Team supported the Solar System Exploration Public Engagement Institute that was led out of APL, which took place from July 23-July 27, 2018. 40 informal science educators from around the country participated. The DREAM2 team welcomed the participants to Goddard for a day full of talks, tours, discussions, networking opportunities, and presentations by DREAM2 team members. Content focused on SSERVI target bodies–Earth's Moon, near-Earth asteroids, and the moons of Mars–including formation and evolution, and the space environment, NASA's current plans to explore these objects, and the upcoming NASA's Apollo 50th Anniversary Celebrations. Participating DREAM2 team members included B. Farrell, J. Bleacher, R. Killen, A. Jones, and J. Cooper, and tours included GSFC integration and testing facilities. A lunch discussion invited participants to spend time talking individually or in small groups with scientists to talk, including learning about their work, how they became scientists, and what inspires them.

Figure 3.1 – The 2018 Solar System Exploration Public Engagement Institute hosted jointly by the VORTICES and DREAM2 teams.

The participants were asked to complete a survey at the conclusion of the workshop to gauge its success. The participants all agreed that they gained considerable knowledge about the Moon, objects in the Solar System, as well as current and future space research. Participants quotes about the talks, discussions and tours are: "Being able to speak directly to the scientist is so valuable." "The interactions were phenomenal." The participants found the tours "Highly valuable. Great field trips. I learned so much and was so energized to plan new programs."

4. Student/Early Career Participation

Undergraduate Students

DREAM2 Co-I Prabhakar Misra at Howard University won a NASA award to fund a number of undergraduates for a 4-year internship with DREAM2 and others at GSFC. The Award is "NASA Early Opportunities Program for Underrepresented Minorities in Earth and Space Sciences" (PI: P. Misra, Howard University; Co-PIs: D. Venable, Howard University; B. Meeson, NASA Goddard; S. Hoban, UMBC; & B. Demoz, UMBC; 8/1/16-7/31/19). The HU students are:

1. Skylar Grammas (Mentor: Farrell)
2. Irima Ajang (Mentor: Killen)
3. Ajani Smith-Washington (Mentor: Sarantos)
4. Marla Brown (Mentor: Collier)
5. Robert Coleman (Mentor: Cooper)

Graduate Students

1. Stephanie Howard, Iowa, Solar wind magnetic anomaly plasma disturbances at the Moon
2. Philip Quinn, UNH, Radiation
3. Fatemeh Rahmanifard, UNH, Radiation

Postdoctoral Fellows

1. Charles Lue, Iowa, Space Plasma and ARTEMIS
2. Dov Rhodes, GSFC, Charging on human systems
3. Anthony Rasca, GSFC, Inner heliospheric plasma flow

at small bodies

4. Parvathy Prem, APL, Exospheres and collisional atmospheres

5. Micah Schaible, Ga Tech, DREAM2-REVEALS SSERVI NPP, biochemistry and passivity of irradiated grains

New Faculty Members

1. Orenthal Tucker, NASA Civil Service, GSFC, Exospheres (a former DREAM2 NPP)

2. Wouter de Wet, UNH, Research Scientist

5. Mission Involvement

Shown are DREAM2 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)

PI, Co-I, and Guest Investigator roles (* = DREAM2 collaborator):

1. PSD/Lunar Reconnaissance Orbiter/Petro*/Project Scientist

2. PSD/Lunar Reconnaissance Orbiter/ Keller/Deputy Project Scientist

3. PSD/Lunar Reconnaissance Orbiter/Schwadron/ CRaTER PI

4. PSD/Lunar Reconnaissance Orbiter/Spence/CRaTER Co-I and former PI

5. PSD/Lunar Reconnaissance Orbiter/Hurley/LAMP Co-I

6. PSD/ Lunar Reconnaissance Orbiter/Elphic/Diviner Co-I

7. PSD/Lunar Reconnaissance Orbiter/Stubbs/ Participating Scientist

8. PSD/LADEE/Elphic/Project Scientist

9. PSD/LADEE/Delory/Deputy Project Scientist

10. PSD/LADEE/Colaprete/UVS PI

11. PSD/LADEE/Hodges/NMS Co-I

12. PSD/LADEE/Stubbs/Guest Investigator

13. PSD/LADEE/Glenar/Guest Investigator (named on the Stubbs GI proposal)

14. PSD/LADEE/Hurley/Guest Investigator

15. PSD/LADEE/Halekas/Guest Investigator

16. PSD/LADEE//Poppe/Guest Investigator (named on Halekas GI proposal)

17. PSD/LADEE/Sarantos/Guest Investigator

18. PSD/OSIRIS REx/Marshall/Co-I and former lead of Regolith Working Group

19. PSD/OSIRIS REx/Nuth*/Deputy Proj Sci

20. PSD/OSIRIS REx/Lim*/Co-I

21. PSD/OSIRIS REx/Hartzell*/Participating Scientist

22. PSD/Phoenix/Marshall/MECA Co-I

23. PSD/MAVEN/Delory/Co-I

24. PSD/MAVEN/Halekas/Co-I and lead build of ion spectrometer

25. PSD/MESSENGER/Killen/Co-I

26. PSD/Curiosity/L. Bleacher/Communications

27. PSD/Cassini/Farrell/RPWS/Co-I

28. AES/Lunar IceCube/Clark/Science PI

29. HSD/ARTEMIS/Halekas/Deputy PI

30. HSD/ARTEMIS/Delory/Co-I

31. HSD/WIND/Collier/Deputy PI

32. HSD/WIND/Farrell/WAVES and MFI Co-I

33. HSD/Parker Solar Probe/Farrell/Co-I

34. HSD/Parker Solar Probe/Schwadron/Co-I

35. HSD/IBEX/Schwadron/Co-I

36. HSD&ESA/Solar Orbiter/Collier/Co-I Heavy Ion Sensor (GSFC lead)

37. HSD&ESA/SMILE/Collier/Co-I

38. HSD/CuPID cubesat/Collier/Co-I and instrument lead

39. ESA/BepiColumbo/Killen/Co-I

40. ISRO/Chandrayaan-1/Holmstorm*/Co-I

41. JAXA/MMX/Elphic/MEGANE Co-I

42. KARI/KPLO/Elphic/MEGANE Co-I

43. DoD (Space Test Program)/FASTSAT/Collier/Co-I and instrument lead

44. DoD (Space Test Program)/USAF DSX/Farrell/Co-I and Search coil build lead

Mission-recognized supporting roles includes:

45. PSD/Lunar Reconnaissance Orbiter/Glenar/LAMP data analysis

46. PSD/ Lunar Reconnaissance Orbiter/Prem/Diviner and Mini-RF data analysis

47. PSD/ Lunar Reconnaissance Orbiter/Wilson/CRaTER data analysis

48. PSD/ Lunar Reconnaissance Orbiter/Jordan/ CRaTER data analysis

49. PSD/LADEE/Marshall/UVS instrument calibration

50. PSD/Cassini/Cooper/CAPS team member, data analysis

51. PSD/Cassini/Hurley/Enceladus modeling

52. HSD/ARTEMIS/Poppe/plasma data analysis

53. HSD/ARTEMIS/Fatemi/plasma data analysis & modeling

Jennifer Heldmann

NASA Ames Research Center

Field Investigations to Enable Solar System Science and Exploration (FINESSE)

CAN 1 Team

1. FINESSE Team Project Report

Multiple research projects pertaining to the geologic processes of impact cratering and volcanism have been completed by the FINESSE project as the two dominant geologic processes shaping the landscapes of the Moon, asteroids, and Phobos & Deimos. In addition to our scientific research, we have conducted field-based research to optimize the science return and operations for future robotic and human missions. Selected highlights from these research activities are presented here.

1.1 Impact Cratering

1.1.1 Geochronology

The impact of asteroids, comets, and meteorites is among the most ubiquitous surface processes in the inner Solar System, and the tempo of impact through time will be a high-value research target for future missions of exploration. However, such research will require the analysis of carefully collected samples and the application of high-precision isotope geochronology. Unfortunately, robust dating of impact-produced rocks (impactites) is challenging. Most contain a mixture of pre-existing and newly formed material, and some isotopic systematics can be disturbed easily during subsequent thermal events. It is critical to develop strategies for optimal sample selection and precise analysis of small sample masses through terrestrial analog studies.

Applying a battery of chronometers – U/Pb, $^{40}Ar/^{39}Ar$, and (U-Th)/He – and multiple analytical protocols to a diverse suite of impactites, we are conducting such

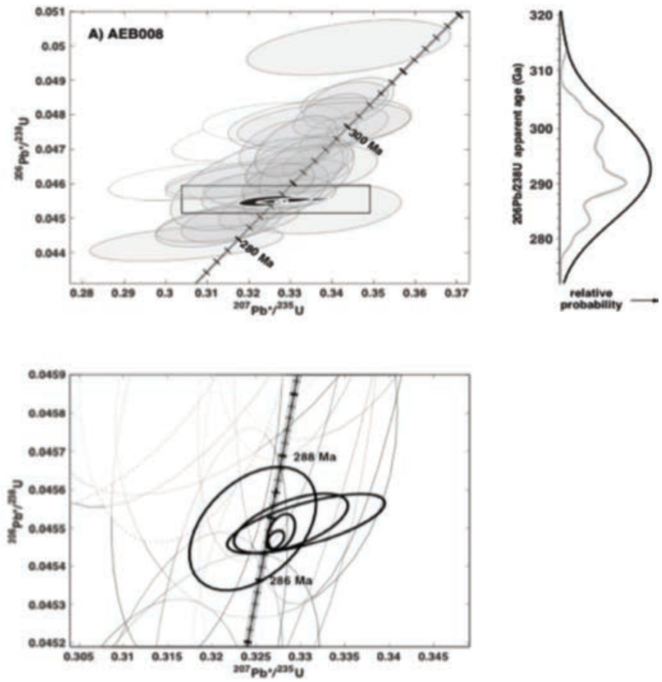


Figure 1. A, top left): LA-ICP-MS and ID-TIMS (black ellipses with white outline, N=5) U/Pb data from impact-generated zircons in clast-poor impact melt (sample ID WCIS14AEB008). The LA-ICP-MS data used in the calculation of the weighted mean $^{206}Pb/^{238}U$ age (N=27 of 33) are shown as gray ellipses with solid dark gray outlines (the dashed gray outlines are reversely discordant LA-ICP-MS data (N=6 of 33) that was excluded from the calculation of the weighted mean). The box indicates the region shown in Fig. 1C. B, top right: The plot on the right shows the KDE (black) and PDP (gray) for all zircon $^{206}Pb^{*}/^{238}U$ ratios measured from sample AEB008. C, bottom) Closer view of ID-TIMS U/Pb data (open ellipses with thicker solid black outlines), with LA-ICP-MS data in the background (gray ellipses with dashed gray outlines indicate "were not included" in the calculation of the weighted mean). All data have been corrected for common Pb (PbC). Error ellipses represent the 95% CI. Gray shaded region around the concordia line reflects the decay constant uncertainties (2σ).

Mineralogic diversity of rock sample selection coupled with a combination of age-dating techniques is critical for enabling accurate geochronology studies.

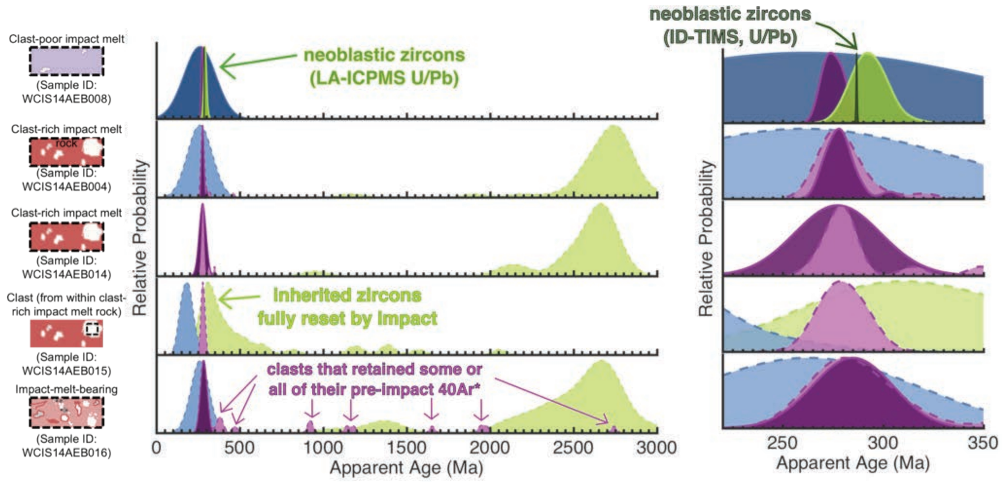


Figure 2. Multichronometer comparison between West Clearwater impact rocks. Plots show the kernel density estimates (KDEs) of the dates measured in five samples. The KDE is a way of representing only the distribution of the dates themselves and does not take uncertainties into account. The plot on the right shows the same data, as the plot in the middle. The data is grouped by chronometer ($^{238}U/^{206}Pb$, $^{40}Ar/^{39}Ar$, or (U+Th)/He), analytical technique, and whether the analysis targeted relict material or impact melt. (Information about the color scheme is in Table 1). The stylized illustrations on the left indicate the sample type and sample ID corresponding to each set multichronometer data.

a study of the West Clearwater impact structure at Lake Wiyâshâkimî, Quebec, Canada (Figure 1). Our results thus far suggest that efforts to select the "best" samples based on traditional field criteria alone (e.g., the avoidance of samples that appear relatively weathered) are only partially successful. The isotopic systematics of pre-impact clasts of individual minerals (xenocrysts) and rocks (xenoliths) are variably reset in West Clearwater impactites, implying that systematic study of such relicts can help increase confidence in dates obtained for melt materials (Figure 2). U/Pb analysis of impact-related zircons by thermal ionization mass spectrometry (TIMS) yielded the most precise age currently available for this impact structure – 286.55 ± 0.33 Ma (2σ, includes decay constant uncertainty) – but such zircons are not found in most samples. We found that screening large numbers of zircons through comparably low-precision laser ablation U-Pb analyses helped identify zircons that were most amenable to high-precision TIMS work. All other methods have yielded highly dispersed results so far, but the combination of low-precision and high-precision chronometric data obtained through a variety of techniques can improve overall confidence in age assignments for impact craters. Unfortunately, not all impactites are amenable to the application of multiple isotopic chronometers, and thus an important criterion for sample selection is mineralogical diversity.

1.2 Volcanism

1.2.1 Rheology of Lunar Lavas – Implications for Sinuous Rille Formation on the Moon

Formation of sinuous rilles on the Moon, such as the

Chronometer	Material analyzed (key for the colors in the figure above)	Analytical techniques	Instrumentation
$^{40}Ar/^{39}Ar$ in multiple K-bearing phases	inherited clasts	*in situ* UV laser ablation of thick sections	Noblesse gas source mass spectrometer (ASU, analyst: A. Brunner)
	impact melt crystals		
(U+Th)/He in zircon	inherited zircons	UV laser ablation of zircon crystals (separated out from crushed rock)	SFT and ICP-MS (ASU, analyst: A. Brunner)
	neoblastic zircons		
U/Pb in zircon (only $^{238}U/^{206}Pb$ dates are plotted)	inherited zircons	Laser ablation, inductively coupled plasma mass spectrometry (LA-ICP-MS)	ICP-MS (ASU, analyst: A. Brunner)
	neoblastic zircons		
	neoblastic zircon	Isotope dilution thermal ionization mass spectrometry (ID-TIMS)	TIMS (Princeton, analyst: B. Schoene)

Table 1. Summary of Geochronology Techniques.

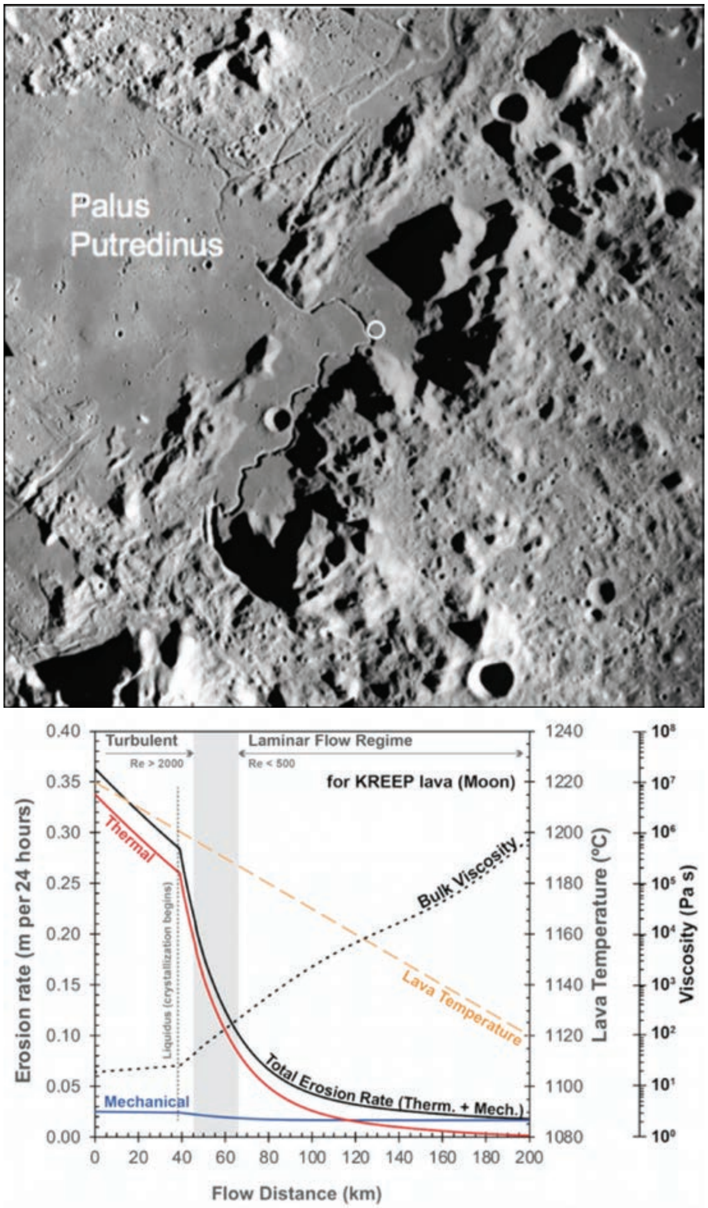


Figure 3: top = Orbital photo of Rima Hadley, a sinuous rille located west of the Apollo 15 landing site (circle) within a KREEP terrain; bottom = example calculation of thermo-mechanical erosion rate as a function of flow distance for a KREEP analog basalt erupted on the lunar surface with a continuous channel width of 480 m and lava thickness of 10 meter on a slope of 0.2º. Erosion rate quickly diminishes upon cooling below the liquidus due to increasing viscosity (in turn lower flow velocity and strain rate). Viscosity calculations include yield strength of the lava. The gray band indicates transition from turbulent to laminar flow regimes shortly after lava cools below the liquidus. This basic model assumes a constant cooling rate of the lava erupting about 20 ºC above the liquidus temperature.

Hadley Rille visited during Apollo 15, is still debated, despite being known as volcanic features for about 50 years. Much of the formation of sinuous rilles is dictated by the rheology of the lava, but rheological data of lunar analogs have yet to be explored. Therefore, we studied the rheology of synthetic KREEP during cooling and crystallization via a series of laboratory experiments. The relationship between temperature, crystallinity, and rheology is fully described, and is then used to model the thermo-mechanical erosion model that incorporates the changes in flow behavior (e.g., Newtonian fluid transitioning to pseudoplastic flow transitioning to a Herschel-Bulkley fluid).

Figure 3 shows the thermo-mechanical erosion potential for lunar KREEP lava for sinuous rilles such as Rima Hadley. From our experimental data, we conculde that sinuous rilles made of KREEP basalt must emplace above ~1210 ºC for thermo-mechanical erosion to be a viable formation mechanism. Our results also imply that sinuous rilles exceeding 40 km in length emplace as tube-fed flows rather than open-channel flows due to radiative heat loss, the rapid increase in viscosity of several orders of magnitude due to crystallization during open-channel flow.

1.2.2 Thermal Properties of Planetary Melts

Heat transport plays a crucial role in the thermal evolution of high-temperature, magmatic regimes on Earth and other planets and moons. Thermal conductivity is a product of density (ρ), thermal diffusivity (D) and heat capacity (C_p). We measured D and C_p as a function of temperature for a suite of planetary analog tholeiites relevant to the Moon, Mars, Mercury, Io and Vesta. Heat capacity measurements were conducted by differential scanning calorimetry (DSC) on glasses and liquids covering temperatures from 400 to 1750 K, D measurements were conducted by laser-flash analyses (LFA) on glasses from room temperature up to their melting point slightly above the glass transition (T_g),

Sinuous rille formation on the lunar surface by thermo-mechanical erosion is restricted to lava erupting above the liquidus temperature, when low viscosity allows for turbulent flow regimes.

Thermal conductivity of silicate glasses and liquids relevant for major silicate bodies in the Solar System are strongly composition dependent. Models of planetary evolution and igneous processes should use composition-specific thermal conductivity data whenever possible.

and densities were already known.

Our results demonstrate that the variability of D and C_p is very composition-specific, making thermal conductivity strongly composition-dependent. We developed a new model to estimate D of glasses as a function of composition and temperature based with 2σ uncertainty

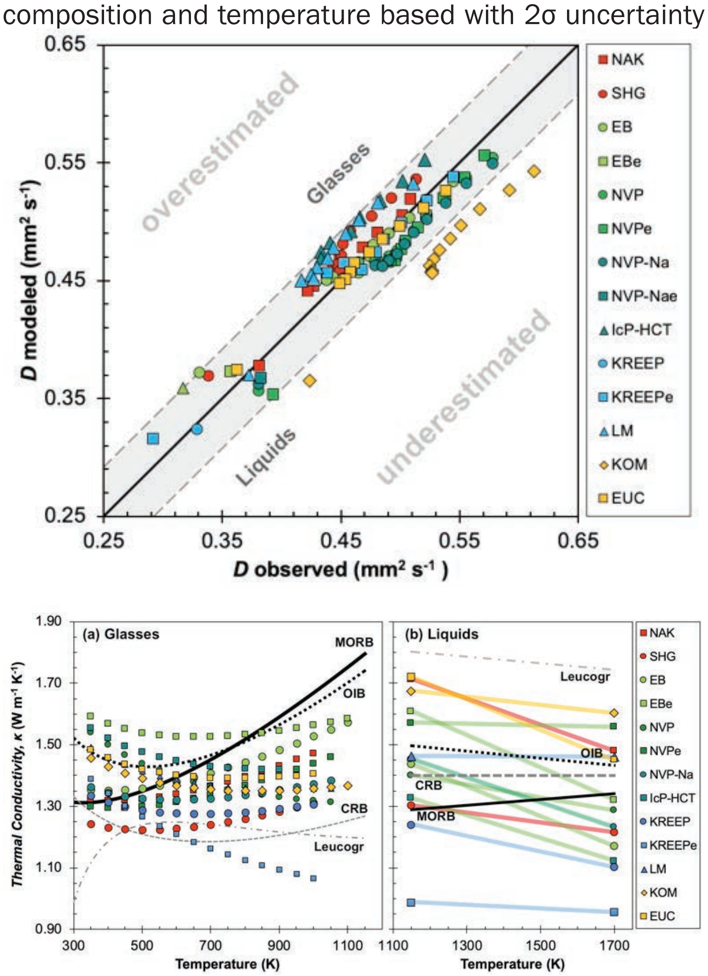


Figure 4: Top: Modeled thermal diffusivity of glasses and liquids (against the measured values. Gray area between dashed lines represent a 2σ RMSD envelope of 0.042 mm^2 s^{-1} between all modeled and measured D values. Bottom: Thermal conductivity of glasses (a) up to 1000 K and their liquids (b). Calculated values are smooth because inputs are smooth. For context, fitting lines for terrestrial samples (Hofmeister et al., 2016) are plotted. MORB = Mid-Ocean Ridge Basalt, OIB = Ocean island Basalt, CRB = Continental Rift Basalt, Leucogr = Leucogranite.

of only 0.042 mm^2 s^{-1} (Figure 4, Top). Thermal diffusivity of the corresponding melt can be calculated with the same uncertainty, but only independent of temperature. The new model for D, in combination with already available models to calculate C_p and ρ, allows us to predict thermal conductivity for planetary glasses and melts to model the thermal evolution of magmatic regimes (Figure 4, Bottom).

All investigated compositions transfer heat much more efficiently by advection rather than conduction, implying that volcanism played a crucial role in the thermal evolution of major silicate bodies in our Solar System, including the Moon. In particular, we found that KREEP and residual/interstitial melts after partial crystallization of KREEP compositions show very low thermal conductivity, which implies that KREEP lavas remain in liquid state much longer than any other magma composition, potentially contributing and dominating to late-stage and recent volcanism on the lunar surface, such as Irregular Mare Patches (IMP's) like Ina D.

1.2.3 Intrinsic Geochemical Variability in Volcanic Rift Zones – Terrestrial Analogs for Magma Evolution in Sill and Dike Networks on the Moon

Field and laboratory analyses of lava flows at the Craters of the Moon National Monument and Preserve (COTM) in Idaho, Kilauea Volcano on the Big Island of Hawai`i, and historic fissure eruptions in Iceland help improve the methods of surface exploration applied to planetary volcanic features. Techniques previously reported to evaluate the magmatic complexities include morphometric analyses of lava surfaces, such as differential GPS, UAV high-resolution imagery and DTM analysis, field and satellite imagery. Current research focuses on the compilation and assessment of nearly 300 geochemical analyses by

XRF for major and trace elements (and comparisons with published data) in order to assess geochemical variations within individual eruptions. Initial field targets at COTM that lie within the northern and southern segments of the Great Rift confirmed a significant chemical diversity along this fissure system (Fig. 5a).

Complexities in magmatic sources and processes of magma mixing and evolution must occur in sill and dike networks (magma reservoirs) that comprise active eruptive fissures. We postulate that multiple reservoirs are important to lunar magmatic systems portrayed in Figure 5b. To address this further we selected regions separate from COTM for field work and sample analysis. Analog targets at Kilauea, which include East Rift Zone eruptions at Mauna Ulu and Kilauea Iki, and fissure eruptions on the floor of the summit caldera, were sampled in late 2017. We also sampled in May 2018 field targets in Iceland, focusing on the Krafla fissure that erupted in 1975 – 1984 along with several other point sites for comparison. The evaluation of geochemical analyses from both the Hawai`i and Iceland excursions are in progress, but initial results confirm the expectations of significant chemical diversity in single fissure eruptions. The models of chemical diversity are also being evaluated to be associated with low shields and eruptive fissures on Mars.

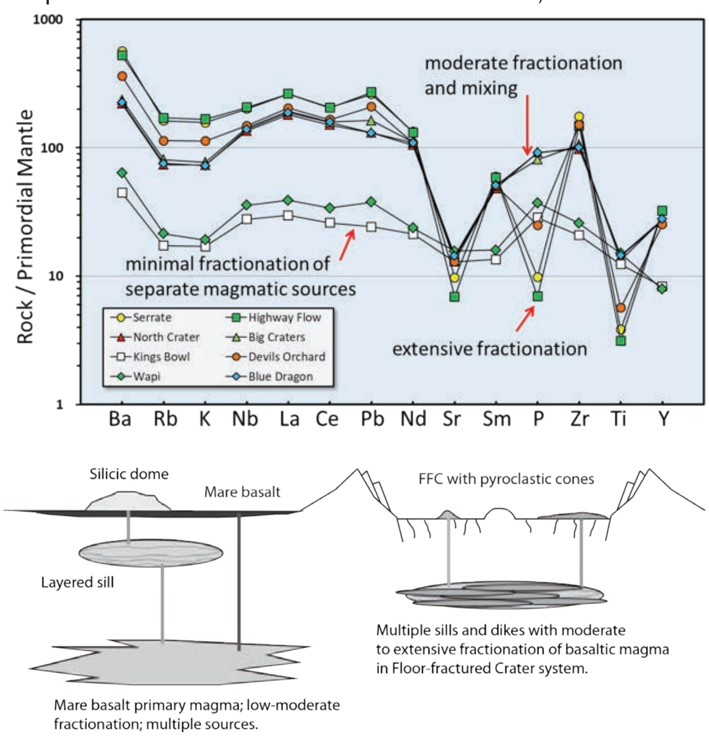


Figure 5: Top-- Geochemical diversity between average compositions of COTM lava fields that depict complex magmatism along the Great Rift fissure system. Bottom--Schematic models of possible subsurface magmatic processes occurring within complex sill and dike networks on the Moon that lead to diverse compositions in magmas related to silicic domes, mare basalts, and floor-fractured craters.

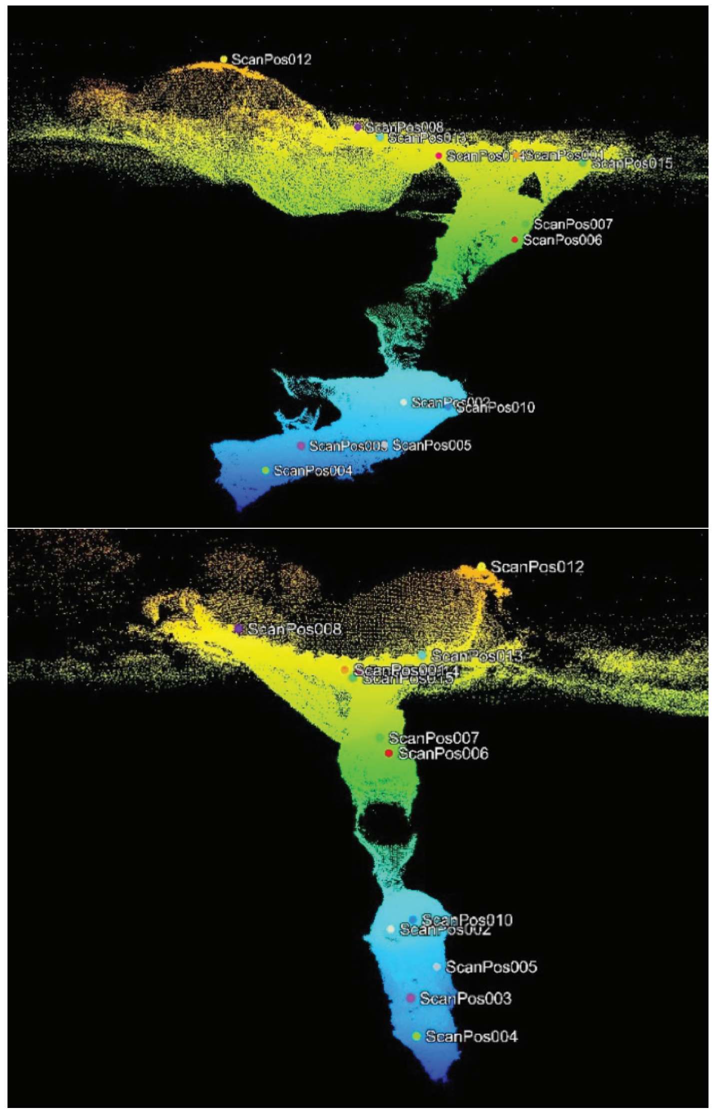


Figure 6. Lidar data of a Triple Volcan lava chamber in Galapagos.

The geochemical diversity within terrestrial analog systems enable an improved understanding of expected magmatic complexities in lunar floor-fractured craters, dike-related linear rilles, and silic domes on the Moon.

1.2.4 Lidar Data Processing and Virtual Reality

Lidar scans of the Triple Volcan lava chamber in Galapagos (collected by Co-Is Brent Garry (NASA GSFC) and Scott Hughes (Idaho State University)) were processed this year (Figure 6) and add to a growing archive of 3D terrain models and pointclouds collected during the FINESSE project.

Virtual Reality Research

The FINESSE team, led by Brent Garry (NASA GSFC), worked closely with the GSFC Virtual Reality / Augmented Reality (VR/AR) lab team to continue development of two projects that have used field data from FINESSE including lidar pointclouds and digital terrain models (DEMs). This year, analysis tools were developed that can be used to make field measurements in the VR environment and produce additional data products useful for scientific analysis such as changing color ramps for DEMs (Figure 7). The team continues to use pointcloud data sets on the Indian Tunnel lava tube and DEM of the mushroom caps at Kings Bowl, two FINESSE field sites in Idaho. A VR lidar tool was developed that collects pointcloud data within the VR environment (Figure 7). The data can be exported and used with various software programs as actual pointclouds. This VR lidar tool can now be incorporated into robotic and human exploration scenarios and simulations for the Moon or other planetary bodies to test the utility of lidar for surface exploration (Figure 8).

2.1 International Collaborations

2.1.1 Canadian Lunar Research Network, University of Western Ontario.

FINESSE works closely with team member Dr. Gordon Osinski (University of Western Ontario, UWO) as the lead of the Canadian Lunar Research Network, an official SSERVI international partner. This year FINESSE has supported the ongoing sample analysis of West Clearwater Impact Structure samples and publication of results regarding

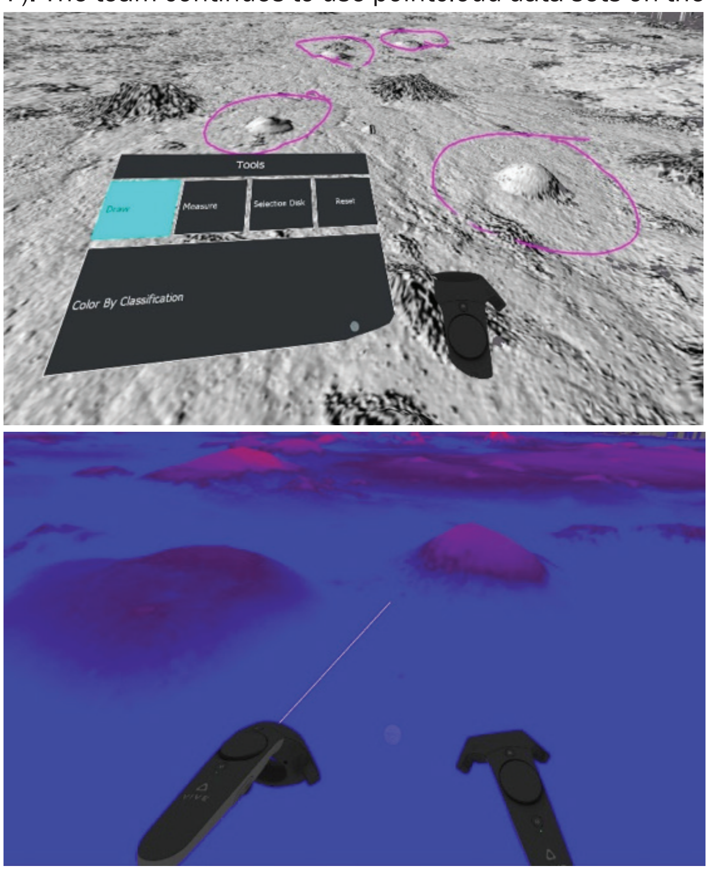


Figure 7. FINESSE contributed to the development of VR tools for science analysis: (Top) Testing of the VR measurement toolkit developed at GSFC on a mushroom cap rock DEM from a FINESSE Idaho field site. (Bottom) A color ramp is applied to the mushroom cap DEM to make the features more easily visualized in the data.

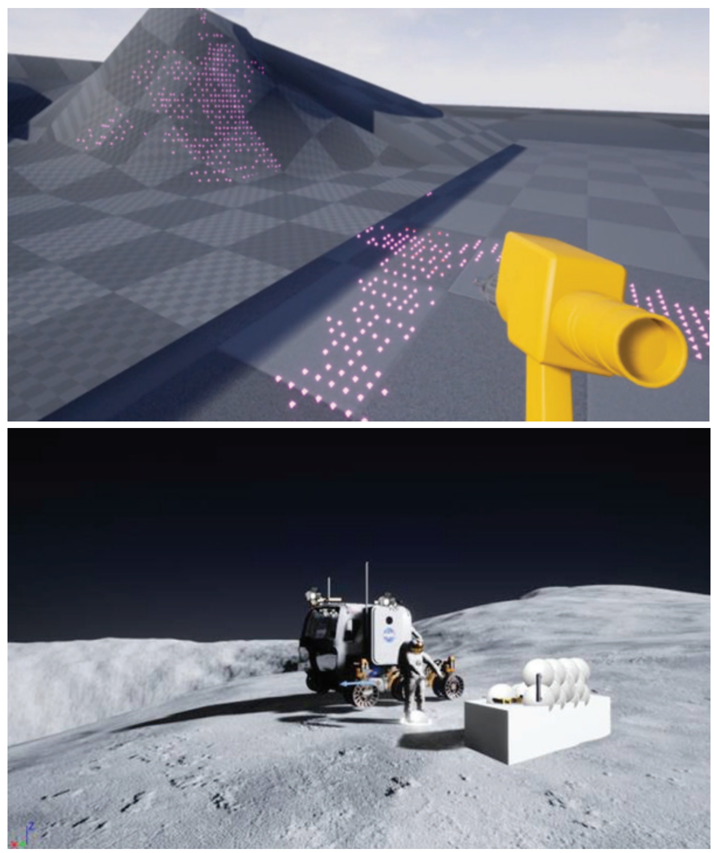


Figure 8. A VR lidar tool was developed to visualize and analyze data for scientific purposes. (Top) Data from the tool (purple dots) can be exported for actual analysis in other software programs. (Bottom) The tool can be incorporated into VR lunar environments to practice surface science operations (e.g., exploration of a lunar pit).

WCIS formation, impact melts, shock history, and melt vein development, among other topics. UWO has also conducted fieldwork in Idaho as ground-truthing for radar data studies of the volcanic fields (C. Neish). FINESSE and UWO are also sharing laboratory instrumentation and sample analysis equipment which is beneficial to both parties for enabling this new science pertaining to WCIS.

2.1.2 Carleton University

Carleton University (Ottawa, Canada) is contributing to the study of using gravity data to map and characterize subsurface volcanic structures such as lava tubes. Ground-truthing of such non-invasive remote sensing techniques to identify subsurface voids in volcanic terrains is important not only to the scientific study of our planet and the Moon, but also for identification of possible lunar structures for future exploration.

2.1.3 KIGAM (Korea Institute of Geoscience and Mineral Resources)

FINESSE Collaborator Kyeong Kim, a researcher with the Korea Institute of Geoscience and Mineral Resources, focuses on lunar science and the applications of XRF analysis on planetary surfaces. Kim deployed to Iceland with the FINESSE team this year (2018) and collected additional basaltic samples for XRF analysis as well as presenting a Korean space science exhibit in Arco, ID for our total solar eclipse public event. She is also the PI of the gamma ray instrument slated to fly onboard the Korean Pathfinder Lunar Orbiter and has involved FINESSE team member R. Elphic as a Co-I with KPLO.

2.1.4 Indian Institute of Technology Kanpur

FINESSE team member Dr. Deepak Dhingra is an Assistant Professor within the Department of Earth Sciences at the Indian Institute of Technology Kanpur in Uttar Pradesh, India. Dhingra continues to work with the FINESSE team and is writing up his research findings in collaboration with the FINESSE remote sensing team regarding volcanic features at Craters of the Moon National Monument and Preserve.

2.2 SSERVI Inter-Team

2.2.1 VORTICES

The FINESSE PI has worked closely with the VORTICES PI (A. Rivkin) to include VORTICES Co-I participation in FINESSE fieldwork. VORTICES team member Matiella-Novak participated in the FINESSE Idaho fieldwork which has led to several conference presentations with manuscript publication underway. Matiella-Novak is also leading a project to incorporate virtual reality into the required field measurements for understanding self-secondary crater formation in Idaho and on the Moon.

2.2.2 RIS^{4}E

FINESSE Volcanics Science Co-Lead Dr. Brent Garry (NASA GSFC) is also a Co-I on RIS^{4}E. In particular, field testing and use of the LiDAR system within both the FINESSE and RIS^{4}E field campaigns has helped to increase the fidelity and operations of this field instrument.

3. Public Engagement Report

3.1 Sharing Analog Research

Through this project, the FINESSE team has stayed committed to publicly sharing our research and interest in planetary science and exploration. In summer 2018, FINESSE Public Engagement Lead Andrea Jones accompanied the field team on their Iceland expedition to help capture and share science highlights from the trip. Dissemination channels included the FINESSE website and social media accounts, as well as NASA flagship accounts like @NASASolarSystem (Figure 9). These accounts, with hundreds of thousands of followers, enabled broad exposure of FINESSE science and added emphasis to the importance of analog research. Samples collected from the field contributed to a kit that will be available for use by FINESSE team members and colleagues in classroom visits and outreach events for years to come.

3.2 SSERVI Seminar Series

FINESSE continued support for a SSERVI Seminar Series, a virtual seminar series highlighting SSERVI science and related public programs and resources for the NASA Museum Alliance and Solar System Ambassadors, who share this content with their audiences around the country and the world. In 2018, the FINESSE, RIS^{4}E,

Figure 9. Highlighting our science through NASA flagship social media accounts enabled broad dissemination of FINESSE science and analog research.

DREAM2, and TREX SSERVI teams, the TubeX research team, and NASA's Lunar Reconnaissance Orbiter (LRO) contributed, adding to participation in previous years from the VORTICES and IMPACT SSERVI teams, as well as SSERVI Central.

3.3 Additional Team Outreach

FINESSE scientists presented at universities and K–12 classrooms around the country – and internationally, including a joint presentation by FINESSE PI Jennifer Heldmann and Deputy PI Darlene Lim at Reykjavik University and a showcase of volcanoes on Earth and throughout the Solar System in a bi-lingual (English/German) 6th grade geography class by team member Alex Sehlke (Figure 10). Sehlke also contributed an article to a public website describing the work of volcanologists (http://mentalfloss.com/article/533613/job-secrets-of-volcanologists). FINESSE's Erika Rader contributed an article to AGU's Eos describing her experiments at the Syracuse Lava Project, with relevance to similar features on the Moon and Mars (https://eos.org/articles/homemade-spatter-bombs-can-reveal-volcanic-secrets).


Figure 10. FINESSE scientist Alex Sehlke engages 6th grade students in a bi-lingual discussion of volcanoes throughout the Solar System.

The FINESSE team also supported International Observe the Moon Night, an annual worldwide celebration of lunar science and exploration and the personal and cultural connections we have with the Moon. 2018 broke all previous records for participation, with 748 registered events and 298 registered individual observers in all 50 US states and 75 countries (10 of them new in 2018), with an estimated 160,000 participants worldwide and 1.4 million participants since the program began in 2010.

Jones and LRO Project Scientist Noah Petro kicked off FINESSE support for the 50th anniversary of the Apollo program in a summer 2018 SSERVI Seminar Series presentation discussing recent advances in our understanding of Apollo landing site geology and encouraging participation in anniversary celebrations as well as International Observe the Moon Night. Many FINESSE team members are planning to support public Apollo 50th anniversary activities nationwide in summer 2019.

4. Student / Early Career Participation

High School Students

1. Chanel Vidal, Iowa City West High School, field geology.

Undergraduate Students

1. Erin, Sandmeyer, Idaho State University, volcanics; tephrostratigraphy at Kings Bowl.

2. Allison, Trcka, Idaho State University, volcanics; tephrostratigraphy at Kings Bowl.

3. Caleb, Renner, Idaho State University, volcanics; remote sensing of lava types.

4. Trevor, Miller, Chico State University, volcanics; lava margins.

5. Omar, Draz, University of Western Ontario, impact cratering; breccias and melt rocks.

6. Bethany, Kersten, Univeristy of Idaho, volcanics, engineering.

7. Hailey, Johnson, Univeristy of Idaho, volcanics, instrumentation.

8. Avery, Brock, University of Idaho, volcanics; aerospace engineering.

9. Mareyna, Karlin, Univeristy of Idaho, volcanics; instrumentation.

10. Jonathan, Preheim, Univeristy of Idaho, volcanics; remote sensing.

11. William, Miller, Univeristy of Idaho, volcanics; technology.

Graduate Students

1. Hester, Mallonee, Idaho State University, volcanics; lava texture classification.

2. Gavin, Tolometti, University of Western Ontario, volcanics; petrographic texture and lava flow morphology.

3. Ethan, Schaeffer, University of Arizona, volcanics; fractal dimensions of lava margins.

4. Chris, Brown, Carleton University, volcanics; lava tubes.

5. Meghan, Fisher, Idaho State University, volcanics; explosive volcano eruptions.

6. Ali, Bramson, University of Arizona, volcanics; lava flow margins.

7. Sean, Peters, Arizona State University, volcanics; lava flow margins.

8. Mary, Kerrigan, University of Western Ontario, impacts; impact-generated hydrothermal systems.

9. Rebecca, Wilks, University of Western Ontario, impacts; impact melt veins.

10. Auriol, Rae, University of Western Ontario / Imperial College London, impacts; shock studies of central uplifts.

11. Audrey, Horne, Arizona State University, impacts; geochronology.

12. Anna, Brunner, Arizona State University, impacts; geochronology.

Postdoctoral Fellows

1. Alexander, Sehlke, NASA Ames Research Center, volcanics; lava flow morphology and physical properties of the flows, handheld field instrumentation.

2. Erika, Rader, NASA Ames Research Center, volcanics; spatter cone deposits.

3. Michael, Sori, University of Arizona, volcanics: lava flow margins.

4. Mark, Biren, Arizona State University, impacts; geochronology.

New Faculty Members

1. Catherine, Neish, University of Western Ontario, volcanics; radar mapping of lava flows.

2. Erika, Rader, Idaho State University, volcanics; spatter cone deposits.

3. Deepak, Dhingra, Indian Institute of Technology, Dept. of Earth Sciences, volcanics; remote sensing.

5. Mission Involvement

1. LCROSS, Anthony Colaprete, Project Scientist

2. LCROSS, Richard Elphic, Science Co-I

3. LCROSS, Jennifer Heldmann, Science Co-I, Observation Campaign Coordinator

4. Resource Prospector Project - closeout, Anthony Colaprete, Project Scientist

5. Resource Prospector Project - closeout, Richard Elphic, Deputy Project Scientist

6. Resource Prospector Project - closeout, Jennifer Heldmann, Science Co-I

7. Resource Prospector Project - closeout, Amanda Cook, Instrument Co-I

8. Resource Prospector Project - closeout, Matthew Deans, Co-I

9. Resource Prospector Project - closeout, Kris Zacny, Instrument Co-I

10. Lunar Reconnaissance Orbiter, Richard Elphic, Diviner imaging radiometer Co-I

11. Lunar Reconnaissance Orbiter, Catherine Neish, Co-I on Mini-RF

12. Lunar Reconnaissance Orbiter, Mike Zanetti, Science Team Member

13. Lunar Reconnaissance Orbiter, Alexandra Matiella Novak, Mini-RF Staff Scientist

14. Lunar Reconnaissance Orbiter, Andrea Jones, EPO Lead

15. OSIRIS REx, Chris Haberle, OTES Instrument Engineer

16. LADEE, Anthony Colaprete, PI

17. LADEE, Richard Elphic, Project Scientist

18. LUNA-H Map, Anthony Colaprete, Co-I

19. Lunar Flashlight, Barbara Cohen, PI

20. Dawn, Brent Garry, Vesta Participating Scientist Team

21. Dawn, Georgiana Kramer, Adjunct Science Team Member

22. ROSETTA, Georgiana Kramer, VIRTIS instrument

23. Chandrayaan-1, Georgiana Kramer, M3 instrument

24. Cassini, Steve Squyres, Imaging Team Co-I

25. Cassini, Catherine Neish, Associate Science Team Member

26. Mars Moon eXplorer (MMX – JAX, Richard Elphic, Co-I on MEGANE gamma ray and neutron spectrometer)

27. Korean Pathfinder Lunar Orbiter, Richard Elphic, Co-I on Korean gamma ray instrument

28. Korean Pathfinder Lunar Orbiter, Kyeong Kim, PI on gamma ray detector

29. Mars Odyssey, Chris Haberle, THEMIS Collaborator

30. Mars Odyssey, Suniti Karunatillake, Gamma and neutron spectrometer team

31. Mars Exploration Rovers, Steve Squyres, PI

32. Mars Exploration Rovers, Barbara Cohen, Associate PI

33. Mars Exploration Rovers, Livio Tornabene, Co-I

34. Mars Exploration Rovers, Sarah Stewart Johnson, Co-I

35. Mars Exploration Rovers, Suniti Karunatillake, Co-I

36. Mars Exploration Rovers, Kris Zacny, Instrument Co-I

37. Mars Science Laboratory (Curiosity rover), Barbara Cohen, Participating Scientist

38. Mars Science Laboratory (Curiosity rover), Chris McKay, Co-I

39. Mars Science Laboratory (Curiosity rover), Raymond Francis, Co-I

40. Mars Science Laboratory (Curiosity rover), Kris Zacny, Instrument Co-I

41. ExoMars Trace Gas Orbiter, Livio Tornabene, CASSIS (Color & Stereo Surface Imaging System) Co-I

42. Mars Reconnaissance Orbiter, Steve Squyres, HiRISE Co-I

43. Mars Reconnaissance Orbiter, Livio Tornabene, HiRISE Co-I

44. Mars Reconnaissance Orbiter, Alexandra Matiella Novak, CRISM Mission Operations

45. Mars Express, Steve Squyres, Science Co-I

46. Mars 2020, Anthony Colaprete, Mastcam-Z Co-I

47. Orion spacecraft, Michael Downs, Test and recovery operations

48. Mars Icebreaker, Chris McKay, PI on proposed Discovery mission

49. Mars Icebreaker, Jennifer Heldmann, Co-I on proposed Discovery mission

50. Mars Icebreaker, Kris Zacny, Co-I on proposed Discovery mission

51. Dragonfly, Catherine Neish, Co-I on proposed New Frontiers mission

52. ELSAH (Enceladus Life Signatures and Habitability), Chris McKay, PI for proposed New Frontiers mission

53. ELSAH (Enceladus Life Signatures and Habitability), Jennifer Heldmann, Science Team Co-I

54. Mars Express, Mike Zanetti, Science Team Member

55. ISS (International Space Station, mission scheduling software), Jessica Marquez, Playbook Co-I

Mihaly Horanyi

University of Colorado, Boulder, CO

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)

CAN 1 Team

1. IMPACT Project Report

The dust accelerator facility at SSERVI-IMPACT at the University of Colorado continues to be a unique and valuable asset for carrying out experiments based on impacts of hypervelocity dust particles with a variety of targets. This includes materials/impact studies (metallic, thin-film, minerals, ices), instrument design, and spacecraft studies. We provided support, testing and follow up calibration opportunities for NASA's Cassini, New Horizons, and Solar Probe Plus missions.

1.1 Dust Accelerator Projects

1.1.1 Cryogenic Target Experiments

We have recently developed a cryogenic ice target that can be exposed to particles from the dust accelerator. This capability is motivated by the need for a quantifiable experimental investigation into the hypervelocity micrometeoroid impact phenomena that contribute to the evolution of planetary icy surfaces, such as the permanently shadowed regions of the Moon. Capabilities granted by this facility are crucial to understanding the interesting complex chemistry and surface weathering

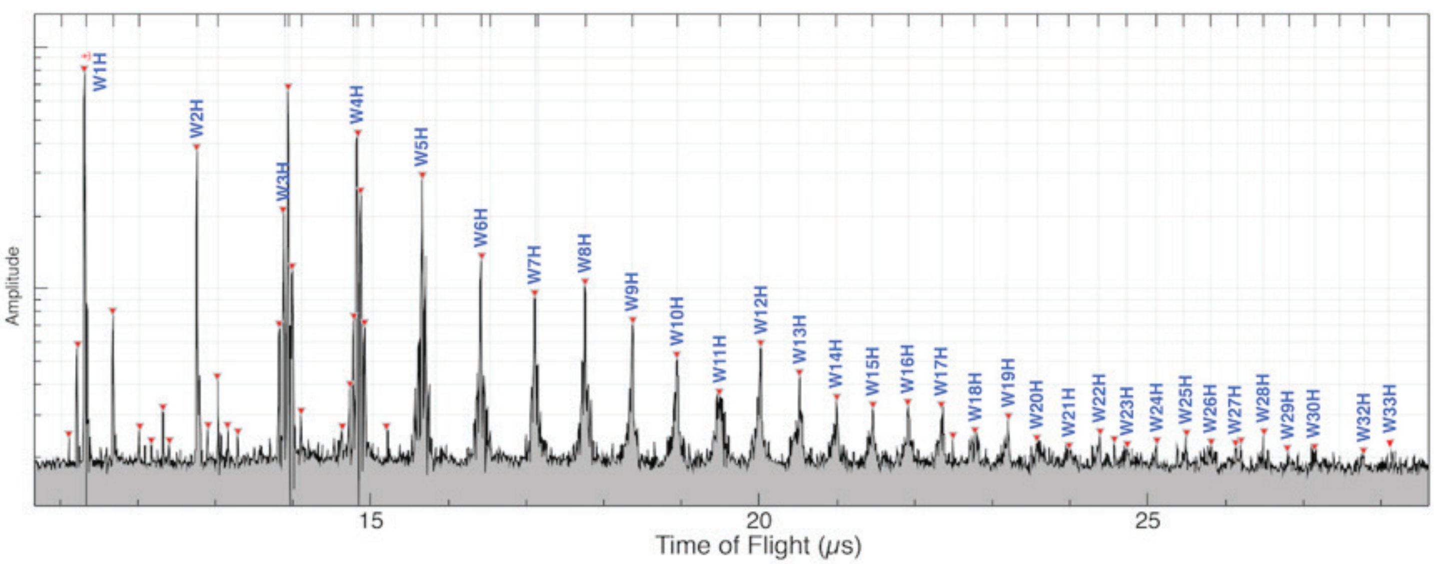


Figure 1. Mass spectrum of ions produced from a single iron projectile impacting an ice target at 16km/s at the Colorado Dust Accelerator. This spectrum was taken with the linear time-of-flight mass spectrometer, currently in regular use. Visible in the plot is an extensive family of $(H_2O)_nH^+$ clusters.

effects that result from hypervelocity dust impacts, and to calibrate instruments for space missions.

Recent experiments making use of the cryogenic target have classified the water cluster production from hypervelocity impacts into water ice at <100K at a variety of impact speeds, which can be critical for the development of new dust instruments. (Such instruments may be useful for the detection of water from the dust exosphere over water-rich lunar regions). These studies can not only describe the detection of water itself, but of any other trace elements entrained in the ice matrix, such as salts or even complex organic molecules.

1.1.2 Gas-Target Experiments

A second specialized target has also been developed at the dust accelerator laboratory, which is a "gas-target." This is a high-pressure (< 0.5 Torr) target isolated from the dust beamline by differential pumping, for studying the interaction of micrometeoroids with planetary atmospheres. Particles accelerated up to 70 km/s are ablated when they come in contact with the relatively high-pressure gas. The ablation process takes place in a gas cell filled to ~100 mTorr pressure. Previous investigations included measuring the ionization efficiency of iron and aluminum dust particles over a 10 – 70 km/s velocity range, and the results are relevant to the interpretation of meteor radar data [DeLuca et al., Planet. Space Sci. 156, 111-116, 2018]. Two new experimental campaigns have been completed recently. The first is to measure the decelerating drag force the particles experience from collisional interaction with neutral gas. The results show that the drag coefficient is approximately 1.3, i.e. it is larger than the typical range of values used in numerical ablation models (0.5 – 1). This means that dust particles experience a considerably stronger drag force when interacting with planetary atmospheres than previously assumed. It is also independent of the type of the background gas used (air, N_2, Ar, CO_2). In the latest experimental campaign, the process of differential ablation was investigated, where the low melting temperature constituents of the dust particle are ablated early while refractory constituents are ablated later in the process.

1.1.3 Charge Measurements from Micrometeoroid Impacts onto Spacecraft

Antenna-based detection of dust grains by spacecraft is a valuable mechanism to enhance the science return from existing missions, and conduct serendipitous observations of interplanetary dust by spacecraft not equipped with dedicated dust instruments. In principle, the detection mechanism is simple: dust grains encountering the spacecraft at high relative speeds undergo ionization upon impact and some fraction of the resulting charged particles is recollected on the spacecraft body or antenna resulting in a measurable signal. However, there is a large uncertainty in calculating the mass of the dust particle from the impact signal. In order to enhance our understanding of the dust impact signals, a series of supporting laboratory measurements have been conducted using the dust accelerator. These included the measurements of the impact charge yield for common spacecraft materials and reproducing the basic signal-generating mechanisms. We identified three mechanisms (spacecraft charging, antenna charging, antenna pickup) that also depend on the geometric arrangement, the impact location, as well as the bias potentials of the elements. We have also determined that the effective temperature of the impact plasma is lower than previously reported in the literature, and is increasing with impact speed.

1.2 Small-Scale Laboratory Experiments

1.2.1 Timescales of Dust Charging and Mobilization

Recent laboratory experiments, along with the newly developed "patched charge model," have shown strong evidence for electrostatic dust transport on the surfaces of airless bodies due to exposure to solar wind plasma and solar ultra-violet (UV) radiation. These new studies provided more insight into the role of electrostatic dust transport process in the surface evolution of these bodies, and several puzzling planetary observations.

Recently we have carried out new laboratory experiments that estimate the timescales of this process in shaping the regolith of airless bodies. Dust lofting rates are recorded over long exposure to energetic electrons that create secondary electrons to best simulate the energy distribution and flux of photoelectrons emitted from the surfaces of airless bodies at 1 AU (e.g. the Moon). It is found that dust lofting is not a constant process; rather it slows down as time progresses. This is likely due to the formation of fewer microcavities and stronger cohesive forces as the porosity decreases with an increase in the depth due to gravity.

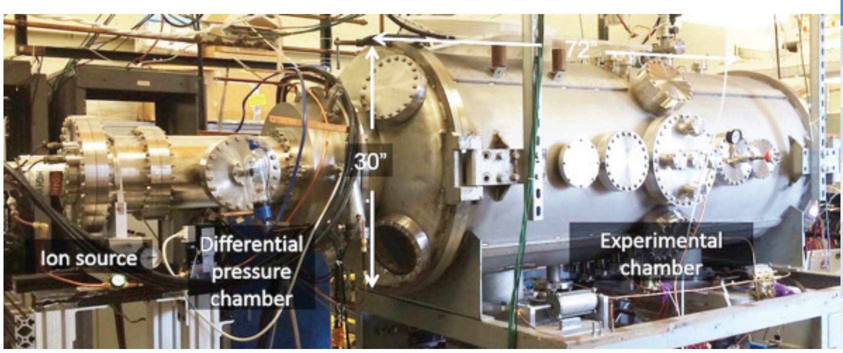
Our laboratory experiments estimate that the transient dust lofting rate at 1 AU could be as high as a few tens of particles cm^{-2} s^{-1}. This rate is sufficient for supplying the 'lunar horizon glow' process. For large bodies such as the Moon, due to their large gravity, the continuously decreasing lofting rate indicates that the geological timescale of electrostatic dust transport is expected to be very long. On the other hand, dust lofting on smaller bodies such as asteroids is expected to be relatively fast with more constant rates due to reduced gravity. This may cause the loss of regolith on small bodies with low escape speeds.

1.2.2 Colorado Solar Wind Experiment

One important phenomenon emerging from the interaction of solar wind with airless bodies is the formation of plasma wakes behind these bodies. The lunar wake has been extensively studied with both in-situ measurements and computer simulations while the studies of wakes of asteroids mainly rely on simulations. Recent experiments at SSERVI-IMPACT have focused on the surface charging and near-surface electric field in the wakes of airless bodies of various sizes. This experimental work was performed at the Colorado Solar Wind Experiment (CSWE) facility [Fig. 2] by characterizing potential distributions as well as plasma densities and temperatures in the wake of an insulating plate. A sheath is formed above the surface in the wake. In the presence of a largely reduced plasma density (i.e., increased Debye length) in the wake, the sheath is expected to expand significantly. This may cause the wake of a small body (such as an asteroid with a radius comparable to or smaller than the Debye length) to form very differently from a large body (such as the Moon with a radius much larger than the Debye length).

1.2.3 Development of Double Hemispherical Langmuir Probe

Langmuir probes are an important instrument used for characterizing space plasmas. However, the local plasma conditions around a probe, due to the interaction of the ambient environment with the spacecraft (SC) and probe itself, could be very different from the true ambient plasmas. These local plasma conditions are often anisotropic and/or inhomogeneous. Most of the existing in-situ Langmuir probes that are made of a single electrode sensor have difficulty minimizing these local plasma effects on the probe measurements, causing errors in the derived plasma parameters. A directional probe is an appropriate instrument for characterizing anisotropic and inhomogeneous plasmas. The split Langmuir probe and the Segmented Langmuir Probe (SLP) have been developed to measure the plasma flow in Earth's ionosphere. At SSERVI-IMPACT we have developed a new type of a directional Langmuir probe, the Double Hemispherical Probe (DHP), aimed at improving the capability and accuracy for space plasma measurements in a broad range of scenarios: low-density



	Solar Wind	Laboratory
Element	Hydrogen	Nitrogen
Velocity, v	400 km/s	91 km/s
Electron Temperature, T_e	10eV	1eV
Ion Temperature, T_i	10eV	4eV
Ion Mach Number $v/(T_e/m_i)^{1/2}$	**9**	**24**
Density, n	$10 cm^{-3}$	$10^6 cm^{-3}$

Figure 2. Left: Photograph of the Colorado Solar Wind Experiment chamber. Indicated on the drawing are the Kaufman ion source, differential pressure chamber, and main experimental chamber. Right: Critical experimental parameters of the CSWE, compared to the Solar wind.

plasmas; high surface-emission (photo and/or secondary electron emission) environments; flowing plasmas; and dust-rich plasma environments. The DHP is composed of two identical hemispheres that are electrically insulated and swept with the same potential biases simultaneously. The differences between the current-voltage (I-V) curves of two hemispheres are used to identify and characterize the anisotropic/inhomogeneous plasma conditions created around the probe, which will aid in removing or minimizing these effects to improve the analysis and interpretation of the I-V curves.

1.2.4 Langmuir Probe Coating Development

Use of Langmuir probes in the atmospheres and ionospheres of planets is complicated by oxidation of the probe surface when the probe is in the presence of high densities of oxygen atoms/molecules and ions. Oxidation of most materials creates a resistive layer on the surface of the probe that will reduce the current collected by a given probe's bias voltage, changing the current-voltage (I-V) curves and the resulting measured plasma parameters (e.g. density, temperature, potential). TiN (Titanium Nitride), DAG (a resin-based graphite dispersion), or Gold are the coatings currently used for Langmuir probes, yet they pose issues when exposed to an oxygen-rich space environment. Iridium and Rhenium are selected as new coating candidates because they strongly resist oxidization and remain highly conductive even in their oxidized forms. Recent studies at SSERVI-IMPACT have investigated the oxidation effect on the measurements of Langmuir probes made of current coating materials (DAG, Gold, TiN) and new coating materials (Iridium and Rhenium) against control materials (Copper and Nickel) in the laboratory. The oxidation process is performed in an oxygen plasma chamber in which both O+ and O2+ are created and accelerated toward the probe surface with the energies of 1.5 and 10 eV and the flux 10^{18} Ions m^{-2} s^{-1}. An argon plasma chamber is used to compare the probe's I-V curves before and after the oxidation process. Our results show that the TiN and Gold probes have significant changes in their I-V curves after exposure to the oxygen plasma. DAG shows a relatively small oxidation effect on the probe measurements but is known to erode over time due to gaseous oxidized forms. Iridium outperforms all the other testing materials with almost unchanged I-V curves after oxidation process. Additionally, due to its extreme hardness, Iridium is a suitable new coating material for future in-situ Langmuir probes. This new coating can also be applied for other plasma instruments in which the electrode surfaces pose a risk of being exposed to oxygen.

1.2.5 In-Situ Resource Utilization

SSERVI-IMPACT team members at the CO School of Mines have developed the ISRU Experimental Probe (IEP), as shown in Fig. 3. The IEP can measure forces and torques as a probe (conical penetrometer, wedge, drill, etc.), interacting with icy regolith surfaces prepared as analogs to the surfaces of target bodies in vacuum. Regolith mixtures include dry and icy regolith mixtures. Samples are held at temperatures ranging from -196 to 150°C and pressures from 1E-6 torr to 1 atmosphere. The IEP can accommodate a variety of probe designs from cone penetrometers, wedges, drills, blunt ended rods, and others. Different probes simulate different ways ISRU

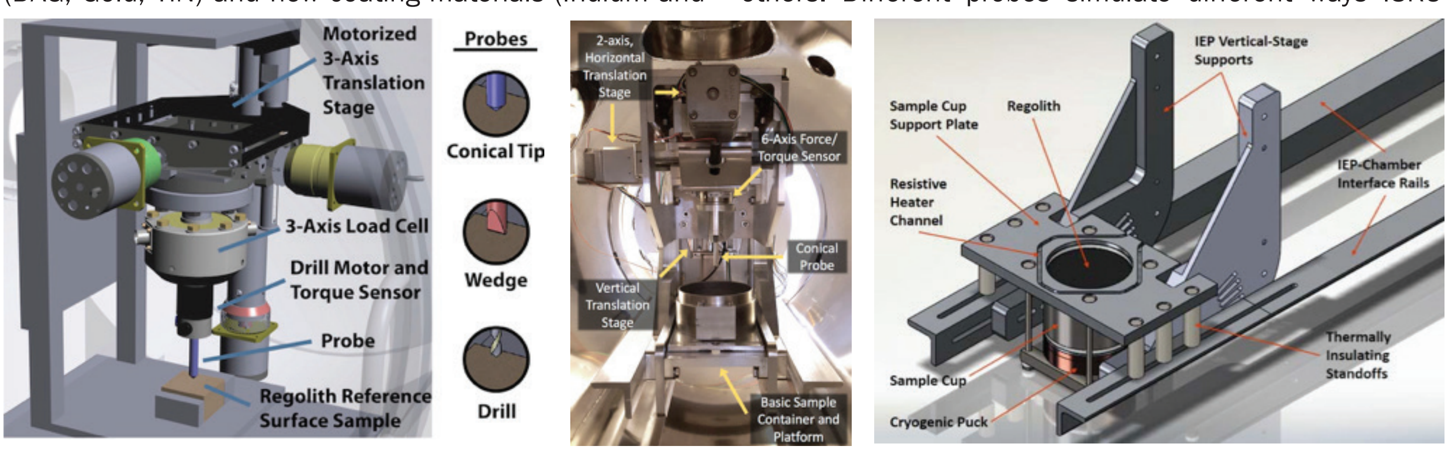


Figure 3. The ISRU Experimental Probe (IEP) schematic diagram (Left) and photograph (Center). (Right) CAD model of the IEP Cryogenic Sample Container design showing integration with the IEP structure.

hardware interacts with a surface (e.g. excavators, drills, wheels, anchors). The sample surfaces can be compacted to light sifted surfaces of regolith (lunar, asteroid, etc.) with frozen volatiles.

The IEP is used to conduct fundamental experiments that advance our understanding of surface properties. In a study with JSC-1A and GRC-3 lunar mare simulants it was found that the penetration resistance curve and relaxation curve can be used to distinguish simulant type (semi-cohesive JSC-1A to non-cohesive GRC-3), bulk relative density (20% to 80%), and test pressure (1E-6 torr to 1 atmosphere using elastic and viscous parameters derived from a Wiechert-Maxwell viscoelastic model fit.

The effects of pressure have also been studied, with penetration resistance and relaxation measured for ambient pressure, ~50 mT, and 1E-6 torr. Penetration resistance shows no change with pressure, however relaxation shows markedly less viscous behavior as the pressure is decreased. This indicates a change in the cohesive behavior of JSC-1A with pressure, which we are continuing to investigate. Tying relaxation behavior (after penetration) to more fundamental bulk soil properties has not been investigated much terrestrially in the field. For space applications, specialized penetrometers could potentially be attached to small landers and use them for large-scale, low resolution exploration of the near-surface of extraterrestrial bodies. This means that the usefulness of a "simple" penetrometer (tried, tested and true) could be extended to determine more fundamental regolith properties (density, pressure, angularity).

1.3 Modeling

1.3.1 Solar Wind Interaction with the Reiner Gamma Lunar Magnetic Anomaly

The Reiner Gamma swirl is one of the most prominent albedo features on the lunar surface. Its modest spatial scales and structure allows kinetic modeling and therefore presents an ideal case to test our knowledge and theories about the formation of lunar swirls and the interaction of the solar wind plasma with the magnetic anomalies that are co-located with these intriguing albedo patterns. In addition, Reiner Gamma may be a prime subject for one of our next landers or low-orbiting missions to the Moon. Specifically, we investigated the effect that the varying upstream plasma conditions have on the surface weathering pattern. Integrated profiles of the solar wind particle flux towards the surface help estimate the long-term effect of solar wind standoff on the lunar regolith.

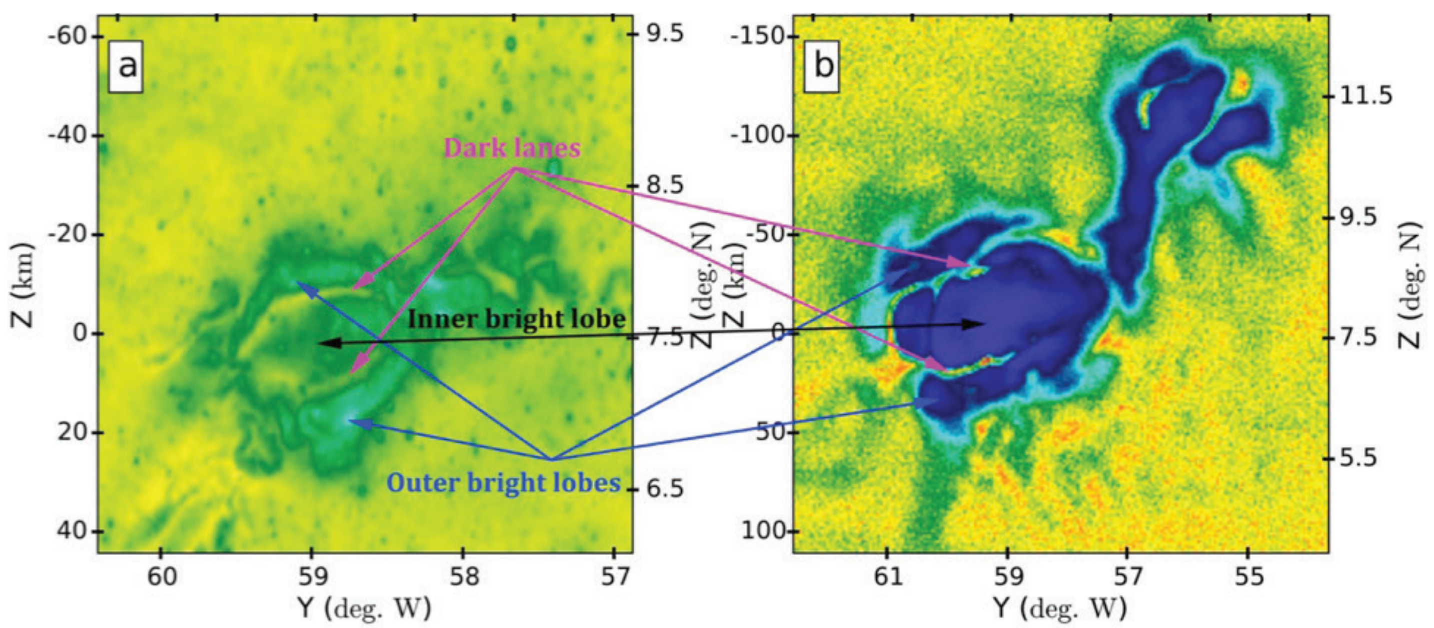


Figure 4. The Reiner Gamma swirl. Left: Lunar Reconnaissance Orbiter-Wide Angle Camera empirically normalized reflectance image (Robinson et al., 2010; Boyd et al., 2012); Right: Normalized energy flux to the surface from iPIC3D, showing that solar wind standoff reproduces swirl features (Deca et al., 2018).

Using the fully kinetic particle-in-cell code, iPIC3D, we have modeled the solar wind interaction with Reiner Gamma for two different scenarios: (1) an idealized one-dipole approximation of the strongest component of Reiner Gamma's magnetic topology, and (2) a realistic setup, in which we couple our code with a surface vector mapping magnetic field model based on Kaguya and Lunar Prospector observations. We showed that solar wind standoff, an ion–electron kinetic interaction mechanism that locally prevents weathering by solar wind ions, reproduces the large-scale signatures of the Reiner Gamma albedo pattern.

2. IMPACT Inter-team/International Collaborations

2.1 IMPACT and CLASS (PI: D. Britt)

Strong common interest in the possibility of Fe-catalyzed chemical reactions on asteroid surfaces which have been weathered by impacting micrometeorites.

2.2 IMPACT and ISET (PI: W. Bottke)

Common interest in measurements to improve models of the dynamics of interplanetary dust particles released from comets and asteroids.

2.3 IMPACT and DREAM (PI: W. Farrell)

Longstanding successful collaboration on vapor and plasma release due to micro-meteoroid impacts and plasma modeling.

2.4 IMPACT and NESS (PI: J. Burns)

Collaboration supports efforts to minimize dust impact hazards for radio antennas, and assess solar wind charging effects on devices placed on exposed planetary surfaces.

2.5 IMPACT and REVEALS (PI: T. Orlando)

Common projects include dust charging, tribo and impact-induced prebiotic chemistry, as well as a jointly mentored NPP Fellow (M.J. Schaible).

2.6 IMPACT and RISE-2 (PI: T. Glotch)

Ongoing projects on understanding the processes related to space weathering by systematically bombarding well-characterized minerals with high-speed dust particles.

2.7 IMPACT and TREX (PI: A. Hendrix)

Ongoing collaborations on laboratory efforts for spectroscopic analysis of granular/regolith materials, and working jointly on Public Engagement opportunities.

2.8 IMPACT and International Partners

2.8.1 Germany: Long-term close collaborations exist between the Cosmic Dust Research Group at the University of Stuttgart, led by Prof. Ralf Srama. We have an active exchange program for students, postdocs and researchers. Theoretical and experimental work on regolith characterization are continuing in collaboration with the dust group at the Technical University, Braunschweig, led by Prof. Jürgen Blum. Impact experiments involving mass spectroscopy are part of an ongoing collaboration with the group at the Free University of Berlin led by Prof. F. Postberg.

2.8.2 Canada: We have recently started common projects with the group at the University of Alberta, led by Prof. R. Marchand on modeling plasma surface interactions.

2.8.3 Norway: Ongoing collaborations with the group at the University of Oslo led by Prof. W. Miloch address new instrument ideas. We have been selected for 2018/9 funding by the Partnership Program with North America, Norway, that pays all travel and living expenses of IMPACT students visiting Oslo, and the Norwegian students visiting us.

2.8.4 Japan: We have been collaborating with the group at the Kobe University led by Prof. Y. Miyake on modeling of plasma - surface interactions to enable a better analysis and interpretation of existing observations and laboratory experiments at IMPACT.

3. IMPACT Public Engagement Report

3.1 Junior Aerospace Engineering Program

2018 was the fifth and final year of the SSERVI-IMPACT Junior Aerospace Engineering program. The program was designed to deliver the science of IMPACT to underserved elementary through high school students from the Casa de la Esperanza housing community. Building on two previous summer camps of rocket-focused projects, the final year of the camp focused on robotics, with particular attention given to those that would function in a simulated lunar environment.

For the final session, Casa recruited ten students from their community to participate in a camp that integrated building and programming LEGO MINDSTORMS robots with more advanced robotics programming involving Arduino and constructing and soldering basic electronic circuits. The first half of the camp involved the students in designing, building, and programming their own robots, while the second half focused on building a simulated lunar habitat from which their robots would theoretically explore the lunar surface.

We administered pre- and post-program evaluations, which revealed that many of our students have retained from prior experience their knowledge of and interest in aerospace engineering and potentially related career options. We also received significant results with regard to new concepts and processes. For example, in response to the question “How much do you know about building basic electronic circuits (like light bulbs, buzzers, switches)?” all students demonstrated significant growth from pre- to post-program evaluation. Results also indicated that the students learned a lot about coding and programming, as well as soldering, how circuits work, and building robots. Program participants indicated that they enjoyed learning about the engineering design process, and they showed an overall increase in their confidence in taking on a project to build a robot.

In addition to the classroom-based component of the camp, students were transported on numerous occasions to local aerospace and engineering companies, where they received tours of SparkFun Electronics and Blue Canyon Technologies, as well as the IMPACT lab and LASP.

A unique aspect of the final camp was that we recruited an older student at Casa to be a mentor for the younger students. Our mentor was a great asset to the LASP professional and CU Boulder undergraduate student who were responsible for the program’s implementation. Not only did he have the opportunity to share his experience with his fellow community members, but he also gained

Figure 5. (Left) CU Boulder undergraduate student, John Fontanese, leads the Junior Aerospace Engineering program participants on a tour of the IMPACT dust accelerator facility. (Center, Right) Students from the Casa de la Esperanza housing community participate in designing, building, soldering, and programming their own robots through simulated lunar environments as part of the SSERVI-IMPACT Junior Aerospace Engineering program.

new experience in teaching related content and serving in an advisory role with his “near peers.”

LASP education and outreach professionals assisted in coordinating the 2018 Boulder International Observe the Moon Night (INOMN) on October 20. Hundreds of individuals and families stopped by to observe our closest celestial neighbor and to catch a glimpse of Saturn through one of two homemade reflector telescopes we set up for the evening’s activities. We also kept busy by handing out hundreds of lunar-related lithographs and literature from NASA missions and programs.

4. Student / Early Career Participation

High-School Students

1. Madeleine Nagle (Boulder High School)
   Spectrometer Control Systems

2. Fiona Kopp (Boulder High School)
   Plasma glow discharge experiments

Undergraduate Students

1. Forrest Barnes
   Control software development

2. Elizabeth Bernhardt
   Accelerator experiments

3. Andrew Bremner (CO School of Mines)
   Dust impact mass spectra

4. Alex Doner
   Accelerator experiments

5. John Fontanese
   Small accelerator experiments

6. Michael Gerard (graduated 2018)
   Lunar swirls modeling

7. William Goode (graduated 2018)
   Accelerator diagnostic design

8. Jack Hunsaker
   Impact plasma formation

9. Zuni Levin
   SIMION studies

10. Liam Merz-Hoffmeister
    Impact charge measurements

11. Destry Monk
    Accelerator control systems

12. Riley Nerem
    Gas target PMT development

13. Alexandra Okeson
    Dust instrument software development

14. Juliet Pilewskie (graduated 2018)
    Dust dynamics modeling

15. George Ressinger
    Solar wind experiments

16. Joseph Schwan
    Dust dynamics in plasma

17. Ted Thayer
    Antenna signals from dust impacts

Graduate Students

1. Jared Atkinson (CO School of Mines)
   ISRU experiments

2. Edwin Bernardoni (NASA GSRP)
   Plasma theory

3. Michael DeLuca (NASA GSRP)
   Micrometeoroid ablation experiments

4. Andrew Gemer
   Instrument development

5. Libor Nouzak (Charles University, Prague) Impact experiments on s/c antennas

6. Marcus Piquette
   Surface/plasma interaction modeling

7. Joseph Samaniego (NASA GSRP)
   Langmuir probe measurements

8. Zach Ulibarri
   Ice target experiments

9. LiHsia Yeo

   Solar wind experiments

Postdoctoral Fellows

1. Jan Deca

   Computer simulations: plasma/surface interactions

5. Mission Involvement

5.1 Instrument Development for Future Lunar Missions

a) Double Hemispherical Probe (DHP): initially funded by SSERVI, now transitioned to NASA's Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program (PI: X. Wang).

b) Electrostatic Lunar Dust Analyzer (ELDA): initially developed by SSERVI support, now funded by NASA's Development and Advancement of Lunar Instrumentation (DALI) program (PI: X. Wang).

5.2 IMPACT Team Involvement in Missions

a) JAXA Destiny Plus (JAXA) Coinvestigators of its dust instrument: M. Horanyi, S. Kempf, and Z, Sternovsky. SSERVI/IMPACT provides testing and calibration at the dust accelerator facility.

b) NASA Interstellar Mapping and Acceleration Probe (IMAP), Interstellar Dust Experiment (IDEX): PI M. Horanyi (PI), Z. Sternovsky and S. Kemp (coinvestigators). IDEX is being developed at IMPACT, and will be tested and calibrated at the dust accelerator.

William Bottke

Southwest Research Institute, Boulder, CO

Institute for the Science of Exploration Targets (ISET)

CAN 1 Team

1. ISET Team Project report

1.1 Theme 1. Formation of the Terrestrial Planets and Asteroid Belt

1.1.1 Planetesimals to Terrestrial Planets: Collisional Evolution Amidst a Dissipating Gas Disk

We utilize the accretion and fragmentation code LIPAD to track growth from planetesimals to planets, examining how dissipation of the solar nebula relates to the total amount of mass loss to collisional grinding and the final relative mass between Earth and Mars. We find that, due to the interaction of collisional fragmentation and the continually evolving gas disk, growth is very inside-out, contrary to some predictions, and the total amount of mass loss to collisional grinding depends on location in the disk. It appears that collisional grinding helps to address the small Mars problem, but does not solve it, and points more generally to the great importance of this type of self-consistent modeling approach. **(Walsh et al. 2019, Icarus, submitted).**

1.1.2 Viscously Stirred Pebble Accretion (VSPA) with the LIPAD Code

VSPA is the first dynamically self-consistent model for forming the giant planets in our Solar System. We can, for the first time, investigate how the growth of giant planets will affect the rest of the Solar System, particularly the asteroid belt. We have found that the growing giant planets will naturally scatter planetesimals from the region where the giant planets form (5-10 AU) into the modern day asteroid belt. Gas drag will circularize these bodies' orbits, detaching them from the giant planets. In this way a substantial fraction of small bodies originally from the outer Solar System are expected to be implanted into the asteroid belt region. Thus, it is likely that the C-complex asteroids are bodies from the outer Solar System implanted into the asteroid belt by the growing giant planets **(Kretke, Levison, Bottke, Kring 2019, Astron J., in press).**

1.1.3 Excitation of the Asteroid Belt by Giant Planet Migration

It is well accepted that the Solar System formed from a disk of gas and dust that surrounded the Sun. It is also assumed that this disk was originally in the equational plane of the Sun. Therefore, planets and other structures, e.g., the Main Asteroid (MB) and Kuiper (KB) belt, are all expected to form in the equatorial plane of the Sun. However, although planets are indeed close to that plane, both the MB and KB present large out-of-plane components. In Gomes et al. (2018), using giant planet instability (GPI) simulations from Nesvorny & Morbidelli (2012), we were able to reproduce the out-of-plane structures of the KB while still leaving the well know cold classical population nearly intact. Similarly, in Deienno et al. (2018) we showed and described a mechanism of natural excitation of the MB via a detailed evolution of Jupiter's orbit during the GPI as in Deienno et al. (2017) **Gomes et al. (2019; Icarus); Deienno et al. (2018; ApJ).**

1.2 Theme 2. Origin of the Earth-Moon and Phobos-Deimos

1.2.1 Origin of Phobos-Deimos via a Large Impact with Mars

Using a hybrid *N*-body model of moon accumulation, we identified new constraints on disk properties needed to produce Phobos and Deimos. We then simulated the impact formation of disks using SPH, including a novel method that resolves the ejecta with order-of-magnitude finer mass resolution. We found that forming Phobos-Deimos requires a Vesta-to-Ceres sized impactor, a much less massive impactor than previously considered. **Canup & Salmon (2018, Science Advances); Canup & Salmon (2018, LPSC)**

1.2.2 Lunar Accretion from an Impact-generated Disk

We conducted the first simulations of moonlet assembly from lower-mass disks produced in the multiple-impact model. We also developed a new model, HydroSyMBA, which combines a hydrocode inner disk model with an *N*-body accretion code. This is the first model capable of accurately tracking both the radial evolution of interior disk and the dynamics of lunar accretion beyond the Roche limit. **Salmon & Canup (2018, LPSC); Salmon & Canup (2019, submitted to AJ); Rufu & Aharonson (2019, in revision at JGR)**

1.2.3 Protolunar Disk Chemistry: Explaining Isotopic Fractionation of Volatiles

We are evaluating expected isotopic fractionation for different Moon origin models. We find that equilibrium fractionation is too small to explain the heavy K isotopic composition of the Moon seen in recent data, and that this enrichment is not a straightforward prediction of either high-energy or low-energy impact models. **Dauphas et al. (2018, LPSC)**

1.2.4 Priority Lunar Science Achievable via Future Exploration and Lunar Origin Studies

We co-authored a Transformative Lunar Science white paper and presented our findings at NASA HQ and COSPAR. We led a critical analysis of all current lunar origin models and geochemical constraints in a 25,000 word invited review chapter. We gave the opening talk “Lunar origin by giant impact: An evolving legacy of Apollo” in the “50 Years of Lunar Science: The Apollo Legacy” LPSC session. **Pieters et al. (2018, white paper); Canup et al. (2019, submitted for New Views of the Moon II); Canup (2019, LPSC**

1.2.5 Evection Resonance in the Earth-Moon System

We are using novel analytical and numerical models to assess how the evection resonance with the Sun would have affected the Earth-Moon system angular momentum. We find a wide range of evolution histories, which include those consistent with proposed “high-angular momentum” impact models, but only for a quite limited range of parameters (see Fig. 1). **Rufu & Canup (2019, LPSC); Ward et al. (2019, in preparation); Rufu & Canup (2019, in preparation)**

1.3 Theme 3. Solar System Bombardment

1.3.1 Evidence for Very Early Migration of the Solar System Planets

The orbital distribution of TNOs provides evidence that Neptune migrated, though no one knows when this occurred. We showed that planetary migration must have started shortly after the dispersal of the solar nebula. We infer this from the survival of the Patroclus-Menoetius binary, which is a pair of Jupiter Trojans with 140 and 113

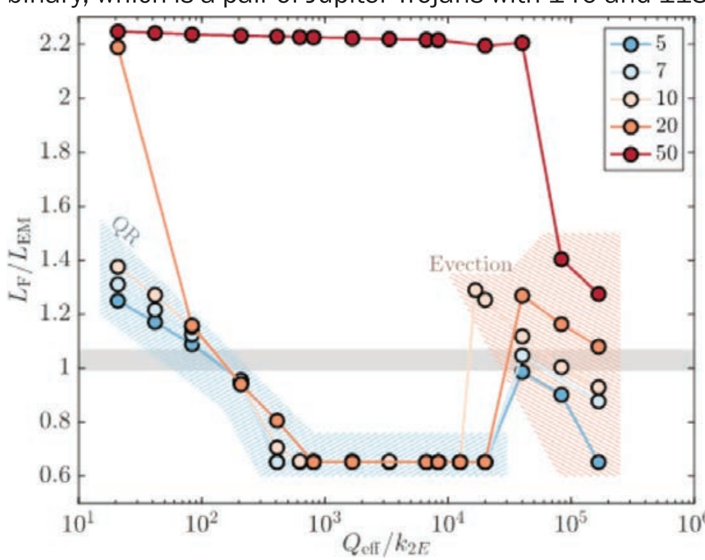


Fig. 1. Final Earth-Moon angular momentum (LF) after interaction with evection resonance, scaled to current Earth-Moon angular momentum (LEM), as a function of the initial terrestrial tidal dissipation factor and Love number, Qeff/k2E, for different values of the relative strength of tides in the Moon vs. the Earth (“A”; colors in legend). Horizontal grey area shows final angular momentum values consistent with current Earth-Moon, accounting for later AM change due to late accretion and solar tides. Only certain values for both the absolute rate of tidal evolution and the relative rate of evolution in the Moon vs. the Earth lead to final systems consistent with the Earth-Moon.

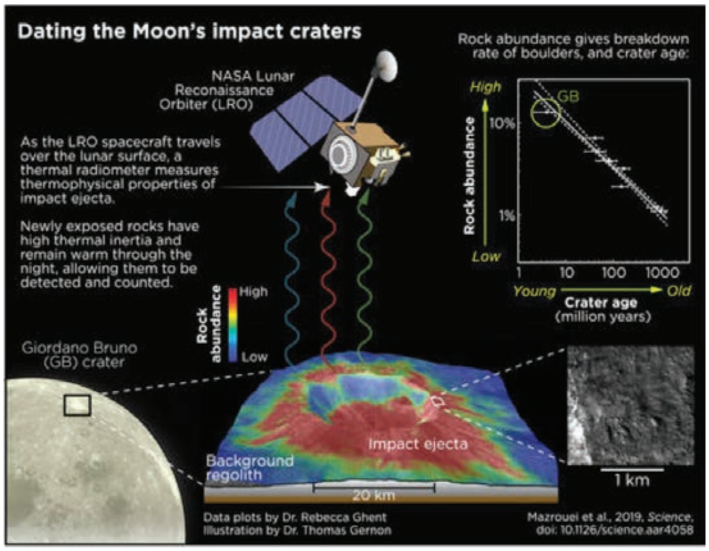


Fig. 2. Dating the Moon's impact craters

km diameters. It formed in the primordial comet disk and was implanted onto its present heliocentric orbit during planetary migration. Its survival places an upper limit on the integrated history of small impacts that could knock the binary components from their mutual gravitational bound. The liberated planetesimals battered the terrestrial planets early and are not responsible for the lunar Late Heavy Bombardment **(Nesvorny, Vokrouhlicky, Bottke, Levison (2018, Nature Astronomy).**

1.3.2 The Earth and Moon Impact Flux Increased at the End of the Paleozoic

The terrestrial impact crater record is commonly assumed to be biased, with erosion thought to eliminate older craters, even on stable terrains. Given that the same projectile population strikes Earth and the Moon, terrestrial selection effects can be quantified by using a method to date lunar craters with diameters greater than 10 kilometers and younger than 1 billion years. We found that the impact rate increased by a factor of 2.6 about 290 million years ago. The terrestrial crater record shows similar results, suggesting that the deficit of large terrestrial craters between 300 million and 650 million years ago relative to more recent times stems from a lower impact flux, not preservation bias. The almost complete absence of terrestrial craters older than 650 million years may indicate a massive global-scale erosion event near that time. **(Mazrouei, Ghent, Bottke, Parker, Gernon. (2019; Science).**

1.3.3 Empirical Crater Scaling Laws and the Projectile Sizes Needed to Make Large Craters

An on-going debate between impact modelers and geochemists concerns the projectile sizes required to form large impact craters. We investigated this issue by proxy by mapping the shape of the near-Earth object (NEO) size-frequency distribution (SFD) into crater SFDs from Mercury through Mars. This allowed us to compute empirical crater scaling laws. Our results indicate crater SFDs on these four worlds are surprisingly congruent for $20 < D < 250$ km craters, and are well fit by the shape of the NEO SFD once projectile diameters are multiplied by a factor $f = 24 \pm 5$. Our work also reproduces projectile diameter estimates derived from Ir and Os abundances for Chixculub, Popigai, Manicouagan, and Sudbury craters. We conclude that certain crater scaling laws and numerical hydrocodes that simulate crater formation may need to undergo revision. **(Bottke, Vokrouhlický, Moore, Sharma, Robbins Banks, Hallock (2019; submitted to Astron. J.)**

1.3.4 A Compositionally Heterogeneous Martian Mantle Due to Late Accretion

We investigated late accretion on Mars using new smooth particle dynamics (SPH) impact simulations. We studied the collisional delivery of highly-siderophile elements (HSE) carried by differentiated projectiles striking on early Mars. Our simulations show that the amount of HSE observed in Martian meteorites requires delivery via 1 to 3 projectiles in the 1000-2000 km diameter size range. This is in broad agreement with observational constraints, such as Borealis basin and Mars' spin rate. We find that delivery of projectile's mantle and core material from a small number of large collisions would result in a heterogeneous Martian mantle (Fig. 3). Our collisional model shows that the observed spread in 182W/184W in Martian meteorites is a natural consequence of collisional delivery, which in turn implies Mars could have formed later than previously thought (15 Myr vs 3 Myr after CAI). **(Marchi, Walker, Canup. Nature Geosciences, 2019, in review)**

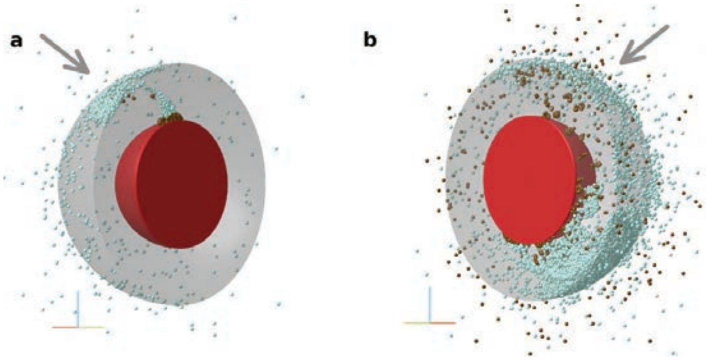


Fig. 3. Heterogeneous projectile mixing in Martian mantle. End-state of two SPH simulations (1.2 x 106 particles, projectile mass M). (a) M = 0.003Mm, v/ve = 2,β = 30°. (b) M = 0.03Mm, v/ve = 2, ,β = 45°. Red/grey half-spheres indicate Martian core and mantle. Projectile's core & mantle particles are indicated by brown and green spheres. The arrows indicate local concentration of projectile mantle (a) and core (b) materials.

1.3.5 New Global Database of Moon Impact Craters >1–2 km

Robbins finished work on a global lunar crater database that is a complete census of all craters as small as 1–2 km in diameter. The database was presented at several conferences, where many lunar researchers promoted the usefulness of the database. It contains 2.0 million craters over the entire lunar surface (1.3 million are ≥1 km). Robbins (2019, JGR-Planets).

1.3.6 Estimating the Ages of Lunar Craters Over the Last 3 Billion Years

Kirchoff has finished determining and refining the formation ages of 42 lunar craters with diameter ≥ 50 km originally categorized as Copernican or Eratosthenian using the densities of small craters superposed on their floors. These ages are then used to explore if recent lunar bombardment by large asteroids (impactor diameter > 2-5 km) in the last 3 billion years has not been constant, but could be characterized by spikes or lulls, assuming that bombardment by the small asteroids (impactor diameter < 1 km) is constant. Analysis indicates there are two statistically significant spikes in large impacts at about 0.2 and 2.2 Ga, and that there is a statistically significant lull in these large impacts between the spikes. Kirchoff et al. 2019 (in preparation).

1.4 Theme 4. Properties and Populations of NEAs

1.4.1 Overview of Physical and Dynamical Evolution of NEAs

The CU team led by Dan Scheeres has continued its research on the effects and implications of non-gravitational forces and weak cohesive bonds within primitive Solar System bodies. Over the last year, 11 papers were published that were supported by the ISET institute. These included papers that studied the granular mechanics of rubble pile bodies when cohesion is present, papers that have probed deeper into the expected dynamical evolution of small bodies under the effect of non-gravitational forces, and exploration themed studies that have probed the exploration of small body surfaces. This work has involved support from Senior Research Scientist Paul Sanchez, post-doc Alex Golubov, Assistant Professor Masatoshi Hirabayashi and PhD students Stefaan Van wal and Jeremy Sautel.

- In the area of cohesive rubble pile asteroids we had several published results. This includes analysis of how an asteroid's shape influences how it fails, how interior strength distribution affects the global shape deformations that can occur, and a very precise analysis of the mechanics of granular systems when cohesion in included (Fig. 4) (Hirabayashi & Scheeres. Icarus 2019; Azema, Sanchez, Scheeres **(2018, Physical Review E; Sanchez & Scheeres. 2018, PSS) Tardivel et al. (2018 Icarus)**
- In the topic of non-gravitational effects on asteroid spin states, we published several articles that predict

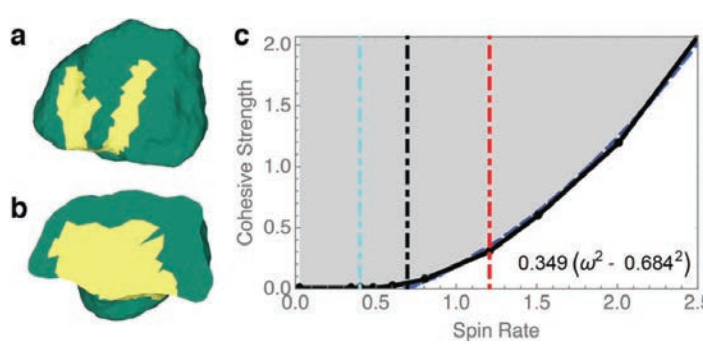


Fig. 4. Failure zones in the asteroid Golevka, from Hirabayashi and Scheeres, Icarus 2019. The yellow regions are where the asteroid is failing plastically, while the green regions are not failing. The graph shows the cohesive strength needed to keep the asteroid stable as a function of spin rate.

the presence of equilibrium states under the YORP effect, meaning that small asteroids can evolve to spin obliquities and spin rates where the YORP effect is "turned off" and the spin state can remain fixed for long durations. This is an important finding, and if verified it would change our concept of how asteroid spin rates evolve in the main belt and NEO populations. **(Golubov & Scheeres (2019 ApJ, in press); Golubov et al. (2018 ApJL); Scheeres (2018; Icarus)**

- In the area of exploration dynamics we published a detailed study of motion on and about Phobos, which was featured in Science magazine. We also supported a detailed analysis of rover deployment onto the asteroid Ryugu, providing support and guidance to the Japanese team that influenced how these maneuvers were carried out. The PhD student who performed that work is now working at ISAS/JAXA as a post-doc in support of the Hayabusa2 mission **(Van wal et al. 2018; J. Spacecraft & Rockets; Fries et al. 2018 (2018; Acta Astronautica).**

1.4.2 Earth's Minimoons: Opportunities for Science and Technology

Jedicke reviewed what is known and can be inferred about Earth's minimoons. A new model of the minimoon population was presented, as well as that of the temporarily captured flyby objects. Several different techniques for discovering these bodies were discussed using existing and near-future assets. The past decade of minimoon studies in preparation for capitalizing on the scientific and commercial opportunities of TCOs in the first decade of LSST operations are also reviewed. **Jedicke et al. (2018 Front. Astron. Space Sci.).**

2. Inter-team/International Collaborations

Members of our team have been interacting with David Kring's team (CLSE), Dan Britt's team (CLASS), Mihaly Horanyi's team (IMPACT), Carle Pieters' team (SEEED), as well as scientists from international institutions.

- Scheeres is a member of the ISET, IMPACT and CLASS SSERVI teams to study the mechanics of cohesive asteroid regolith. As such, he participates with these teams:
  - Scheeres presented a lecture as part of the CLASS SSERVI seminar series in February 2018 entitled *"The role of cohesive strength in the evolution of asteroid interiors and surfaces."*
  - Scheeres and Sanchez have collaborated with the STRATA-I space station experiment with support of the CLASS SSERVI team.
  - Scheeres and Sanchez have had meetings to coordinate research activities with researchers from the Colorado School of Mines as part of the SSERVI IMPACT team.
- Robin Canup worked with the LPI and Brown teams on the Transformative Lunar Science document (Pieters et al. 2018) and related presentations.
- Robin Canup co-led an *Origin of the Earth and Moon* chapter with K. Righter, a member of the LPI team.
- Simone Marchi and Robin Canup collaborated with Richard Walker of the CLSE team on constraining the early bombardment of Mars. Results are described above, and have been submitted to *Nature Geoscience*.
- David Kring (CLSE) and William Bottke shared SSERVI postdoc Katherine Kretke, with the work leading to the paper, "*Implementation of C-type asteroids during giant planet formation*" by Kretke, Levison, Bottke, Kring 2019, Astron J., in press. Work is described above in 1.1.2.
- Bottke and Marchi interact with L. Elkins-Tanton (SEEED) on a number of early planetary formation and bombardment projects, most prominently the Psyche mission. Elkins-Tanton is the PI of that mission.
- In collaboration with Craig O'Neill of the SSERVI Australia team, Bottke/Marchi are investigating the long term effects (e.g. volcanism) of early collision on the Archean/Hadean Earth.
- Bottke has interacted with a wide range of international

scientists over the past year, the main ones being: David Vokrouhlicky (Charles U., Prague, Czech Republic), Alessandro Morbidelli (Observartorie de la Cote d'Azur, Nice, France), Rebecca Ghent/Sara Mazrouei (U. Toronto, Canada), and Tom Gernon (Ocean and Earth Science, University of Southampton, Southampton, UK). The combined work has covered a wide variety of collisional, dynamical, and cratering projects.

- David Nesvorny has interacted with the IMPACT team on interpreting the dust flux striking the Moon as revealed by LADEE data.

- Canup and Bottke gave lectures for the CLASS-SSERVI "*Origin and Evolution of the Moon*" Course

  - Class 3: September 19: The Formation of the Moon: Current Scenarios: Robin Canup (SWRI)

  - Class 6: October 10: The Lunar Cratering Record and the Late Heavy Bombardment: Bill Bottke (SWRI)

3. Public Engagement Report

Summer Science Program (SSP). Our collaboration with SSP continues to be a success. Kretke, Dones, Kirchoff, and a new participant, Deienno, served as science instructors for the 36 high-school students each in New Mexico and Colorado in July, 2018. ISET members guided the students through a SSERVI-rich participatory experience using the numerical integrator SWIFT to integrate the orbits of their observed asteroids into the future. The students then analyzed and presented their results on the fate of their asteroid to their peers. This was the first opportunity many of these high-school students had to participate in a scientific presentation. We also provided scientific lectures to the students on asteroid populations and their dynamical evolutions, including chaos theory.

The survey about their experience with the ISET research project generated by Shupla was once again given to the students in Colorado. In this year's survey, 97% of the students either agreed or strongly agreed that participating in the research project expanded their knowledge and skills. In addition, 100% agreed or strongly agreed that the discussions and interactions with the ISET scientists were valuable (up from 90% last year). We think these two student comments summed up the experience best: "I ... really enjoyed learning about chaos and uncertainty..." and "Getting to put the orbital elements I calculated to use."

Denver Comic Con. For the past few years ISET scientists have participated in the Denver Comic Con presenting SSERVI science and exploration to public audiences ranging in age from preschoolers to adults. This year was no exception and featured a partnership with the Lucy mission. Katherine Kretke from the ISET team is now leading the Communications, Public Outreach and Workforce development for the Lucy Mission. She is working closely with the SSERVI outreach team to provide complementary outreach opportunities. For example, Kretke teamed up with Kirchoff to design and present an activity for elementary children to teach them about different types of exploration. For this activity, children first learned about recent missions exploring small bodies in our Solar System focusing on how they all explore in different ways, and then they carried out their own explorations where they had to use their senses (sight, hearing, and touch) to try to figure out what pop culture character / story was represented at each station. Kretke also presented a talk on "The sounds of science" focusing on how scientific data can be represented as sound and how sound and music relate to our exploration of the Solar System.

Other highlights included the participation of several of our female scientists in the well-attended and received "*Women in Science and Engineering*." Another popular talk was "*How to Have a Career in NASA*," where our scientists described how they had reached their current positions. We also had fun talks on SSERVI topics, such as "*Armageddon or Are-Mistaken*?" discussing what is wrong with asteroid movies, "*What's next for NASA*?" discussing upcoming NASA missions, and whether the predicted "*Planet 9*" was real. Some of our talks were also all about public engagement, with panel discussions between scientists, authors, and artists that compared known worlds to worlds in science fiction, and a "*Superheroes on other Planets*" activity for elementary children.

Sharing Results. Many in our group (e.g., Bottke, Nesvorný, Marchi) also gave public presentations to a variety of audiences in Boulder and the nearby Denver area.

4. Student/Early Career Participation

Graduate Students

1. Stefaan Van wal, University of Colorado, Aerospace Engineering

Van wal is currently supported as a PhD student by the SSERVI grant. His focus is on the dynamics of motion on the surfaces of small bodies, with applications to both exploration activities and to geophysical processes on small bodies. He has graduated and will start a post-doc working with the Hayabusa2 mission.

2. Travis Gabriel, University of Colorado, Aerospace Engineering

Gabriel performed research at CU under the SSERVI grant focused on the energetics of stable configurations of rubble pile asteroids. He finalized his Master's degree at CU in 2016, published his research in a journal paper and has now transitioned into the PhD program at Arizona State University where he is working with Dr. Erik Asphaug.

Postdoctorate Fellows

1. Raluca Rufu (post-doc at SwRI as of 8/18)

Dr. Rufu is working with Canup on a variety of projects, including the evection resonance and modeling giant impacts.

Early Career Scientists

1. Paul Sanchez, University of Colorado, Planetary Science

Sanchez has been promoted to Senior Research Scientist from Research Associate since the start of the SSERVI grant. He has been supported for a majority of his time, performing research on the mechanics and physical evolution of rubble pile bodies subject to rapid spin rates. Sanchez also has pursued collaboration with members of the University of Colorado-based SSERVI IMPACT team.

Fate of Test Particles	Number of Particles	Percentage (52 particles total)
Survived > 40 Myr	42	80.8 %
Collide with Sun	6	11.5%
Earth Impactor	4	7.7%

An example results slide from a team presentation.

2. Oleksiy Golubov, University of Colorado, Small Body Dynamics

Golubov has had yearly visits to CU from the Ukraine, where he is a junior faculty member. During his visits he works with Prof. Dan Scheeres on the effect of solar radiation on the dynamical evolution of small asteroids.

3. Masatoshi Hirabayashi, Colorado University, Planetary Science

Hirabayashi was initially supported by the SSERVI grant to perform stress and failure analysis of asteroids using commercial and custom continuum mechanics models. He subsequently had a post-doc position with Dr. Jay Melosh at Purdue University. In the last year he has started as an Assistant Professor of Aerospace Engineering at Auburn University.

4. Julien Salmon, Southwest Research Institute, Planetary Science

Salmon has been working with R. Canup on performing accretion simulation of the Moon, Phobos, and Deimos. He also started a new project on assessing the dynamics of the accretion of the Moon in a multi-impact framework.

5. Miki Nakajima (post-doc)

Miki Nakajima has recently been hired as a new Assistant Professor at the Univ. of Rochester. Dr. Nakajima has been working with Canup on models of volatile loss after a Phobos-Deimos forming impact.

6. Alex Evans (former post-doc)

Alex Evans was a postdoc working with ISET member Jeff

Photo of Bottke presenting at 2018 Denver Comic Con.

Andrews-Hanna, but has recently been hired as a new faculty member at Brown University. Alex has worked to use GRAIL data to understand early bombardment on the Moon.

7. Katherine Kretke (former post doc)

Katherine Kretke from the ISET team is now leading the Communications, Public Outreach and Workforce development for the Lucy Mission.

5. Mission Involvement

1. Lucy, Hal Levison, Principal Investigator.

Hal Levison is the PI of the mission Lucy that will perform a tour of Jupiter's Trojan Asteroids. The mission was selected for phase B in January 2017. Launch is scheduled for 2021.

2. Lucy, Julien Salmon, Sequencing.

Salmon has been assisting PI Levison in designing encounters of each of the mission's targets, demonstrating that the mission scientific requirements could be achieved. He helped design sequences of observations that would provide the necessary spatial coverage and minimum resolution with each of the instruments.

3. OSIRIS-REx, Kevin Walsh, Regolith Development Working Group, Lead Scientist

Kevin Walsh is a Co-I on NASA's asteroid sample return mission OSIRIS-REx. He is the lead scientist for the Regolith Development Working Group, whose responsibilities include mapping the global geology of the asteroid Bennu, helping to select the sample-site and interpreting the outcome of the Spacecraft-Asteroid interaction.

4. OSIRIS-REx, William Bottke, Dynamical Evolution Working Group, Lead Scientist

Bottke is a Co-I on NASA's asteroid sample return mission OSIRIS-REx. He is the lead scientist for the Dynamical Evolution Working Group, whose responsibilities include understanding the collisional and dynamical evolution of the asteroid Bennu and measuring the Yarkovsky and YORP effects on this body.

5. Psyche, William Bottke, Co-I on the Science Team

Bottke is a Co-Is on NASA's Psyche mission, a planned orbiter mission that will explore the origin of planetary cores by studying the metallic asteroid 16 Psyche. His job will be to understand the origin, dynamical, and collisional evolution of Psyche.

6. Lucy, William Bottke, Co-I on the Science Team

Bottke is Co-I on NASA's Lucy mission, the first space mission to study Jupiter's Trojan asteroids. His role will be to understand the origin, dynamical, and collisional evolution of the Trojan asteroids observed by the spacecraft.

7. NEOCAM, William Bottke, Co-I on the Science Team

Bottke is Co-I on NASA's Near-Earth Object Camera (NEOCam) mission. It is designed to discover and characterize most of the potentially hazardous asteroids that are near the Earth. His role will be to understand the origin, dynamical, and collisional evolution of the NEOs and main belt asteroids observed by the survey. This mission is in extended Phase A, with its fate not yet determined.

8. Dawn, Simone Marchi, Co-I on the Science Team

Marchi is a Co-I on NASA's Dawn mission to Vesta and Ceres. He has mainly contributed to the characterization of cratering histories of Vesta and Ceres, as well as their surface compositions, and geological evolutions.

9. Rosetta, Simone Marchi, Associate Scientist on the OSIRIS camera

Marchi is an Associate Scientist to ESA Rosetta's OSIRIS camera system Science Team. He has conducted geomorphological studies of comet 67P and pursued how these studies could inform the origin of 67P.

10. Lucy, Simone Marchi, Deputy Project Scientist (DPS)

Marchi is DPS of NASA's Lucy mission to Jupiter's Trojan asteroids. Marchi contributes over a wide range of activities, including the definition of the mission's science goals, instrument performance, observation planning etc.

11. Psyche, Simone Marchi, Relative Ages Working Group, Lead Scientist

Marchi is a Co-I on NASA's Psyche mission, a planned orbiter mission that will explore the origin of planetary cores by studying the metallic asteroid 16 Psyche. Marchi's role will be to understand the collisional evolution of Psyche, and map craters on Psyche.

12. JUICE, Simone Marchi, Associate Scientist on the JANUS camera system Science Team

Marchi is an Associate Scientist on ESA JUICE Janus camera system. JUICE will study Jupiter, Ganymede, Europa and Callisto. His role is to characterize the cratering histories of the Galilean satellites.

13. BepiColombo, Simone Marchi, Co-I on the Science Team

Marchi is a Co-I on ESA's BepiColombo SIMBIOSYS stereo camera. BepiColombo will study Mercury. His role is to provide cratering model ages and support to geomorphological investigations.

14. OSIRIS-REx, Daniel Scheeres, Radio Science Working Group lead

Scheeres is a Co-I on NASA's asteroid sample return mission OSIRIS-REx. He is the lead scientist for the Radio Science Working Group, whose responsibilities include estimating the mass and gravity field of the target asteroid Bennu, measuring the Yarkovsky and YORP accelerations for that body, and using this information to constrain and analyze the geophysics of the asteroid.

15. Hayabusa2, Daniel Scheeres, Interdisciplinary Science Team Co-I

Scheeres is a Co-I on the Interdisciplinary Science team of the Japanese Hayabusa2 mission to asteroid Ryugu. He will contribute his expertise to the analysis of that asteroid's dynamical environment, and through a collaboration with the OSIRIS-REx team will analyze the tracking data in order to constrain the asteroid's mass.

Timothy Glotch

Stony Brook University

Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS4E)

CAN 1 Team

1. RIS⁴E Team Project Report

The RIS⁴E team is organized into four distinct themes, which in addition to our Public Engagement and E/PO efforts, form the core of our science and exploration efforts. Results from the fifth year of RIS⁴E activities for each of the four themes are discussed below.

1.1 Theme 1. Preparation for Exploration: Enabling Quantitative Remote Geochemical Analysis of Airless Bodies

In 2018, the RIS⁴E Theme 1 team utilized simulated airless body environment spectroscopy to understand spectral properties of lunar and Phobos-analog materials. We also continued our development of light scattering models, investigation of high-pressure/high temperature mineral transformations associated with impact processes, and space weathering experiments in collaboration with the IMPACT team. We discuss highlights of these efforts below.

1.1.1 Simulated Airless Body Environmental Spectroscopy: Application to the Moon and Phobos

Former Stony Brook graduate student and current postdoctoral researcher, Dr. Katherine Shirley, has conducted a detailed study of the effects of particle size on the mid-infrared (~5-25 μm) spectra of common lunar analog minerals in a simulated lunar environment (Shirley et al., 2019). Her work confirms previous studies that demonstrated substantial differences between thermal infrared spectra acquired in an ambient terrestrial environment and those acquired in a simulated lunar environment. Furthermore, Dr. Shirley's work is the first to demonstrate that the effects of grain size on these spectra differ between ambient and simulated

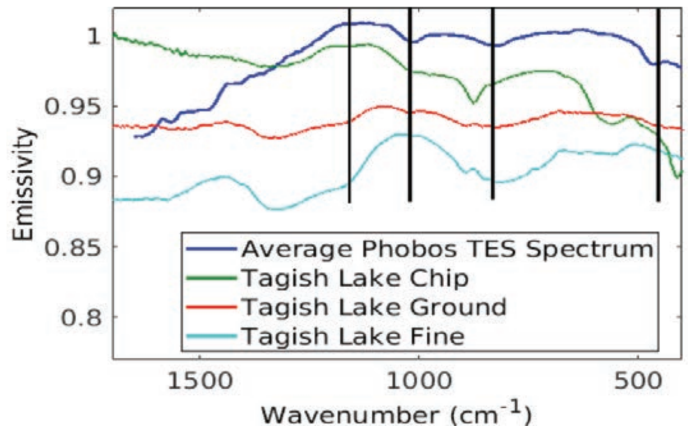


Figure 1.1. Mid-IR spectra of the Tagish Lake meteorite at three different grain sizes are all dis-similar to mid-IR spectra of Phobos (dark blue). Low albedo basalt is the best spectral match. Adapted from Glotch et al. (2018).

lunar environment conditions. Her work shows that as grain size of a mineral decreases, its simulated lunar environment spectrum increases substantially in spectral contrast and the position of its Christiansen feature (CF) emissivity maximum shifts to longer wavelengths. At ambient conditions, the CF position does not change with grain size, and spectral contrast decreases, rather than increases with decreasing particle size.

In addition to this study, Glotch et al. (2018) compared simulated Phobos environment spectra of several materials to Mars Global Surveyor Thermal Emission Spectrometer (MGS-TES) data of Phobos. The Tagish Lake meteorite has often been cited as a visible/near-infrared (~0.35 – 4 μm) spectral analog for D-type asteroids. At those same wavelengths, Phobos is spectrally similar to D-class asteroids, leading some to suggest that Phobos (and likely Deimos) is a captured asteroid. However, the capture hypothesis is hampered by dynamical considerations related to the shape and inclination of Phobos' orbit. Glotch et al. (2018) compared mid-infrared spectra of Tagish Lake, nontronite (a common clay mineral), and basalt acquired in a simulated Phobos environment to MGS-TES spectra of Phobos. At mid-IR wavelengths, Tagish Lake and Phobos are spectrally dis-similar (Figure 1.1). Phobos is also dis-similar to other carbonaceous chondrites at mid-IR wavelengths. Instead, finely particulate basalt (a major component of the Martian crust) artificially darkened with nano-phase carbon is the best spectral analog to Phobos.

> The surface regolith of Phobos may be at least partly derived from a large impact on Mars.

1.1.2 Improvement of Light Scattering Models

Building off of our previous work in developing a hybrid T-matrix/radiative transfer model for mid-IR spectroscopic applications, we have extended our modeling efforts to VNIR wavelengths, with a focus on better understanding the effects of nanophase metallic Fe size and abundance on the spectra of space weathered materials. Stony Brook graduate student Carey Legett has found that for single silicate particles with low abundances of Fe, simplified Mie codes that make use of average optical properties of Fe and the host particles are adequate to model reflectance. However, for high nanophase Fe abundance in a host particle (e.g., for a mature lunar soil), simplified Mie codes can differ by up to 70% compared to a case with more realistic geometry and separate optical constants for the host and Fe particles (Figure 1.2).

1.1.3 Space Weathering and High Pressure/High Temperature Experiments

We have continued our collaboration with the IMPACT team and utilized their Dust Accelerator Laboratory to test the effects of high velocity (~10 km/sec) impacts on the structure, chemistry, and infrared spectral properties of oriented olivine single crystals. SBU postdoctoral researcher Sarah Nicholas and graduate student Jordan Young led this work. Interestingly, the high velocity impacts

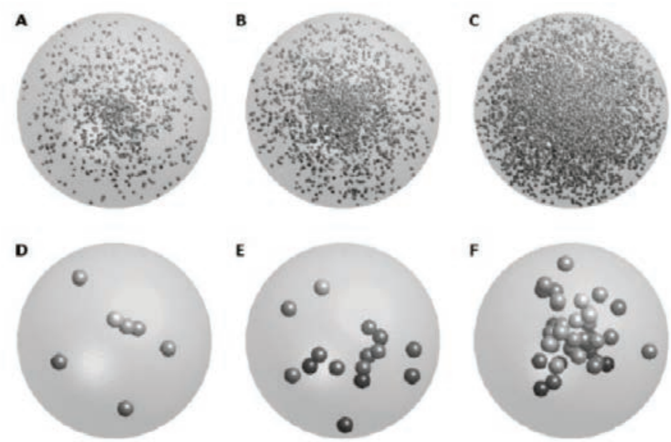


Figure 1.2. Fe particle geometries (dark spheres) in a host particle (large sphere) for 6 different spectral modeling cases: A) 20 nm Fe, 1 wt%, B)20 nm Fe, 2 wt%, C) 20 nm Fe 5 wt%, D) 100 nm Fe 1 wt%, E) 100 nm Fe 2 wt%, F) 100 nm Fe 5 wt%.

appear to have had less of an effect on the samples than previous lower-velocity (~5 km/sec) impact experiments. We hypothesize that this is because the high velocity impactors are ~10-100x smaller than lower velocity impactors, and the cumulative damaged surface area on the sample surface is correspondingly smaller. We are currently engaged in synchrotron X-ray absorbance spectroscopy, nano-IR spectroscopy, and transmission electron microscopy experiments to further characterize the samples.

In addition to our space weathering work, Stony Brook graduate students Melissa Sims and Melinda Rucks have engaged in a number of studies designed to understand the effects of high pressure and high temperature on mineral structures associated with impacts. Rucks et al. (2018) synthesized tissintite, a mineral with a plagioclase feldspar composition and a pyroxene structure. Her work provided the first constraints on the formation conditions of this mineral, which has been suggested to be an important indicator of shock conditions in meteorites. Sims et al. (2018) used novel membrane diamond anvil cell techniques in conjunction with time-resolved synchrotron X-ray powder diffraction to study how compression rate and peak pressure affect the amorphization of plagioclase feldspar, a mineral which is often used to estimate the shock conditions in terrestrial and extraterrestrial rocks.

1.2 Theme 2. Maximizing Exploration Opportunities: Development of Field Methods for Human Exploration

1.2.1 Handheld and Portable Instruments

During Year 5, the RIS^{4}E Theme 2 team was highly productive. The team conducted its final field deployment to the Potrillo Volcanic Field in NM. At the Kilbourne Hole maar crater and Aden low shield, the team worked to analyze ash deposits containing xenoliths and to study emplacement of sheet lava flows and development of pits that are both associated with tubes and that are not linked to subsurface void spaces. As in previous years, a major focus of the field campaign was the design and testing of simulated extravehicular activities (EVAs) that used handheld and portable geochemical and mineralogical tools to evaluate the geology of the region. Co-I Young provided an overview of these activities, which included use of hand-held X-ray fluorescence and Raman instruments and portable X-ray diffraction, hyperspectral infrared, and LiDAR instruments (Young et al., 2018). In addition, Stony Brook graduate student Gen Ito detailed the analysis of several years' worth of mid-IR multi-spectral and hyperspectral imagery acquired at both the Hawaii and New Mexico field sites (Ito et al., 2018). This work demonstrated that IR imagery offers several advantages in field campaigns, including documentation of major compositional variations within scenes, the ability to detect visually subtle and/or concealed variability in (sub) units, and the ability to characterize remote or inaccessible outcrops.

1.2.2 Prototype Field EVA Interface

An additional field activity this year included the first tests of a prototype field EVA interface that ties various operations and science instrumentation data into a single time-based product. This tool will enable scientists who participated in the field work to visualize time and location of scientific measurements and recall how they were coordinated with other activities. This tool also provides critical context for scientists who did not participate in the field activities. Figure 1.3 shows screen captures from a video demonstration of the prototype tool interface. It includes three streams of video from two crew chest-

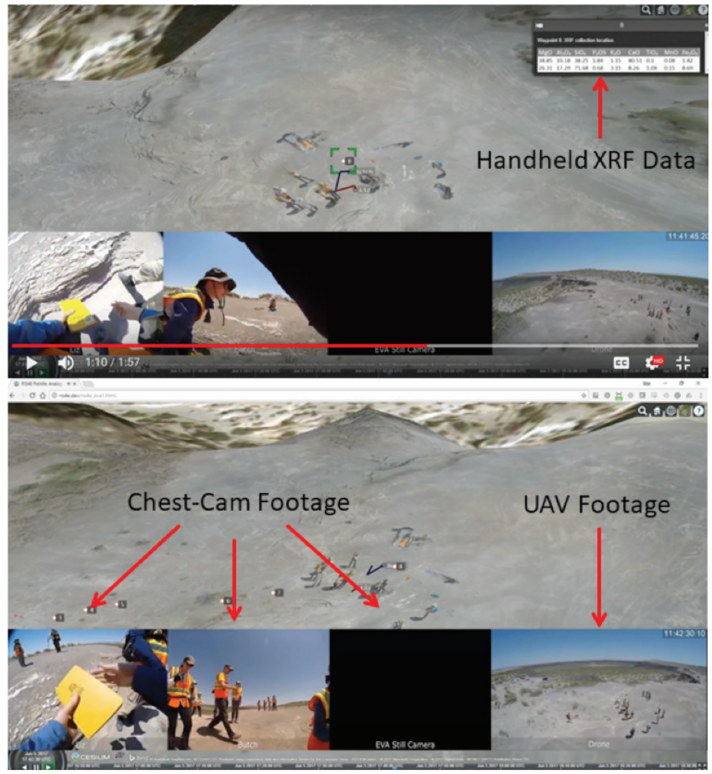


Figure 1.3. Still frames from a prototype interactive EVA interface tool. The top frame of each image includes a LiDAR-based topographic map of the field site with GPS waypoints indicated. Time-synchronized chest-cam and UAV footage appears below the map. In the top image, a data table displays the results from a handheld XRF measurement at one of the waypoints.

cams and a UAV acquired during the Kilbourne Hole field deployment. Still images acquired by the crew appear as they are taken in EVA real time. The top image in Figure 1.3 contains a digital terrain model of the EVA area that was created by the UAV and is used to provide position context of crew activities in time sync using GPS data for each crew member. Marked waypoints are created in time sync and within these waypoints are the resultant science instrumentation datasets (see top image of Figure 1.3). A video of the prototype tool in action can

NASA will directly benefit from the development of a time-synchronized science management tool that records and provides context for field measurements at key investigation sites.

be found at https://drive.google.com/open?id=1iy-MRqN6G6aGmnYAKIrPpSP85Np0PRAe. The audio channel has been removed from this demonstration product, but is available in the full tool. The video demonstrates XRF data called up in the context of a crew-ordered measurement at one of the waypoints.

1.2.3 Testing of GPS-denied Autonomous Navigation

A new partner in our field campaign in Year 5 was Astrobotic Technology's Future Missions and Technology team. A primary goal of Astrobotic's research is to demonstrate the capability to navigate and map, using both LiDAR and vision, and to seamlessly transition between the two sensing modalities mid-flight when environmental conditions change rapidly. This capability, referred to as AstroNav, could enable a small spacecraft to explore these underground environments autonomously, returning from the darkness to send data back to Earth, return a sample to the surface, or refuel. The Astrobotic team accompanied RIS^{4}E scientists to Aden Crater in the Potrillo Volcanic Field, NM, where they tested the AstroNav software capabilities in local volcanic pits and lava tubes using a UAV. The Astrobotic team collected valuable data during the deployment that is being used to refine AstroNav and plan extensions to the capability that would enable spacecraft to land on unmapped planetary surfaces and perform satellite or asteroid rendezvous.

Figure 1.4. Astrobotic field-tested their autonomous navigation capabilities at Aden Crater, NM. The geologic features in the region (lava pits and tubes) are analogs for GPS-denied environments on the Moon and Mars.

1.3 Theme 3. Protecting our Explorers: Understanding How Planetary Surface Environments Impact Human Health

In Year 5, the Theme 3 team continued its work to develop assay techniques that were designed to assess the identity and concentration of reactive oxygen species (ROS) produced by interactions between lunar regolith simulants pulverized in the laboratory and various liquid media. In addition, we have correlated the reactivity of lunar regolith simulants (measured by production of ROS) with toxicity as measured by cell death counts and DNA damage assays. We have also made the first attempts to quantify the differences in reactivity and toxicity between fresh and experimentally space weathered lunar regolith simulants.

1.3.1 Mineral Reactivity and Toxicity

SBU Graduate student Donald Hendrix completed our study of the generation of hydroxyl radicals (OH*) by freshly pulverized (to simulate impact comminution) minerals when subjected to liquid media (Hendrix et al., 2019). He found that mineral pulverization time is inversely correlated to OH* generation, while OH* generation is positively correlated to mineral fluid incubation time for phases that have iron in their chemical formulae. This, in turn suggests the possible action of the Fenton reaction (where Fe is essentially a catalyst for the generation of OH* form H_2O_2) as a cofactor in increasing the reactivity of these phases.

In addition to this reactivity work, we also completed our initial study of nuclear and mitochondrial DNA damage caused by exposure to lunar regolith simulants (Caston et al., 2018). This study resulted from nearly four years of assay and technique development designed to reduce noise in the data and produce consistent results for a variety of materials. Caston et al. (2018) produced some rather counterintuitive findings. They found that lunar soil simulants caused both cell death (cytotoxicity) and DNA damage (genotoxicity) in neuronal and lung cell lines, and that freshly crushed simulants caused more cell death and DNA damage than uncrushed simulants. However the ability of the simulants to generate reactive oxygen species in aqueous suspensions (Hendrix et al., 2019) was not correlated with their cytotoxic or genotoxic affects, and cytotoxicity was not correlated with the accumulation of detectable DNA lesions. These findings suggest that the physical properties of the simulants (grain size, roundedness, etc.) may have to be evaluated as causes of cell death and that geochemistry alone cannot account for the observed toxicity.

1.3.2 Reactivity and Toxicity of Experimentally Space Weathered Regolith Simulants

In the past year, we have begun to investigate the effects of space weathering on the reactivity and toxicity of lunar regolith simulants. We started by experimentally "space weathering" a sample of JSC-1A simulant. RIS^{4}E graduate student Carey Legett (SBU) baked finely ground olivine grains in a hydrogen atmosphere at 600 °C for 30 minutes. The resulting powder was visibly darker than the starting material, and VNIR reflectance measurements showed the expected characteristics of space weathered olivine (low albedo, reduced spectral contrast, and red slope). Transmission electron microscopy (TEM) analysis by Kate Burgess (NRL) shows the formation of <10 nm iron particles on the surface of the grains. Electron energy loss spectroscopy (EELS) is consistent with these particles being metallic Fe.

We used the techniques described by Hendrix et al. (2019) and Caston et al. (2019) to test the reactivity and toxicity of the experimentally space weathered material and found that it is substantially more reactive and toxic than fresh lunar simulant. The experimentally space weathered simulant generates 2-5 times as much OH* as various unweathered simulants. In addition, exposing cells to experimentally space weathered regolith simulant leads to substantially more cell death than is seen for

> Some form of space weathering occurs on every airless body in the Solar System. Further study is needed to understand the effects of space weathering on mineral reactivity and toxicity.

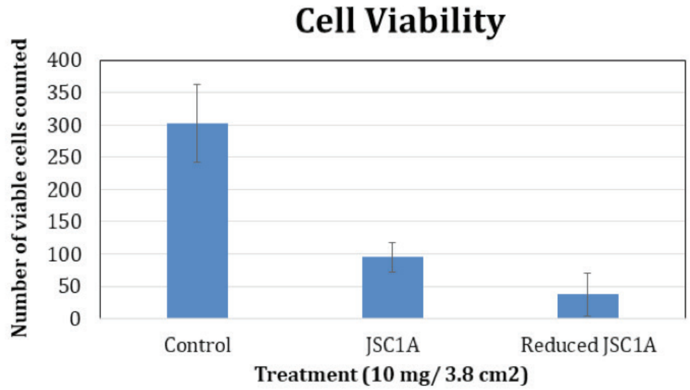


Figure 1.5. Viability for cells exposed to a control substance (anatase), lunar regolith simulant JSC-1A, and experimentally space weathered JSC-1A. The experimentally space weathered material killed many more cells than either the control or the unweathered simulant.

unweathered simulant (Figure 1.5). Future work will include assessing the effects of other experimental space weathering techniques and utilizing the reactivity and cell death assays on fresh and heavily space weathered lunar soils.

1.4 Theme 4. Maximizing Science from Returned Samples: Advanced Synchrotron and STEM Analysis of Lunar and Primitive Materials

During Year 5, the theme 4 team continued expanding its work analyzing returned samples, including meteorites and interplanetary dust particles, using synchrotron X-ray and infrared and transmission electron microscopy (TEM) techniques to investigate planetary materials at submicron spatial scales.

1.4.1 Transmission Electron Microscopy

Co-I Rhonda Stroud conducted the first-ever infrared characterization of individual GEMS (glass with embedded metal and sulfide) particles using the scanning transmission electron microscopes at the Naval Research Lab and Rutgers University (Figure 1.6). She is pioneering the technique of monochromated electron energy loss spectroscopy (EELS) at low energies to investigate early Solar System, presolar, and terrestrial standards to better understand how to make the scanning transmission electron microscopy-infrared spectroscopy (STEM-IR) a quantitative tool for analysis of individual sub-micron dust grains.

This proof-of-concept will enable direct measurements of cosmic dust grains to match with remote sensing and telescope-based measurements.

In addition to the work with GEMS particles, Co-I Bradley De Gregorio has obtained preliminary data to locate meteoritic nanodiamonds in situ, in insoluble organic matter (IOM) residues from meteorites, using scanning transmission electron microscopy. His data show that the nanodiamonds appear to be preferentially associated with "fluffy" IOM. By identifying the nanodiamonds in situ, he hopes to enable contextual analysis, e.g., isotopic composition of the associated organic matter that could help constrain the origins of the nanodiamonds.

1.4.2 Synchrotron X-ray and Infrared Analyses

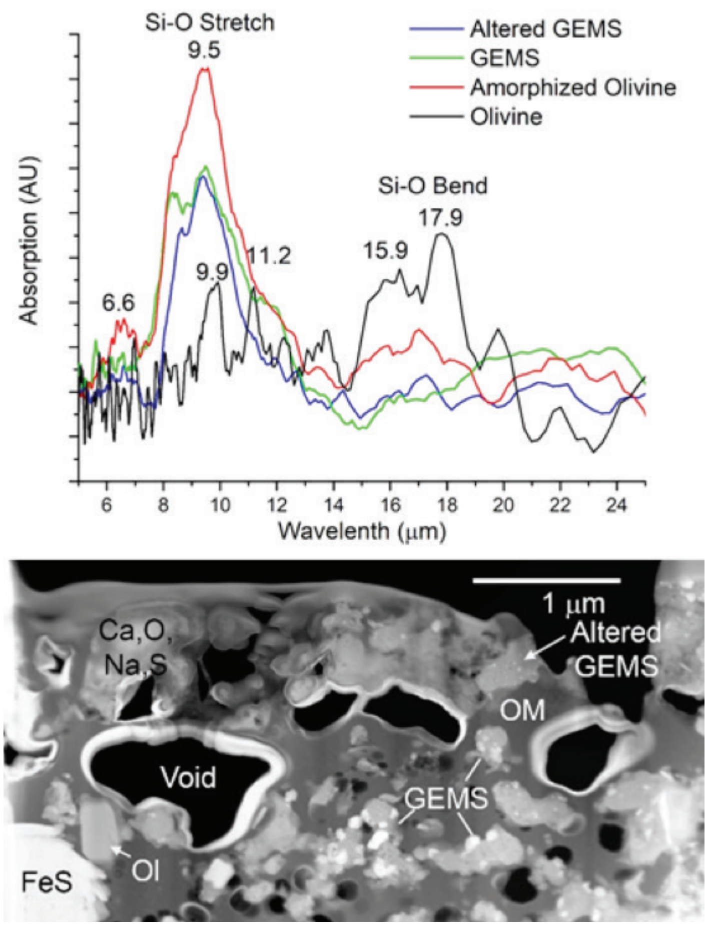


Figure 1.6. Electron energy loss spectroscopy (EELS) spectra (top image) show the mid-IR range features of the olivine (OL), GEMS and hydrated GEMS grain in the meteorite section (bottom image).

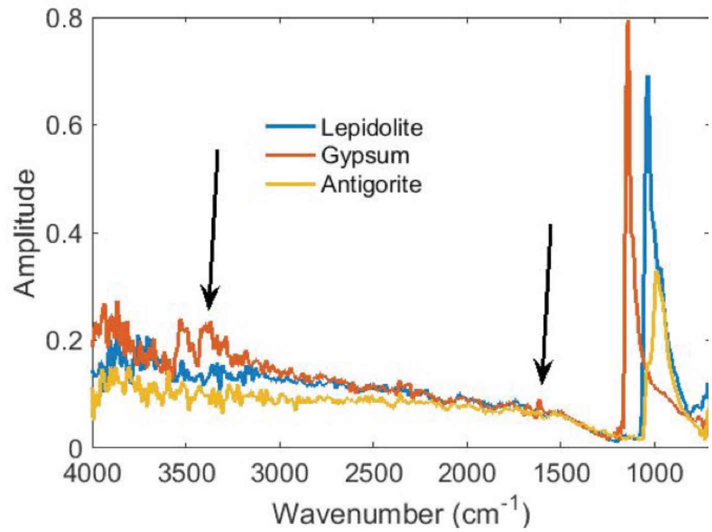


Figure 1.7. Nano-IR spectra of hydrated and hydroxylated minerals. Arrows denote water bands at ~3500 and 1600 cm^{-1}.

Stony Brook postdoc Sarah Nicholas was awarded synchrotron beamtime at the Advanced Photon Source to collect grazing-incidence X-ray absorption spectra on experimentally space weathered single mineral samples. She was assisted by beamline scientist and Co-I Tony Lanzirotti. She also completed six days of synchrotron nano- and micro-infrared beamtime at the ALS (Berkeley National Lab) with grad students Jordan Young, Melinda Rucks, and Allison Zastrow. Among the nano-IR measurements we made were, to our knowledge, the first demonstration of near-field infrared spectroscopy in the 3-μm OH/H_2O region (Figure 1.7). Using this technology, we could eventually map water distribution in samples at 20 nm spatial scales.

2. RIS4E Inter-team/ International Collaborations

The RIS^{4}E team is dedicated to the concept of inter-team collaboration within the overall structure of SSERVI. Our experiences in Year 4 have provided evidence that the whole of SSERVI is greater than the sum of its parts.

2.1 Collaboration with the IMPACT Team

The RIS^{4}E and IMPACT SSERVI teams have continued our successful collaboration that started in Year 4. The goal of the ongoing collaboration is to understand the structural and chemical effects of dust impacts on mineral standards and correlate those with resulting changes in infrared spectra. Stony Brook postdoctoral researcher Sarah Nicholas and graduate student Jordan

Young traveled to the University of Colorado with oriented olivine single crystals for the impact experiments. Prior to the impact experiments, one sample was irradiated with low energy protons at the Brookhaven National Laboratory Tandem Van de Graaf accelerator to simulate solar wind bombardment. Both samples were analyzed pre-impact using synchrotron X-ray absorption spectroscopy, infrared, and Raman spectroscopy. The irradiated sample and an unirradiated sample were subjected to ~10,000 dust impacts each at the CU dust accelerator at velocities of ~ 10 km/s. The samples were subsequently analyzed using the same techniques. Interestingly, the high velocity impacts resulted in less overall change to the structural and chemical characteristics of the samples compared to lower velocity (~5 km/s) impact experiments conducted in 2017. We hypothesize that this is because the high velocity impactors are ~10-100x smaller than lower velocity impactors, and the cumulative damaged surface area on the sample surface is correspondingly smaller. We are in the process of evaluating the chemistry of a new dust impact material (SiO2 glass) and actively coordinating with the IMPACT team for another suite of experiments.

2.2. Collaboration with the TREX and ESPRESSO Teams

The RIS^4E 2018 field season at the Potrillo Volcanic Field in New Mexico included collaborators from the TREX team (Dr. Shawn Wright) and the ESPRESSO team (Dr. Kevin Lewis, Dr. Marcella Yant, and Dr. Alex Parker). As the TREX and ESPRESSO teams prepare for their own field seasons, their team members participated in analyses of the physical properties and geochemistry of the rock and ash layers of the Kilbourne Hole site.

2.3. International Collaborations

Dr. Ed Cloutis (University of Winnipeg) is a RIS^4E collaborator and a Canadian Lunar Research Network (CLRN) team member, providing a link between the two teams. In each of the five years of our SSERVI collaboration, he has hosted a U.S. undergraduate student as a SSERVI summer research fellow. In 2018, he was awarded a Canadian Space Agency grant to conduct lunar field analog work in the Canary Islands during the summer of 2019. We anticipate that one or more RIS^4E team members will assist with that work.

Dr. Neil Bowles (University of Oxford) is a RIS^4E collaborator, providing a link to the UK and broader European Solar System science and exploration communities.

Former RIS^4E postdoctoral researcher Dr. Mehmet Yesiltas is now a professor at Kirklareli University in his home country of Turkey. He is now a RIS^4E collaborator, working with PI Glotch and SBU graduate student Jordan Young on Raman spectroscopic measurements of ordinary and carbonaceous chondrites. In December, 2018 he traveled to the Princess Elizabeth Antarctic Station (operated by Belgium) to learn how to work and operate on the Antarctic ice sheets. One expedition led to the recovery of three meteorites which are currently being analyzed and classified in Turkey.

3. Public Engagement

Throughout 2018, the RIS^4E team continued to support public engagement through the activities noted below.

3.1 Social Media

As a joint effort, multiple team members help to keep the public informed of RIS^4E science and exploration activities going on throughout the year over several social media platforms, including Twitter (@RIS4E_SSERVI) and Facebook (RIS4E Science and Exploration.) Updates from the lab, field, outreach events, and the exciting science happening throughout the RIS^4E team are shared with the general public in short, digestible bursts in order to excite the public about RIS^4E science and exploration. A highlight this year was public reporting on the final RIS^4E field season to the Potrillo Volcanic Field in New Mexico.

3.2. Public Events

The RIS^4E team supported public engagement at many events, including talks, interviews and hands-on activities.

RIS^4E team members supported outreach at multiple events for the 2018 International Observe the Moon Night. This is a night to inspire people to take a moment and look up at the Moon. RIS^4E scientists talked about their science, research, and exploration analogue work with the public in the evening followed by viewings of the full Moon where weather allowed. The event at NASA Goddard, supported by N. Whelley, had over 400 participants, and over 1000 events were hosted worldwide.

Several RIS^{4}E team members spent time at Union Station in Washington, DC giving talks and helping with hands-on activities for Earth Day 2018, with students, teachers, parents, and passersby.

RIS^{4}E team members supported the Planet Walk, an event that attracts families and people of all ages as they explore a scale model of the solar system, with the complete course being 4.7 miles long. The participants walk, run or cycle the whole distance while stopping at interactive booths to learn about each of the planets, and the Moon, along the way.

3.3. Boston Red Sox NASA STEM Day

On May 30, 2018, PI Glotch and RIS^{4}E students and postdoctoral researchers from Stony Brook University, along with NASA scientists from around the country shared highlights of NASA science and exploration activities with over 4,200 students and teachers from 58 schools from the Boston area at Fenway Park. The RIS^{4}E team supported the event by hosting a booth, and talking with both students and teachers. The event included a first pitch by astronaut Sunita Williams, the National Anthem played by Goddard Planetary Scientist Maria Banks, observing the Sun through a solar telescope, exploring a supernova in virtual reality, and launching water bottle rockets. After the event, teachers were sent home with a packet of materials for their classrooms, in order to continue the science discussed at the stadium.

Figure 3.1. Stony Brook postdoctoral researcher Katherine Shirley (red shirt) explains the uses of infrared light to students at Fenway Park in Boston, MA.

4. Student/Early Career Participation

Undergraduate Students

1. Dylan McDougall, Stony Brook University, Diviner data analysis, thermal IR spectroscopy (now a M.S. student at Brigham Young University)

2. Alexander Kling, Stony Brook University, Thermal IR spectroscopy of airless bodies

3. Grace Kim, Preparation of Bennu spectral analog mixtures

4. James Lightner, Stony Brook University, lunar petrology

5. Melvin Li, Stony Brook University, Macrophage response to lunar soil simulants

6. Katie Luc, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants

7. Rami Areikat, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants

8. Oliver Lockwood, Stony Brook University, Mineral synthesis and characterization

9. Kristina Finnelli, Stony Brook University, Infrared spectroscopy of basalts from Hawaii and New Mexico

10. Lindsey Rollosson, Harvey Mudd College, Mineral sample preparation and characterization

11. Jane Watts, Harvey Mudd College, Mineral sample preparation and characterization

12. Danielle Michaud, Harvey Mudd College, Mineral sample preparation and characterization

13. Miriam Eleazer, Mount Holyoke College, Spectroscopic data analysis

14. Adam Leschowicz, Purdue University, Spectroscopy environment chamber design/construction

Graduate Students

15. Gen Ito, Stony Brook University, Light scattering models and infrared imaging (now a postdoctoral researcher at NASA GISS)

16. Melissa Sims, Stony Brook University, Novel high pressure/temperature mineral physics experiments (now a postdoctoral researcher at Johns Hopkins University)

17. Melinda Rucks, Stony Brook University, Synthesis and characterization of tissintite

18. Carey Legett IV, Stony Brook University, Light scattering models and space weathering experiments

19. Jordan Young, Stony Brook University, Space weathering experiments and Raman spectroscopy

20. Donald Hendrix, Stony Brook University, EPR and XPS spectroscopy of lunar analog dust

21. Tristan Catalano, Stony Brook University, Pigeonite synthesis and electron microprobe characterization

22. Douglas Schaub, Stony Brook University, Plagioclase synthesis and electron microprobe characterization

23. Nicholas DiFrancesco, Stony Brook University, Olivine and plagioclase synthesis and characterization (now a Visiting Assistant Professor in the Department of Atmospheric and Geological Sciences at SUNY Oswego)

24. Kaitlyn Koenig Thompson, Stony Brook University, Lung inflammation processes

25. Nathan Smith, Northern Arizona University, Phobos thermal modeling

26. Marina Gemma, Columbia University, Simulated asteroid environment spectroscopy of ordinary chondrites

Postdoctoral Fellows

27. Sarah Nicholas, Stony Brook University/Brookhaven National Laboratory, X-ray spectroscopy (now a Beamline Scientist for the XFM beamline at Brookhaven National Laboratory).

28. Steven Jaret, Stony Brook University, Spectroscopy and geochronology of impact shocked materials (now a postdoctoral researcher at the American Museum of Natural History)

29. Rachel Caston, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants (now a postdoctoral researcher at Indiana University)

30. Katherine Shirley, Stony Brook University, Thermal IR spectroscopy in a simulated lunar environment.

5. Mission Involvement

1. Lunar Reconnaissance Orbiter, Timothy Glotch, Diviner Lunar Radiometer Experiment, Co-I

2. Lunar Reconnaissance Orbiter, Neil Bowles, Diviner Lunar Radiometer Experiment, Co-I

3. Lunar Reconnaissance Orbiter, Noah Petro, Project Scientist

4. OSIRIS-REx, Timothy Glotch, OTES/OVIRS, Participating Scientist Co-I

5. OSIRIS-REx, Deanne Rogers, OTES/OVIRS, Participating Scientist Collaborator

6. ORISIR-REx, Christopher Edwards, OTES, Participating Scientist Collaborator

7. OSIRIS-REx, Neil Bowles, Co-I/Sample scientist—spectroscopy

8. OSIRIS-REx, Thomas Burbine, Collaborator/Asteroid scientist—spectroscopy

9. ORISIS-REx, Ed Cloutis, Co-I/Asteroid scientist—spectroscopy

10. Emirates Mars Mission, Christopher Edwards, EMIRS, Instrument Scientist

11. 2001 Mars Odyssey, Deanne Rogers, THEMIS, Co-I

12. 2001 Mars Odyssey, Christopher Edwards, THEMIS, Co-I

13. 2001 Mars Odyssey, Scott McLennan, GRS, Co-I

14. Mars Science Laboratory, Christopher Edwards, Participating Scientist

15. Mars Science Laboratory, Darby Dyar, ChemCam, Participating Scientist

16. Mars 2020, Joel Hurowitz, PIXL, Deputy PI

Carlé Pieters

Brown University, Providence, RI

SSERVI Evolution and Environment of Exploration Destinations (SEEED)

CAN 1 Team

1. SEEED Team Project Report

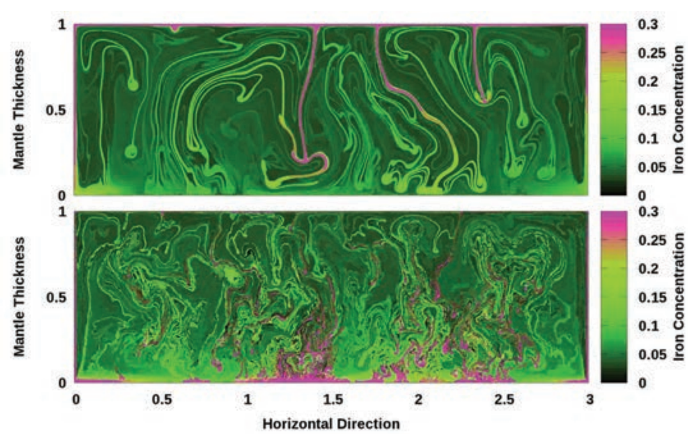
SEEED Science and Exploration Themes

Members of our SSERVI Evolution and Environment of Exploration Destinations (SEEED) team (PI & Co-Is, students, postdocs and collaborators) focus on broad interrelated themes that are linked to understanding the evolution and environment of NASA's prime exploration destinations [the Moon, asteroids and Phobos]. We are grounded in an academic environment and draw on the strength of ongoing and new research activities (including missions) led by diverse and highly motivated scientists coupled to significant involvement (and mentoring) of young scientists and engineers. Two SEEED Co-Is were recognized by their peers in 2018: Darby Dyar (also a Co-I with RIS^{4}E, TREX) was awarded the prestigious SSERVI Shoemaker Medal, and Brandon Johnson received the AGU Ronald Greeley Early Career Award given annually to a scientist in recognition of significant early career contributions. In this report we highlight a few examples of the achievements made by the SEEED team during the fifth year of SSERVI support. SEEED 2018 peer-reviewed publications mentioned below are in italics. More detail, depth, and breadth of our accomplishments can be found in our complete SSERVI-related peer-reviewed publications at: http://www.planetary.brown.edu/html_pages/brown-mit_sservi_pubs.htm .

1.1 Thermal/Chemical Evolution of Rocky Bodies

1.1.1 Magma Ocean Solidification (Boukaré et al., 2018, EPSL)

SEEED Postdoc 'ChEd' Boukaré has provided keen insight into the implications for the lunar interior as the lunar magma ocean (MO) crystalized (Boukaré et al., 2018,

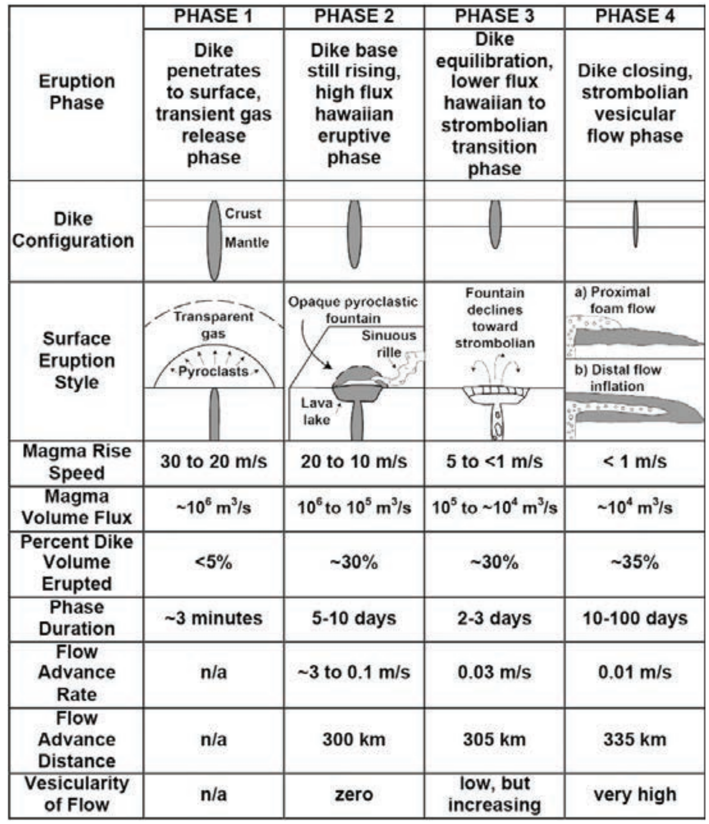


Two time slices for modeled lunar mantle convection that began before the end of MO solidification, illustrating a likely compositional complexity of the lunar mantle.

EPSL). Solidification of MOs formed early in the evolution of planetary bodies sets the initial condition for their evolution on much longer time scales. For the Moon, ideal fractional crystallization would generate an unstable chemical stratification that subsequently overturns to form a stably stratified mantle. The simplest model of overturn assumes that cumulates remain immobile until the end of MO solidification. However, overturning of cumulates and thermal convection during solidification may act to reduce this stratification and introduce chemical heterogeneity on scales smaller than the MO thickness. The effects of mantle cumulates overturning before the end of MO crystallization are explored together with the possible consequences for mantle structure and composition. In this model, increasingly dense iron-rich layers, crystallized from the overlying residual liquid MO, are deposited on a thickening cumulate layer. Effects of overturn are compared for endmember examples that occur before and after MO crystallization is complete. See insightful detailed movies of mantle solid-state convection over time that begin before [and also after] the end of MO solidification as supplemental materials at: https://www.sciencedirect.com/science/article/pii/S0012821X18301614?via=ihub - se0100

1.1.2 Phases of Lunar Volcanism Associated with Gas Release (Wilson and Head, 2018, GRL)

Co-Is Wilson and Head produced an integrated and highly accessible publication summarizing much of their work on gas release patterns and how it controls the morphology of lunar basaltic materials. In Wilson and Head, 2018 they subdivided typical lunar eruptions into four phases: Phase 1, dike penetrates to the surface, transient gas release phase; Phase 2, dike base still rising, high-flux hawaiian eruptive phase; Phase 3, dike equilibration, lower flux hawaiian to strombolian transition phase; and Phase 4, dike closing, strombolian vesicular flow phase. They showed how these four phases of mare basalt volatile release, together with total dike volumes, initial magma volatile content, vent configuration, and magma discharge rate, can help relate the wide range of apparently disparate lunar volcanic features (pyroclastic mantles, small shield volcanoes, compound flow fields, sinuous rilles, long lava flows, pyroclastic cones, summit pit craters, irregular mare patches, and ring moat dome structures) to a common set of eruption processes.

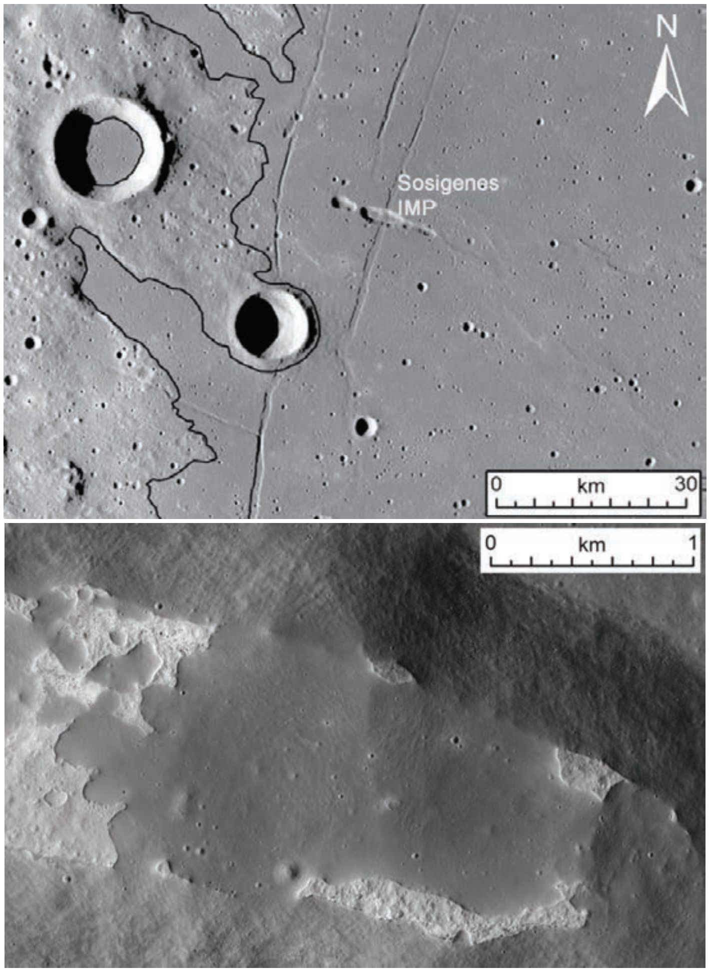


	PHASE 1	PHASE 2	PHASE 3	PHASE 4
Eruption Phase	Dike penetrates to surface, transient gas release phase	Dike base still rising, high flux hawaiian eruptive phase	Dike equilibration, lower flux hawaiian to strombolian transition phase	Dike closing, strombolian vesicular flow phase
Dike Configuration	Crust Mantle			
Surface Eruption Style	Transparent gas Pyroclasts	Opaque pyroclastic fountain Sinuous rille Lava lake	Fountain declines toward strombolian	a) Proximal foam flow b) Distal flow inflation
Magma Rise Speed	30 to 20 m/s	20 to 10 m/s	5 to <1 m/s	< 1 m/s
Magma Volume Flux	~10^6 m^3/s	10^6 to 10^5 m^3/s	10^5 to ~10^4 m^3/s	~10^4 m^3/s
Percent Dike Volume Erupted	<5%	~30%	~30%	~35%
Phase Duration	~3 minutes	5-10 days	2-3 days	10-100 days
Flow Advance Rate	n/a	~3 to 0.1 m/s	0.03 m/s	0.01 m/s
Flow Advance Distance	n/a	300 km	305 km	335 km
Vesicularity of Flow	n/a	zero	low, but increasing	very high

Summary of four phases of lunar mare dike eruption and gas release. (Wilson and Head, 2018)

1.1.3 Low Crater Retention on the Moon Resulting from Late-stage Products (Qiao, et al., 2018, MaPS)

Co-Is Head and Wilson have continued the multinational studies they lead focusing on the products of lunar volcanism (reported last year: Head and Wilson, 2017; Wilson and Head, 2017a,b; Qiao et al., 2017; F. Zhang et al., 2017). In *Qiao et al., 2018* they examined the role of substrate characteristics on late-stage products at the Sosigenes lunar irregular mare patch (IMP) that occurs on the floor of an elongate pit crater in western Mare Tranquillitatis. Although crater retention of the interior surface by itself might suggest a young age (~18 My), it is instead interpreted to represent the surface manifestation of magmatic dike propagation from the lunar mantle during the late stage of a mare basalt emplacement era billions of years ago. Using integrated volcanological interpretations for the ascent and eruption of magma in dikes, along with dike degassing and extrusion behavior in the final stages of dike closure (mentioned above



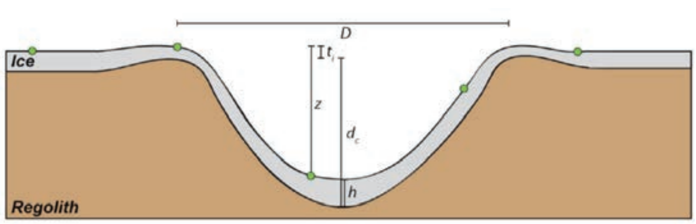
Sosigenes IMP feature in Mare Tranquillitatis (top). High resolution LRO-NAC image of this IMP interior illustrating the smooth texture of the stratigraphically young materials (bottom).

in 1.1.2), the special morphology of the IMP units is interpreted to be related to the late-stage behavior of an ancient dike emplacement event involving a highly porous foam.

1.2 Origin and Evolution of Volatiles in the Solar System

1.2.1 The Thickness of Mercury Polar Ice Deposits (Deutsch et al., 2018, Icarus)

The thickness of radar-bright polar ice deposits on



Model of a small impact crater in Mercury shadowed polar region with an infilling layer of ice.

Mercury, and thus their total mass and volume, is poorly constrained. Graduate student Ariel Deutsch and colleagues derive estimates of thickness for selected ice deposits using the degree of infilling for small, simple craters visible within the permanently shadowed, radar-bright deposits. Assuming the deposits are relatively young and infill pre-existing craters, they derive ice thickness estimates and calculate the total amount of water ice currently contained in Mercury's polar deposits, resulting in a value of ~10^{14}–10^{15} kg. This is equivalent to ~100–1000 km^3 ice in volume.

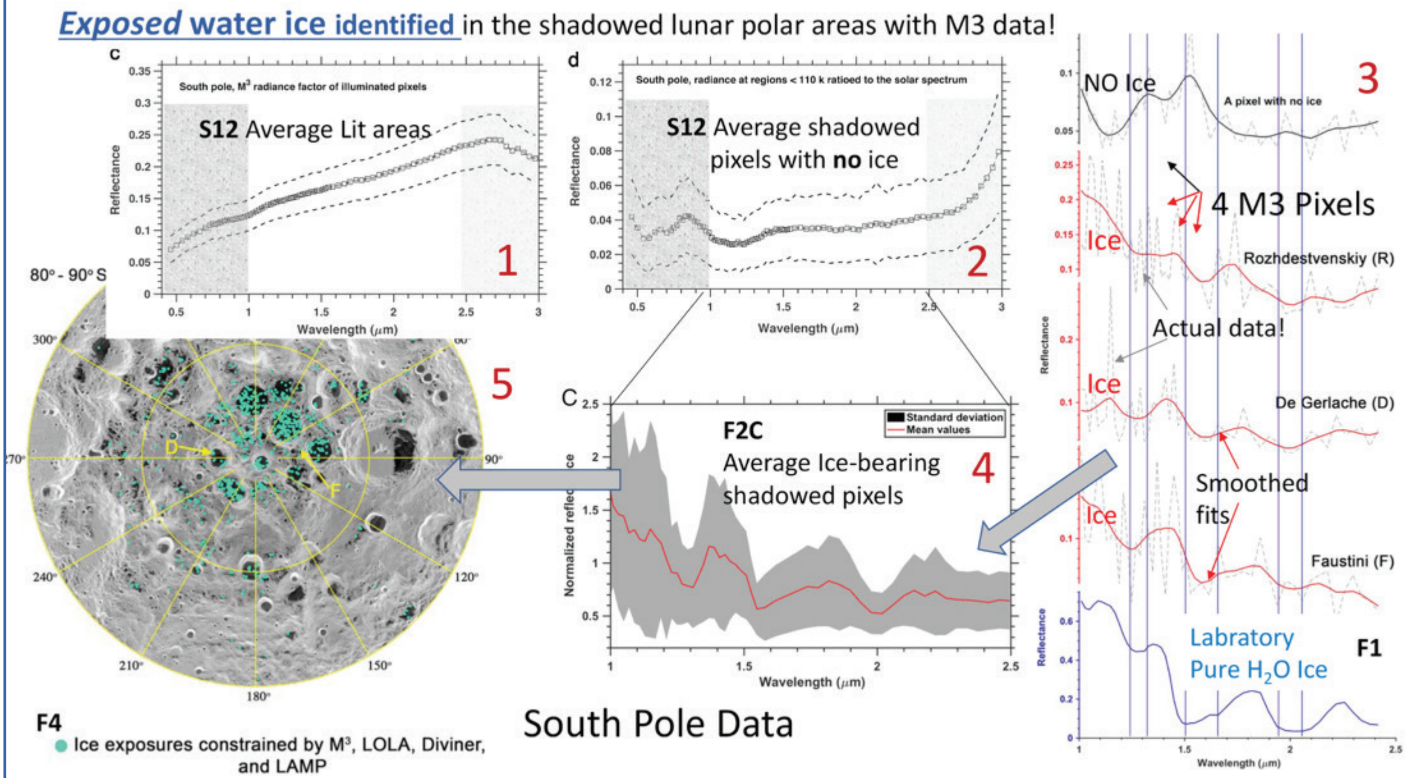
1.2.2 Unambiguous Detection of Water Ice/frost at the Lunar Poles (Li et al., 2018, PNAS)

A detailed statistical analysis of M^3 near-infrared spectra for lunar polar areas identified the clear diagnostic signature of water ice in small areas scattered across permanently shadowed terrain.

See Highlighted Box (next page) on Exposed water ice identified in shadowed lunar polar areas.

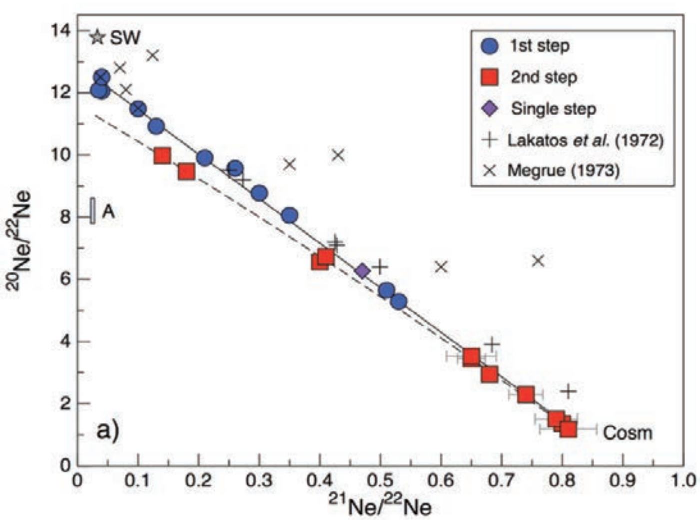
1.2.3 High Precision Isotopic Data for Volatile & Weakly Volatile Lunar Elements (Füri et al. 2018)

Working with colleagues at two institutes in France and the Open University (UK), Co-I Saal has initiated several productive new directions: (a) exceptionally high precision volatile element (noble gasses and H) measurements are achieved in single volcanic glass bead by step-wise CO2 laser extraction static mass spectrometry analysis (Füri et al., 2018, Geochem. Persp. Let.). Noble gas data are encouraging and may enable lunar indigenous noble gases to be constrained by deviations from solar wind and cosmogenic components. [See fig. a) next page] (b) In a separate project underway, in-situ SIMS spot and depth profiles analyses of Li and B isotopic abundance in single glass beads allow us to assess magmatic degassing and suggests these components were partially mobilized as volatile elements into the volcanic gas during processes that generated the lunar volcanic glasses, leaving a key signature on the glass beads due to kinetic fractionation. (See: Saal, A. E., M. Chaussidon, A. A. Gurenko, and M. J. Rutherford (2018), Boron and lithium contents and isotopic composition of the lunar volcanic glasses, Lunar



Despite multiple previous measurements and analysis approaches, direct evidence for water ice exposed on the lunar surface remained elusive. A detailed statistical analysis of M3 near-infrared spectra for lunar polar areas showed that illuminated areas exhibit typical spectra for well-developed soils (1), and most shadowed areas (with only secondary, scattered radiation) exhibit low reflectance values with no diagnostic features (2). However, after data smoothing to constrain noise, several shadowed individual pixels (140-280 m across) do exhibit distinct absorption bands of water ice (3) which, when averaged together (4), make the compelling case for small local areas of exposed water ice. The mapped distribution of such water ice detections (5 - with pixels enlarged) is consistent with LRO thermal models, but highly spotty in extent.

Li[1,2,3], S., P. G. Lucey[3], R. E. Milliken[2], P. O. Hayne[4], E. A. Fisher[2,5], J.-P. Williams[6], D. M. Hurley[7,8], and R. C. Elphic[7] (2018), Direct evidence of surface exposed water ice in the lunar polar regions, Proc. Nat. Ac. of Sci., 115, 8907-8912. Doi: 10.1073/pnas.1802345115. SSERVI-2018-061.
[1]PostDoc; [2]SEEED, [3]Univ. Hawaii, [4]Univ. Colorado, [5]GraduateStudent, [6]UCLA, [7]DREAM2, [8]VORTICES



a) Modern three-isotope plot for neon in Apollo pyroclastic glasses (blue and red) enables subtle deviations to be discerned from solar wind (SW) and cosmogenic (Cosm) abundances.

and Planetary Science Conference, XLIX, # 2575). (c) In addition, modern isotopic analyses of Zn (by MC-ICPMS in bulk rock) are being combined with measurements of H and Cl isotopes in apatite crystals (by in-situ NanoSIMS) to determine how much the Zn isotope ratios in lunar melts have been affected by magmatic degassing and to estimate the primitive Zn isotope ratios of the Moon.

1.3 Regolith of Airless Bodies

1.3.1 Lunar Soils Do Not Degrade in Terrestrial Curatorial Facilities (Taylor et al., 2018, MaPS).

When a technique was recently used to re-measure the particle size distribution of several lunar soils, a claim was made and published in Nature that lunar soils had deteriorated (into smaller particles) in terrestrial laboratories (including curatorial facilities). Co-I Taylor and several experienced colleagues undertook new analyses of lunar soils to investigate this remarkable suggestion. Their integrated data thoroughly refuted the claim and provided examples of lunar soil measured over decades using several different techniques (including the same instrument used in the original claim). Taylor et al demonstrated that no significant change in the size distribution of natural lunar soil particles has occurred since the soils were made available for investigators to study in terrestrial laboratories.

1.3.2 FT Application for M³ Data Enables Improved Compositional Analysis (Shkuratov et al., 2018)

Ongoing collaboration with Yu. Shkuratov at Kharkiv University and his students (Shkuratov et al., 2018, Icarus) resulted in dramatic improvement for small areas of M3 data through the application of advanced image processing techniques. This involved Fourier transform to minimize along-track detector variability due to [unplanned] spacecraft conditions. Initial results allowed pyroclastic glass to be clearly distinguished from local basalts and mapped across the Aristarchus plateau based on its broad diagnostic ferrous absorption near 1 μm.

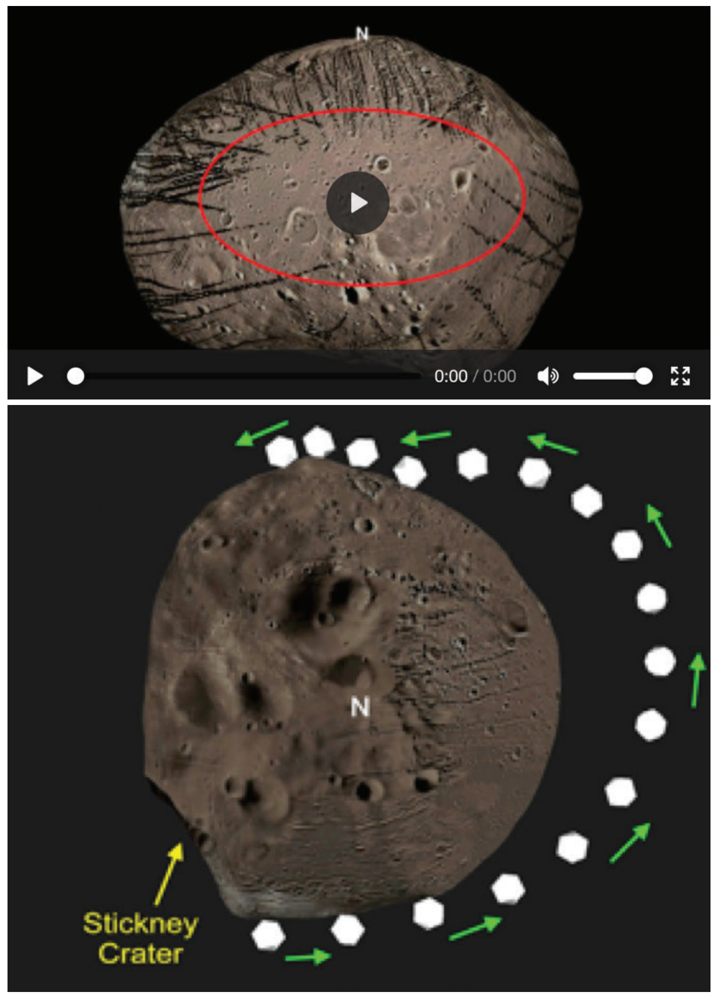
1.3.3 Phobos Grooves: Visualization and Testing Origin Hypotheses (Ramsley and Head (2018, P&SS)

This manuscript, and especially the attached series of well-illustrated tutorial videos, provides clear simulations of a viable model for the formation of the pattern of grooves on Phobos associated with Stickney crater.

> With Space Policy Directive #1, NASA and partners are poised to initiate Transformative Lunar Science, which can reveal the early history of our Solar System and the evolution of the enigmatic Earth-Moon system at 1 AU.

1.4 *Science and Engineering Synergism*

A SSERVI white paper on Transformative Lunar Science (TLS) was prepared [led by C. Pieters (SEEED), R. Canap (ISET), D. Kring (CLSE), J. Head (SEEED), and D. Scott (SEEED)], reviewed by SSERVI PIs, and transmitted to NASA Headquarters by SSERVI Central. Some of the most fundamental science objectives that can be achieved as NASA moves forward to the Moon are discussed, as well as institutional/engineering issues that must be addressed in the modern highly technical international environment. Several TLS invited presentations (with discussion) were made at NASA HQ, CAPS-NAS, COSPAR, etc. The full document can be found at: https://sservi.nasa.gov/wp-content/uploads/2018/02/TransformativeLunarScience.pdf . Topics include:



Supplementary data with five very informative tutorial movies include a rotational global view of the location of grooves as well as a model for how the 'zone of exclusion' (red oval) can be explained by ejecta launched from Stickney that becomes sub-orbital before returning to Phobos. These movies can be found online at https://doi.org/10.1016/j.pss.2018.11.004.

Science. a) Establish the period of giant planet migration and its effects in our Solar System. b) Provide an absolute chronology for Solar System events. c) Use the accessible vantage from the lunar farside to view the universe. d) Understand and utilize the special water cycle of the Moon and other airless bodies. e) Characterize the Moon's interior to reveal how this differentiated neighbor of Earth formed and evolved. f) Evaluate the extended record of space weather and fundamental processes of plasma interactions with surfaces.

Engineering/Policy. a) Achieve global leadership in lunar exploration. b) Establish a solid lunar exploration infrastructure. c) Coordinate planning and implementation of human/robotic partnership. d) Optimize commercial involvement.

An Appendix includes brief summaries of relevant National Research Council reports and recommendations.

Detailed plans were subsequently initiated by Co-I Head and PI Pieters for the March 2019 Microsympoium 60 – Forward to the Moon to Stay: Undertaking Transformative Lunar Science with Commercial Partners.

2. Inter-team/International Collaboration

2.1 International Partners/Collaboration

During 2018 SEEED has enjoyed productive collaboration with partners from Canada, France, Germany, Japan, Russia, UK, and Ukraine and with colleagues from Israel, as well as multilateral interactions with Chinese colleagues.

- **International mission participation:**

Co-Is Hiroi and Milliken were invited to participate and spend several weeks in Japan working with the Hayabusa II team as the spacecraft began operations near Ryugu. They are assisting with calibration of the spectral sensors.

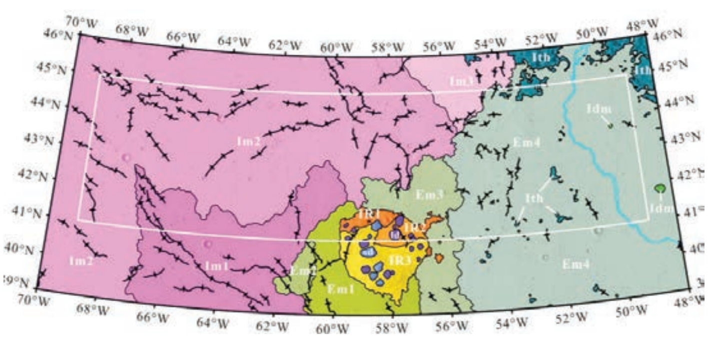
- **Manuscripts on lunar landing sites:**

SEEED has worked with our international partners and colleagues in assessing landing sites for lunar missions such as Luna Glob, Chang'E 4, and Chang'E 5: *Ivanov et al. 2018, PSS; Huang et al. 2018, JGR; Qian et al. 2018, JGR*.

- **Example other international-led collaborative analyses with SEEED participants:**

Wilson & Head sequence [see sections 1.1.2 and 1.1.3]; Füri et al. 2018, Geochem. Persp. Let. [see section 1.2.3]; Shkuratov et al 2018, Icarus [see section 1.3.2]. In addition, Hiroi and Milliken are co-authors on Hayabusa II initial results papers currently under review.

- **SEEED 2018 International Workshop interactions and oral presentations:**
- New Views of the Moon II: April, Aizu, Japan
- European Lunar Symposium: May, Toulouse, France
- International Symposium on Lunar & Planetary Science*: June, Macau
- Atmosphereless Solar System Bodies*: June, Kharkiv, Ukraine
- COSPAR*: July, Pasadena, CA
- Ninth Moscow Solar System Symposium* (9M-S3): October, Moscow
- [*multiple lunar or asteroid presentations/ discussions]



Geologic map of Rümker hill area in NW Procellarum. White box denotes the CE5 landing region.

2.2 Cross-Team Partners/Collaborators

- See section 1.4: SSERVI Transformative Lunar Science white paper that was led by SEEED but involved all SSERVI teams at different levels.

- Of the thirty-eight SEEED peer-reviewed publication in 2018, almost half involved other SSERVI teams or international collaboration. SEEED also produced 50 LPSC49 2018 extended abstracts (oral and poster presentations) of ongoing research concerning the Moon, laboratory characterization and tools, small bodies and meteorites, craters and basins). Approximately 20% of these LPSC projects involve other SSERVI teams.

See Highlighted Box (next page) on Origin and Evolution of the Moon: Graduate-level Seminar Course that was led by SEEED and CLSE with several SSERVI participants.

3. Public Engagement and EPE Report

SEEED Student Initiatives

3.1.1 Ladd Observatory

Graduate student Ben Boatwright assists with public observing nights at Brown's historic Ladd Observatory, which has a manual dome operation and a mechanical Earth-tracking drive system. Ben helps operate the main refractor, a 12" equatorially mounted scope, built and maintained in its original condition since 1891 [said to have been a favorite of H.P. Lovecraft]. He serves as the lunar and planetary geology consultant when the telescope is aimed at the Moon or other Solar System bodies. Ben answers people's questions about what they're seeing and gives broader context, including our activities with SSERVI-SEEED.

3.1.2 Lunar Course Behind the Scenes

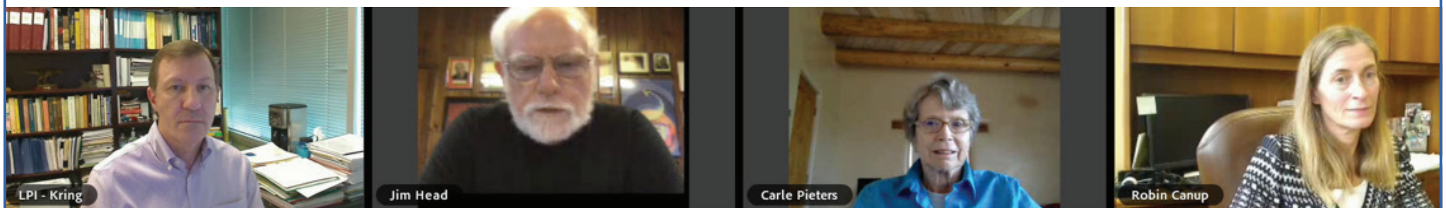
A group of students at Brown University have been working closely with engineers at OrbitBeyond along with TeamIndus and their commercial partners through a collaborative project stemming from the SSERVI-sponsored class, "Origin and Evolution of the Moon" offered during the Fall 2018 semester. Because the OrbitBeyond Z-01 mission is planned for a location that contains valuable information for understanding the origin and evolution of the Moon, the students set out to explore ways to optimize the scientific return of the mission through the development of a Design Reference Mission (DRM) to Mare Imbrium. Their goal was to characterize the Z-01 landing site from a scientific and geologic perspective and define key scientific goals that can be accomplished by the lander and rover during a 10-Earth-day mission lifetime. A full report is in preparation.

Brown students discussing lunar course issues with astronaut Terry Virts. [Advisor Head is on the left.]

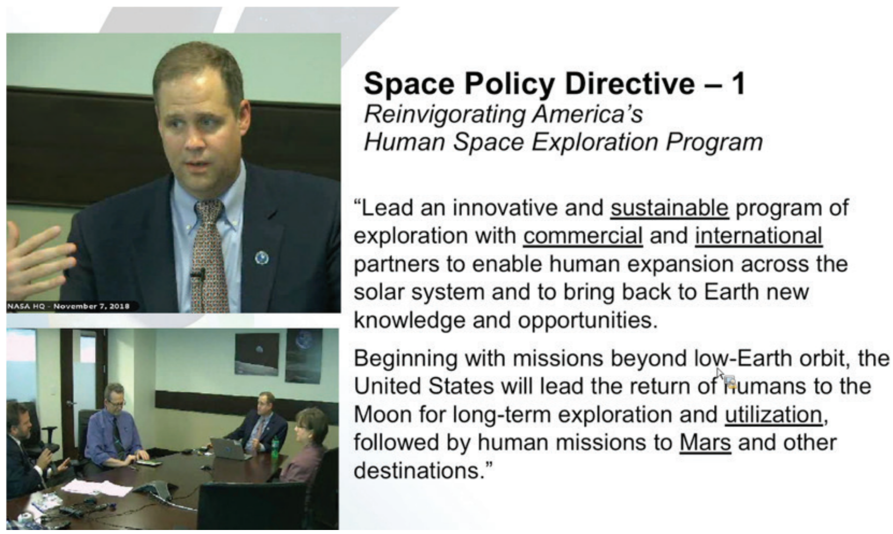
3.2 Joint SEEED and CLASS SSERVI Education and Public Engagement (EPE)

Throughout the fifth year of the SSERVI grant, the SEEED and CLASS EPE team was actively engaged in training pre-service and in-service educators from both formal

Origin and Evolution of the Moon: Graduate-level Seminar, September-December 2018. SSERVI supported an on-line course organized and led by SEEED & CLSE. Recommended reading and lecture recordings are found at: http://www.planetary.brown.edu/html_pages/geo2870_2018-2019.html



Sept. 5: Transformative Lunar Science: David Kring (CLSE), Jim Head (SEEED), Carle Pieters (SEEED), and Robin Canup (ISET).
Sept. 12: History of Lunar Exploration: Jim Head (SEEED).
Sept. 19: Formation of the Moon: Current Scenarios: Robin Canup (ISET).
Sept. 26: Formation of the Lunar Crust: The Magma Ocean Hypothesis: Marc Parmentier (SEEED)
Oct. 3: Structure of the Lunar Crust, Mantle and Core: Maria Zuber (SEEED)
Oct. 10: Lunar Cratering Record and Late Heavy Bombardment: Bill Bottke (ISET)
Oct. 17: Highlands Rock Suite: Clues to Early Lunar Evolution: Clive Neal (Notre Dame)
Oct. 24: Lunar Mare Volcanism: Emplacement of Secondary Crust: Jim Head (SEEED)
Oct. 31: Impact Cratering and Formation of Basins: Gordon Osinski (CLRN) and Brandon Johnson (SEEED)
Nov. 7: Space Directive-1: To the Moon to Stay: NASA Administrator James Bridenstine
Nov. 14: Origin and Evolution of the Lunar Magnetic Field: Sonia Tikoo (Rutgers) and Ben Weiss (SEEED)
Nov. 28: Thermal Evolution of the Moon: Lindy Elkins-Tanton (SEEED)
Dec. 5: Lunar Polar Deposits and Surface Water: Dana Hurley (DREAM2; VORTICES) and Ralph Milliken (SEEED)



Dec. 19: Future Exploration of the Moon: The Road Ahead: Apollo 17 Astronaut Harrison "Jack" Schmitt

and informal institutions across the country, working with students and engaging the public on SSERVI-related topics. This included 15 separate Public Engagement Events/Activities (four of which included greater than 1000 participants) as well as three courses for teachers and undergraduate students.

Tactile Books and Resources. Over 3,000 copies of Understanding Small Worlds in Our Solar System: A Tactile Guide and 1,500 copies of the recently updated tactile book, Getting a Feel for Lunar Craters were distributed to Schools for the Blind, State libraries, Museums and Science Centers and the Library of Congress here in the US. Additionally, the tactile books are being used by students who are Blind/Visually Impaired at schools in Italy, Poland, France, England, South Africa, Ethiopia, Chile, Argentina, Australia, China, Japan and more, and have been highlighted at several national and international conferences. The books were showcased at the 2018 Vis-U Summer Camp at Space Center Houston (a science and engineering camp for students who are Blind/Visually Impaired) and the inauguration of 'Inspiring Stars' at the International Astronomical Union meeting in Vienna, Austria. The books are being translated into Spanish and are being signed. These accessible versions of the text are available online using the 'QR' code on the front of the books: https://lunarscience.arc.nasa.gov/books

In addition, currently in press is Abre tus Sentidos a los Eclipses: Sud America. This tactile book covers the upcoming 2019 and 2020 eclipses in Chile and Argentina, respectively. It will be printed in Spanish, including the Braille. English and Spanish translations of the text will be available online.

4. SEEED Student/Early Career Participation and Faculty Transitions

Graduate Students

1. Michael Bramble, Brown University, Lunar and asteroid environment spectroscopy
2. Benjamin Boatwright, Brown University, Extended outreach at the Ladd Observatory
3. Ariel Deutsch, Brown University, Polar and circumpolar ice deposits, Moon and Mercury; Received Best Poster Award at International Symposium on Lunar & Planetary Science 2018
4. Erica Jawin, Brown University (now at Smithsonian NMNH), Human explorations destinations
5. Hannah Kaplan, Brown University (now at SwRI/OSIRIS-REx), Spectroscopy of organic materials
6. Leif Tokle, Brown University, Key facilitator for student Design Reference Mission Project
7. John Bierstecker, MIT, magnetic fields within the early Solar System
8. Tess Caswell, Brown University (now at Blue Origin), Experiments on ice under extreme conditions
9. Clara Maural, MIT, meteorite paleomagnetic analyses; Received an AGU outstanding student presentation award
10. Sean Wiggens, Brown University, Lunar impact crater and basin formation

Postdoctoral Fellows

1. Kevin Robertson, Brown University, Laboratory studies of lunar and asteroidal materials
2. Charles-Edouard Boukaré, Brown University (now in France), Modelling of lunar magma oceans and aftermath
3. Shuai Li, Brown University (now at University of Hawaii), Remote analysis of lunar water species
4. Elizabeth Silber, Brown University (now at Defense Research and Development Canada), Analysis of impact crater characteristics
5. Elizabeth Sklute, Mount Holyoke College, Spectroscopy of nanophase iron
6. Daniel Moriarty, (now at Goddard), Study of the South Pole-Aitken basin
7. Claire Nichols, MIT, meteoritic magnetic and structural characterization; Received AGU outstanding presentation award

Co-I/Faculty Transitions

1. Eric Hauri, Carnegie, Experimental sample analyses [Eric’s passing is deeply mourned]
2. Alexander Evans, Brown University, Lunar Geophysics [energetic addition to our team]

5. SEEED PI/Co-I Mission Involvement

Table 5.1 lists some of the mission activities for which SEEED PI/Co-Is have been involved. [Planned or upcoming missions are necessarily incomplete.]

Mission	SEEED Investigator	Instrument/Experiment	Role
Chandrayaan-1	Pieters, Carle	Moon Mineralogy Mapper	Instrument PI
Chandrayaan-1	Head, Jim	Moon Mineralogy Mapper	Co-I
Chandrayaan-1	Mustard, Jack	Moon Mineralogy Mapper	Co-I
Chandrayaan-1	Runyon, Cass	Moon Mineralogy Mapper	Co-I/EPO
Dawn	Pieters, Carle	Science Team	Co-I
Dawn	Zuber, Maria	Science Team	Co-I
Mars Ex (Phobos)	Head, Jim	HRSC	Co-I
LCROSS	Schultz, Peter	Science Team	Co-I
LRO	Zuber, Maria	LOLA	Instrument PI
LRO	Head, Jim	LOLA	Co-I
MESSENGER	Head, Jim	Science Team	Co-I
GRAIL	Zuber, Maria	Discovery Mission	Mission PI
GRAIL	Head, Jim	Science Team	Participating Scientist
GRAIL	Johnson, Brandon	Science Team	Affiliate
GRAIL	Evans, Alex	Science Team	Affiliate
OSIRIS REx	Binzel, Rick	Science Team	Co-I
Hayabusa2	Hiroi, Takahiro	NIRS3 [JAXA invited]	Team Member
Hayabusa2	Milliken, Ralph	NIRS3 [JAXA invited]	Team Member
Psyche	Elkins-Taunton, Lindy Discovery Mission	Mission PI	
Psyche	Weiss, Ben	Magnetometer	Instrument PI
Psyche	Zuber, Maria	Radio Science	Instrument PI
Psyche	Binzel, Rick	Asteroid Composition	Science Team
SpaceIL	Head, Jim	New Lunar Mission	Science Team
SpaceIL	Weiss, Ben	New Lunar Mission	Science Team
MoonDiver	Head, Jim	Discovery Lander Concept	Science Team
MoonDiver	Pieters, Carle	Discovery Lander Concept	Science Team
NAME-TBA	Pieters, Carle	Discovery Orbiter Concept	Science Team
NAME-TBA	Pieters, Carle	Discovery SmallSat Concept	Science Team
NAME-TBA	Pieters, Carle	SIMPLEX in review	Science Team
NAME-TBA	Pieters, Carle	DALI accepted	Collaborator
NAME-TBA	Pieters, Carle	LSITP Concept	Collaborator

Table 5.1: SEEED Mission Involvement

Andy Rivkin
Johns Hopkins University/ Applied Physics Lab, Laurel, MD

Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES)

CAN 1 Team

1. VORTICES Team Project Report

The Volatiles, Regolith and Thermal Investigations Consortium for Exploration and Science (VORTICES) team has been carrying out research since 2014 on four broad themes: "Volatiles: Sources, Processes, Sinks;" "Regolith Origin and Evolution;" "Resource Identification;" and "Strategic Knowledge Gap Analysis." In the intervening time, significant cross-theme and interdisciplinary work has occurred. Therefore, the sections below are aligned with current research avenues.

> The VORTICES team studies the interrelationship between airless body regolith and volatile materials from formation to transport to sequestration or destruction.

1.1 Lunar and Asteroidal Volatiles

The formation, transport, and destruction or sequestering of lunar volatiles has been a major research interest of VORTICES Co-Is since before the team's beginning: VORTICES evolved from an NLSI team focused on lunar volatiles. The final years of VORTICES are bringing some of the major questions in lunar volatile studies to closure, as geochemical and geophysical pathways are being studied in tandem with reconsideration of remote sensing data. In addition, VORTICES-sponsored work on the distribution of asteroidal volatiles has implications for ISRU/asteroid mining and for lunar science.

1.1.1 Lunar Volatile Distribution and Transport

1.1.1.1 Micrometeorite Vapor Plume Modeling

Building on our previous modeling work (Hurley and Benna (2018) PSS), we applied the model to LADEE NMS data of water vapor measurements in the lunar exosphere to understand impact vapor plumes from meteoroids. We found that the distribution of stochastic water vapor plumes requires that more water is released than the mass of the impactors. This implies that the water released primarily is derived from the lunar regolith, and not from the meteoroid itself. Furthermore, small impactors appear to be ineffective at releasing water, implying that a desiccated layer exists on the Moon. The associated paper is in review.

1.1.1.2 Compositional Associations with Hydroxyl

Team member Wilson has been examining Lunar Prospector epithermal neutron and gamma-ray data sets at the statistically highest resolving capability, using pixon reconstruction methods. This work has enabled a more direct comparison between the GRS compositional data and better resolution datasets including M3 OH−, building on the work of Klima et al. (2013) for Bullialdus. Image-reconstruction has improved the spatial resolution of Lunar Prospector Thorium Gamma Ray Spectrometer (GRS) data by a factor of ~2 (Fig.1, left). Previously several OH− anomalies that coincide with thorium enhancements (a proxy for KREEP) were identified (e.g., Bullialdus, Orientale and Korolev); however, there were also notable locations with enhanced OH− that lacked a thorium signal. With the updated map some of these OH− features (e.g., Montes Alpes) are now seen to be enhanced in Th (Figure 1, right). Most of the remaining

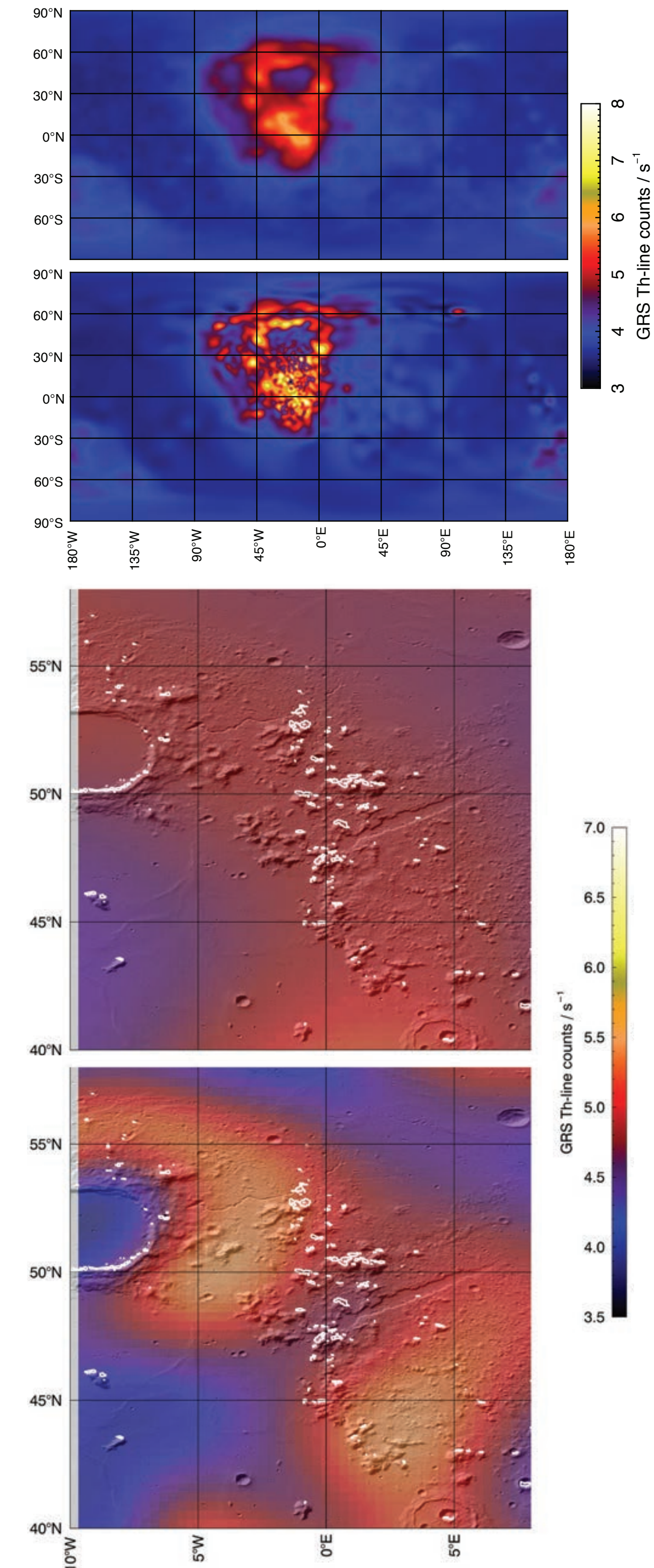


Figure 1. (Top) Lunar Prospector GRS Th data before (above) and after (below) reconstruction. (Bottom) Zoom centered on Montes Alpes, with the enhanced OH– areas outlined with white contours. The Alpes are clear in the underlying LOLA topographic map. Vallis Alpes can also be seen cutting through the Montes and coincides with a Th low in the reconstruction.

localized OH– anomalies that don't have a Th counterpart are small (e.g. Chaffee S at 19 km diameter) and may be below the limit of detection of the GRS.

1.1.1.3 Lunar Water Mission Concepts and Proposals

Multiple VORTICES team members have been involved with lunar mission concepts (both studies and proposals) designed to further investigate the lunar water cycle. These investigations build on the research conducted under SSERVI (and the prior NLSI polar node). Specifically, SSERVI funded some of the advance work to determine how one might design a low-cost mission to observe the Moon, and the Moon's purported water cycle from orbit, which was then supported as a low-cost mission study by NASA and described by Hibbitts et al. at LPSC in 2018. Additionally, team member Klima served as the Deputy PI for a small sat mission proposal (Lunar Trailblazer) to conduct near-infrared and thermal infrared measurements of the Moon.

1.1.1.4 Experimental Investigation of Hydration Variations as a Function of Photometry

SSERVI has supported experiments to investigate a possible photometric origin for the observed variation of the lunar 3-μm band depth with time of day, which correlates to solar incidence and emission angle and to temperature. A team, led by Hibbitts, has designed and conducted laboratory experiments to investigate the increasing depth of the 3-μm absorption feature with increasing latitude on the Moon to test the hypothesis that a significant contribution to the increase in band depth is a result of photometric change with latitude. Specifically, they are exploring whether the increasingly grazing solar incidence angle with increasing latitude, coupled with the likely distribution of hydroxyl in grains' rims, results in a greater optical path through OH-bearing materials for lower-angle (more grazing) illumination than for high-angle (more equatorial) observations.

Images have been successfully collected for each filter at each angle, and the water-related absorption is clearly identifiable. However, challenges remained, especially related to stability and measurement repeatability.

> The pixon reconstruction techniques being developed by the VORTICES team are conceptually related to image deconvolutions, and are applicable to many other neutron and gamma-ray spectrometer data sets.

The InSb camera and the light source and camera system together take almost two hours to warm up to a stable signal level before experimentation can begin. These experiments will continue in the next period of performance.

1.2 Remote Sensing Across Many Wavelengths

1.2.1 Integrating Lunar Data Sets

VORTICES team members are pursuing several projects that integrate numerous lunar data sets to provide a more robust assessment of the composition and surface properties of the Moon. These include jointly analyzing Diviner, mini-RF and microwave data, examining space weathering effects across multiple wavelengths, and comparing spatially deconvolved gamma ray and neutron data with other data sets.

Team members Siegler, Cahill, Hayne and others are attempting to leverage the underutilized Chang'e-2 MRM microwave data to get a better handle on lunar regolith loss tangent effects for subsurface interpretation of chemistry and rock abundance. Both radar and microwave are sensitive to a range of material properties, some of which may inhibit depth of detection. For example, LRO's Mini-RF is an S-band (12.5 cm) synthetic aperture radar that is sensitive to surface and subsurface point scatterers, corner reflectors, roughness, and composition. In areas of low titanium (ilmenite), Mini-RF should penetrate roughly 1 to 2 meters into the regolith. Similarly, with areas of low titanium using microwave (e.g., 3 GHz MRM channel; 10 cm wavelength) may be sensitive to a considerable amount of emitted radiation from up to ~3 m depth. However, in high-Ti areas the effective penetration depth of each of these wavelength regions is diminished. The team has been working to begin quantifying these effects, and presented initial results at LPSC (Siegler, et al., 2019).

Team members Cahill, Blewett, and others have been examining unoxidized vs. oxidized Fe and Ni optical constants from the FUV (160 nm) to the NIR (4100 nm) at a high spectral sampling. This work should enable a more robust look at how weathering might effect analysis of the 3 μm hydration feature on the Moon as well as analysis of M-Type asteroids like Psyche. This work was recently published in Icarus (Cahill et al, 2019).

Team members Wilson's efforts to spatially reconstruct Lunar Prospector epithermal neutron and gamma-ray data sets at the statistically highest resolving capability (Wilson et al., 2018, Section 1.1.1.2) also allows new investigations into variations of hydrogen with optical maturity indices. The improvement in resolution reveals a correlation between albedo and thermal neutron flux within many craters. The modeling results confirm that Hertzsprung is one of the most anorthositic parts of the lunar crust, containing nearly pure anorthite over regions tens of km in diameter. At Orientale, the improvement in spatial resolution of the epithermal neutron data show that there is a mismatch between measures of regolith maturity that sample the surface and those that probe the near-subsurface, which suggests a complex layering scenario. However, the same region shows similarities with radar observations suggesting a very young, immature region despite its old age.

Team members Klima and Greenhagen worked with an undergraduate summer intern, Jordan Bretzfelder, during the summer of 2018 and remotely throughout the school year. Jordan has worked to integrate Diviner and M3 observations to characterize the pyroxene and olivine-bearing massifs around Imbrium, Apollo, and Moscoviense basins. Previous work examining the materials around the Imbrium basin using combined near- and mid-infrared analyses concluded that most mafic minerals were mixed with substantial amounts of plagioclase, except in the southeast portion where some ultramafic pyroxenite is exposed. In order to better understand the origin of compositional differences around Imbrium and their relationship to the structure of the upper crust and mantle, we are beginning similar analyses on the Moscoviense and Apollo Basins (the latter in cooperation with Noah Petro of the RIS^{4}E team). Prior studies have identified ultramafic exposures around the Moscoviense basin, and the differences in crustal thickness and geologic setting of the three basins allow for analysis of a spectrum of scenarios. This work was presented at LPSC (Bretzfelder et al., 2019).

1.2.2 Asteroid Hydration and Thermal Properties

PI Rivkin (with co-author DeMeo) studied hydrated NEOs by using a visible-wavelength absorption due to oxidized iron that accompanies water/OH absorptions in carbonaceous chondrites and low-albedo asteroids. They predicted the fraction of low-albedo and hydrated bodies using the dynamical models developed to study transport of objects from the main asteroid belt into near-Earth space (Bottke et al. 2005), and find that the observed fraction of objects is lower by a factor of 2-3 compared to the dynamics-based prediction. Even so, roughly 10-30 hydrated asteroids larger than 1 km are thought to exist and be easier to reach from a delta-v perspective than the Moon. Additional characterization work will be necessary to identify the specific asteroids, but asteroid mining and ISRU concerns will be interested in finding them. This work was published in JGR as Rivkin and DeMeo (2018).

Team member Howell has been working to compare the work of Emery et al. (2014) model to the SHERMAN model of Spitzer observations of Bennu. One hemisphere fits well, but the other does not. The parameterization of surface roughness using hemispherical craters covering a fraction of each facet is different in each model. We are currently working to find the equivalent parameters using each formalism to better compare the results.

1.3 Regolith Creation and Evolution

Charles El Mir graduated from JHU in September with the doctoral dissertation "The Multiscale Mechanics of Surface Modification Processes on Asteroids." His work developed techniques to bridge the varying timescales related to three surface evolution mechanisms on asteroids: thermal fatigue, mechanical disruption, and gravitational reaccumulation. The thermal fatigue mechanism is first considered, and a numerical model is formulated to capture the crack tip driving force throughout an asteroid's diurnal cycle (a few hours) until the complete fracture of a surface rock occurs (103–106 years). The efficiency of thermal fatigue is demonstrated and compared to breakdown estimates from mechanical erosion by micrometeorite impacts. A simple analytical scaling model is derived that allows the prediction of rock breakdown rates by thermal fatigue for different airless bodies in the Solar System. All of this is described in a manuscript that is currently sub judice in Icarus (El Mir et al, in revision). An example of a key result is presented in Figure 2. In addition, we have examined the consequences of weak interfaces on the thermal fatigue problem, based on some published experiments of Guy Libourel.

In a second manuscript that has just appeared in Icarus (El Mir et al. 2019), attention was shifted to the timescales related to hypervelocity impacts onto asteroids. Two regimes with drastically different timescales were considered: the material mechanical response (from a few microseconds up to some tens of seconds), and the gravity response (from hours to days). A hybrid framework was developed to capture the mechanical response during the first seconds after impact through a multiscale material model implemented in a Material Point Method code, which was then coupled with an N-body gravity code (with the assistance of Prof. Derek Richardson of the University of Maryland, College Park) to examine the fate of the fragmented material as the ejecta interacts with the asteroid's gravitational field during the subsequent hours. It was shown that large asteroids (tens of km in diameter) may sustain higher impact energies than previously expected. This newly formulated hybrid approach is able to simulate a variety of asteroid impact events, such as angled impacts and spinning targets, from fragmentation to ejection and gravitational reaccumulation.

For the purposes of remote sensing, and even interactions between astronauts and the lunar surface, understanding the nature of the epitregolith (top mm of the regolith) is critical. Team member Greenhagen has spearheaded investigations of the epiregolith, leading

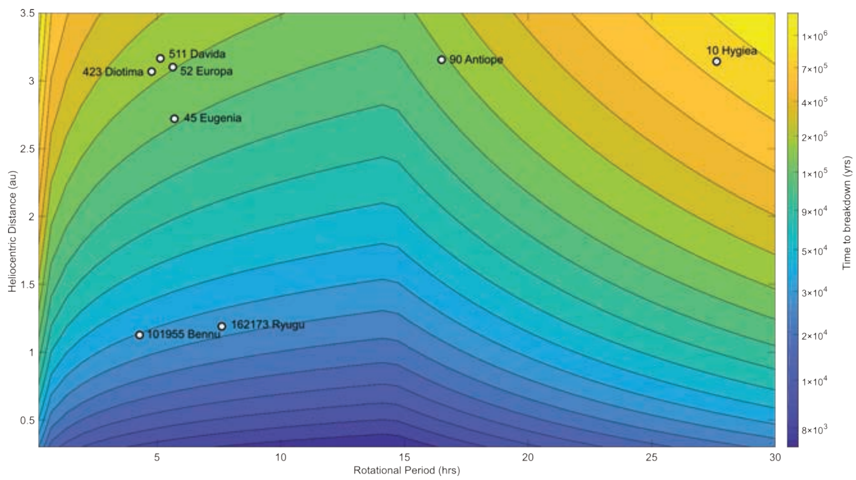


Figure 2. Predicted time (in years) to break down a 10 cm diameter rock on C-type asteroids as a function of period of rotation and heliocentric distance, using the new scaling relationship.

studies to determine the spectral effects of strong thermal gradients. This ongoing work includes laboratory experiments, numerical modeling, and data analysis of remote sensing datasets, and preliminary results were presented at the SSERVI-sponsored European Lunar Symposium. Recent studies have evaluated the thermal environment produced in the laboratory by altering the lamp wattage to produce different surface temperatures (Figure 3). For the first time, incidence angles for remote sensing observations of specific Apollo sampling sites have been matched to the illumination angle of the laboratory apparatus (~48 degrees) to set the surface temperature for measurement of Apollo soils returned from those stations. This methodology has significantly improved the match between remote sensing and laboratory data.

Team member Plescia has continued studying the rate of overturn in lunar regolith. Observations of new crater formation from LRO are inconsistent with Apollo cores: the canonical view is that the regolith is continuously (uniformly) overturned with time and that during exposure at the surface, the material is space weathered (including agglutination, nanophase Fe, implantation of H). However, overturn is episodic, spatially stochastic on relatively small scales and tied to impact events. None of the models predict significant overturn to depths of multiple meters on timescales less than the age of the Solar System. At such rates, there is no way to generate mature / space weathering regolith at depths of 3-4 m (Apollo sample depth). This implies that early (but still <3.5 Ga) rates must have been significantly greater.

Apollo cosmogenic nuclide data indicate overturn ranging from several cm <1000 yrs., to 1-3 cm in 1 - 10 Ma, to undisturbed for geologic time scales. New crater formation (based on LROC observations) suggest rates of 2 cm in 81 Ka to 20 cm in 10 Ma. Recent models are thus inconsistent with cosmogenic nuclide data from Apollo cores. At Shorty Crater, in particular, we know that the impact occurred at about 10 Ma. The Apollo 17 drive tube from station 4 (74001 / 2, 67 cm long) contains orange black glass, and is characterized as mature from 0-4.5 cm and immature from 4.5 cm to the base of the core. This implies that in the 10 Ma since the impact occurred, there has only been 4.5 cm worth of reworking at Shorty Crater. However, cold spot ejecta, observed from orbit, indicate a physical disturbance to ~10 cm depth. To remove this thermal signature requires normalization of regolith physical and thermal properties. The Shorty Crater reworking rate would imply that cold spots should persist for 20 Ma.

1.4 Community Engagement and Service

VORTICES team members have been heavily involved with the lunar and small bodies communities at large, including supporting the writing of the New Views of the Moon 2 book, taking an active role in mission and instrument concepts for science and exploration, and developing laboratory facilities that are made available for collaboration throughout the planetary community. Furthermore, we have continued to support the highly successful " Friends of Lunar Volatiles" telecons, started by team member Hurley but now led by team member Prem. These telecons now have begun to include industry partners, providing a direct, regular line of communication between the growing lunar commercial industry, scientists, and engineers.

For the New Views of the Moon 2 effort, the Surface Volatiles and Regolith Chapters were both led by VORTICES team members (Hurley and Plescia, respectively), and

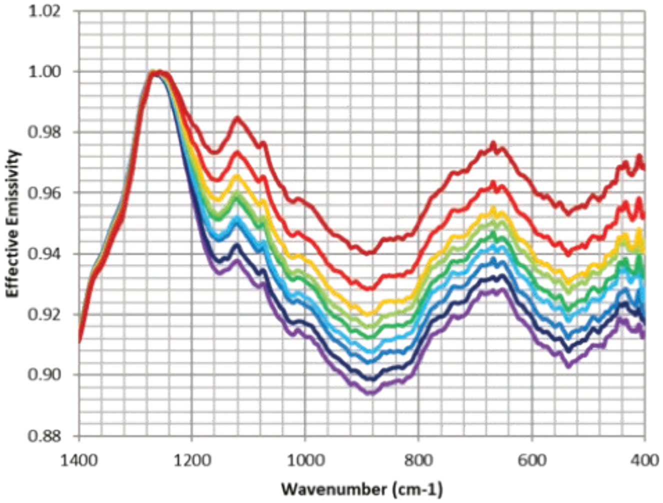


Figure 3. Increasing the lamp wattage (warmer colors) decreases spectral contrast and shifts the maximum emissivity (Christiansen feature) to longer wavelengths (smaller wavenumbers).

team members provided substantial contributions to these chapters as well as the Interior Volatiles, Space Weathering, and Lunar Crust chapters.

SSERVI supported team member Hibbitts attending the LEAG meeting, where he presented the concept of the MIMSI instrument, a simple camera for observing hydration on the Moon. As a result, MIMSI is being considered as a payload on an upcoming lunar mission. Team member Greenhagen compiled a set of science, technology, and exploration motivations for human exploration of the Mare Moscovience region, including several different levels of missions ranging from short-term reconnaissance through sample return, long-term monitoring, and Curiosity-level rovers. This was presented at the Lunar Science for Landed Missions workshop. Rivkin represented VORTICES at the UN-Holy See Exploration and Development of Space Opportunities and Issues in the Context of the Sustainable Development Goals (Albano, Italy) and the Asteroid Science Intersections with In-Space Mine Engineering (ASIME) in Esch-sur-Alzette, Luxembourg, giving invited talks at each. Team member Stickle attended the Luxembourg meeting with PI Rivkin. PI Rivkin also attended the NASA Autonomy Workshop in Pittsburgh, which included discussion with commercial autonomy experts (including founder of Amazon Prime Air and self-driving car engineers). Based on this meeting, attendees will generate white papers including design reference missions that take advantage of future autonomous spacecraft concepts.

> The work by the VORTICES team in collaboration with US and international scientists shows that thermal stresses are important in shaping the surfaces of airless bodies and that both thermal and impact processes need to be considered when studying regolith creation and evolution.

SSERVI has supported some of team member Hibbitts' time to install upgrades to the LabSPEC, including setting up and testing the ion gun and installing a femptosecond laser in the facility to simulate micrometeroid impacts. By having both these capabilities focused on a sample under vacuum at relevant temperatures, space weather effects can be simulated and researchers can observe the results spectrally from 150 to 8000 nm.

2. VORTICES Inter-team and International Collaborations

2.1 *Inter-team Collaborations*

VORTICES team members have established and continue strong collaborations with scientists throughout the SSERVI program. These collaborations include active collaborations with members of DREAM2, TREX, FINESSE, CLSE, SEEED, IMPACT, ESPRESSO, RIS^{4}E, and REVEALS, many of which have spawned new avenues of research and exploration. The VORTICES team is willing to provide laboratory support to other SSERVI nodes as well as members of the planetary community looking to collect pilot data for potential future research.

Team members Hurley, Zimmerman, and Prem have been critical in conducting inter-team research between the VORTICES and DREAM2 teams. This collaboration with the DREAM2 team resulted in a paper (Tucker et al. (2018) JGR) coauthored by Hurley on the diffusion of solar wind implanted hydrogen and the production of an H2 exosphere. Team member Matiella Novak has continued research and field work with the FINESSE team. Team members Klima, Hibbitts, and Gillis-Davis have conducted laboratory experiments in support of a potential Ureilite space weathering project with Cyrena Goodrich at LPI (CLSE). Klima has also worked extensively with Juliane Gross, also of CLSE, to explore microspectroscopy of lunar and analog materials, which has grown into a project recently funded by SSW. Team members Klima, Greenhagen, and intern Jordan Bretzfelder are coordinating with Dan Moriarty and Noah Petro (RIS^4E team) on linking Diviner and M3 data to examine the materials excavated by the Apollo basin. Team members Hibbitts and Dyar have continued close collaborations measuring and modeling volatile transport with Thom Orlando and the REVEALS team, and Rivkin remains on their advisory committee.

This year also included several strong collaborations with the TREX team. The presence of many TREX team members in the vicinity of APL has led to the use of VORTICES space for TREX meetings, including cross-team meetings. Team member Cahill worked with TREX to start a new study on lobate scarps which are among the youngest landforms on the surface of the Moon. In particular, they are examining a lobate scarp near the Apollo 17 landing site in the Taurus Littrow Valley that is estimated to have originated ~75 Ma. In the exercise, they have been examining whether the materials on the scarp are more or less mature than the surrounding regional regolith. High resolution LROC NAC photometric observations and OMAT data products derived from Kaguya Multi-spectral Imager are being used for the analysis. In an unusual twist, the young scarp is not present in the MIOMAT data products. This work was presented at the 2019 LPSC (Watkins, R. N. et al.).

Several team members (Hurley, Greenhagen, Hayne and Cahill) have worked with Hendrix (TREX) to revise and resubmit a manuscript on FUV-determined hydration with varying Diviner TIR-determined temperature. A new photometric correction from Liu for the LAMP data has been applied that improves the results for interpretation. A thermal desorption model including latitudinally-varying desorption activation energy reproduces the observations. We interpret the observed variability in spectral slopes as water molecules in the uppermost lunar regolith (<1% of a monolayer) thermally adsorbing and desorbing from grains depending upon the local temperature and availability of chemisorption sites. The LAMP data also demonstrate that in the Earth's magnetotail, where the solar wind source of protons is absent, a decrease in H_2O on the surface is not observed. This rules out a steady state process involving a prompt solar wind source and favors a migration mechanism for the distribution of adsorbed water on the Moon.

2.2 International Collaborations

VORTICES members collaborate regularly with international colleagues and support meetings with SSERVI partners overseas. This year we had several team members present at the European Lunar Symposium as well as at the New Views of the Moon-2 Asia conferences. Ongoing European collaborations include small bodies research work with Marco Delbo of Observatoire Cote d'Azur, Patrick Michel of OCA, and Guy Libourel of Nice and lunar, small bodies, instrument development and laboratory research with Neil Bowles, Tristram Warren and Kerri Donaldson Hanna at Oxford University in the UK. Deputy PI Klima is also serving on the Ph.D. thesis committee for Mélissa Martinot at the VU University Amsterdam, the Netherlands. Rivkin has continued supporting international meetings about asteroid resources and planetary defense, both of which have significant international interest. VORTICES members also actively collaborate with colleagues in Asia, including Junichi Haruyama, Hiroyuki Sato, Sarah Crites and others at JAXA as well as Seiji Sugita at the University of Tokyo.

3. Public Engagement Report

The fifth year of VORTICES public engagement activities built upon past SSERVI partnerships and leveraged resources to continue implementing a program that targets a diverse audience. Our activities engaged students, educators, and the general public with SSERVI and VORTICES science and engineering themes.

3.1 Student Engagement

Among our engagement activities were efforts to reach out to diverse students of various ages to convey the excitement of planetary science exploration. Team members visited several middle schools in the Anne Arundel County STEM Magnet program, including hosting events with the Magic Planet at Old Mills Middle School in Millersville, MD and Lindale Middle School. About 300 students were taken on a tour of the Solar System, where science and exploration themes were discussed. Team members also visited local elementary schools, including Phelps Luck Elementary School in Howard County, MD, a Title 1 school with ~85% minority enrollment. Over the summer, VORTICES members supported the Maryland Summer Center for Gifted and Talented Students Space Camp at the Applied Physics Laboratory, attended by about 50 students. During this presentation, students learned about planetary mission planning, how scientists and engineers work together to identify and answer Solar System exploration science questions, as well as how they build mission spacecraft to explore and answer those questions. It also included a Magic Planet presentation.

3.2 Engagement Institutes

3.2.1 Solar System Exploration Public Engagement Institute

This summer, VORTICES held its 3rd Solar System Exploration Institute with informal educators and educators who conduct public outreach for underrepresented communities. The goal of the program is to provide an experience for those who conduct public engagement to support their interest and enthusiasm for engaging audiences in Solar System exploration, and to increase their ability to do so by providing appropriate activities and content, including making new connections to subject matter experts. 36 participants from across the US attended the 4-day Institute at APL. The program focused on Solar System exploration content and interaction with VORTICES scientists, who gave 10 presentations on a variety of topics across the 4 days. Facilitators modeled over a dozen Solar System exploration activities that can be conducted with public audiences in a variety of venues and programs. Tours included a tour at APL of the meteorite lab, spectroscopy lab, and CRISM Science Operations Center, the Smithsonian's Air and Space Museum and Natural History Museum, and NASA Goddard Space Flight Center (GSFC). All participants (100%) rated the event overall as excellent. Based on follow-up evaluations, fifteen events hosted by alumni of this year's institute have already been reported, including events at a planetarium, scout meetings, a science center, a garden club, libraries, schools, and at a program for children with autism.

3.2.2 Planetary Scientist Engagement Institute

VORTICES team members Ms. Shupla and Dr. Matiella-Novak have been working together to plan a planetary scientist engagement institute, modeled after the successful institutes for informal educators but targeted towards planetary scientists who would like to increase their public engagement skills. A survey to gauge interest among planetary scientists was conducted in August-September 2018, which included an assessment of preferences for days and locations. Sixty-one scientists responded with moderate to strong interest in attending the institute. An institute was tentatively planned for December, 2018, to be held at APL, to take advantage of the American Geophysical Union conference in nearby Washington DC. Registrations were collected but the institute was postponed due to low numbers for the selected timeframe. The institute is currently being planned for March 22-23, 2019, and will be hosted at LPI.

4. Student/Early Career Participation

Undergraduate Students

1. Jordan Bretzfelder, University of Southern California, Geological mapping and spectral modeling (VORTICES and RIS^{4}E team collaboration for Apollo basin work). She won the undergraduate oral Dwornik award for her presentation about this work at LPSC in March 2018.

2. Carlos Eytan Gary Bicas, University of Colorado Boulder, Mars atmospheric sounding and the polar radiation budget*

3. Tyler Horvath, University of Colorado Boulder, Lunar thermal analysis*

Graduate Students

4. Sakshi Braroo, Johns Hopkins University, Impact

modeling

5. Charles El Mir, Johns Hopkins University, Impact modeling (defended during 2018)

Postdoctoral Fellows

6. Pavarthy Prem, Johns Hopkins Applied Physics Laboratory, Thermal and volatile modeling (VORTICES, TREX and DREAM2 collaborations)

7. Jack Wilson, Johns Hopkins Applied Physics Laboratory, Thermal and volatile modeling

New Faculty Members

8. Paul Hayne, University of Colorado Boulder, Thermal modeling

*Funding for Co-I Hayne did not complete transfer from JPL to CU Boulder until near the end of 2018. Dr. Hayne's group at LASP includes three undergraduate students, two PhD students, and two research associates. VORTICES supports the ongoing development of thermal and vapor diffusion models used by several members of Dr. Hayne's group. Specifically, new adaptations of the model for application to rough surfaces and small bodies have been developed during the last few months.

5. Mission Involvement

1. DART, Andy Rivkin, Investigation Team Lead

2. DART, A. Stickle, Co-I

3. Dawn/FC, A. Rivkin, Associate Team Member

4. Dawn/GRaND, D. Lawrence, Participating Scientist

5. Dawn, David Blewett, Participating Scientist

6. LRO / LROC, J. Plescia, Co-I, geology

7. LRO/Mini-RF, L. Carter, Participating Scientist

8. LRO/Mini-RF, B. Bussey, PI

9. LRO/Mini-RF, P. Spudis, Co-I

10. LRO/Mini-RF, A. Matiella Novak, Co-I

11. LRO/Mini-RF, J. Gillis-Davis, Co-I

12. LRO/LAMP and Mini-RF, J. Cahill, Participating Scientist and Co-I

13. LRO/LAMP, D. Hurley, Co-I

14. LRO/Diviner, B. Greenhagen, Deputy PI

15. LRO/Diviner, P. Hayne, Co-I

16. LRO/Diviner, M. Siegler, Co-I

17. LRO/Mini-RF and LAMP, A. Stickle, Science Team Member

18. MRO/CRISM, A. Matiella Novak, Team Member

19. LADEE/NMS, D. Hurley, guest investigator

20. MESSENGER/GRNS, D. Lawrence, Instrument Scientist and Participating Scientist

21. MESSENGER/GRNS, R. Vervack, Participating Scientist

22. MESSENGER/MASCS, R. Klima, Team member

23. OSIRIS-REx, E. Howell, Spectroscopy Collaborator

24. MGS/MAG-ER, D. Hurley, Associated Scientist

25. Europa Clipper, R. Klima, Project Staff Scientist

26. New Horizons/LORRI, A. Rivkin, Team member

27. Rosetta/Alice, R. Vervack, Team member

28. Psyche/GRNS, D. Lawrence, Instrument PI

29. MMX/MEGANE, D. Lawrence, Instrument PI

30. NEA Scout, A. Rivkin, Co-I

31. Lunar Flashlight, B. Greenhagen, Co-I

32. Lunar Flashlight, P. Hayne, Co-I

Alex Parker

Southwest Research Institute in Boulder, CO

Exploration Science Pathfinder Research for Enhancing SS Observations (ESPRESSO)

CAN 2 Team

1. ESPRESSO Team Project Report

In 2018, the Project ESPRESSO team continued to develop all of its major programs, including completing its first reduced gravity flight campaign, testing laser spectroscopy instruments in the field, and applying new methods for determining optical constants of minerals relevant to inner Solar System surfaces. Most team members were also involved in multiple planetary mission milestones, including the flyby of the Kuiper Belt Object 2014 MU69 and OSIRIS-REx's arrival at Bennu. The team convened for its first full in-person meeting to assess progress and develop plans for going forward. Project ESPRESSO team members developed a public engagement strategy focused on improving the accessibility of NASA planetary exploration programs.

1.1 Reduced Gravity Flight Campaign

A primary goal of Project ESPRESSO is developing facilities to deliver relevant pressure and gravity environments for experimenters seeking to understand processes and hardware performance on the surfaces of the Moon and near-Earth asteroids. The team's Airborne Space Environment Chamber will be the primary facility to deliver this capability, but during development the team identified the need to fly a smaller demonstration chamber to test operational procedures in the NRC-CNRC Falcon 20 reduced gravity research aircraft. These procedures include chamber loading and unloading, chamber component cleaning and handling procedures to prevent contamination of aircraft systems, and regolith handling mechanisms and procedures for zero-g flight. We constructed a demonstration chamber and experiment in September 2018, and performed four test flights in October 2018, ridesharing on Project PoSSUM flights to reduce the overall cost. Team members also supported the primary flight objectives by acting as equipment technicians for the Final Frontier Design spacesuit being tested in zero-g conditions.

1.1.1 Demonstration Chamber

An 8-liter vacuum vessel was designed and built to meet the mounting requirements for the Falcon 20 aircraft, and instrumented with an IMU and camera system. An internal regolith bed was designed to separate internal electronics from free-floating regolith disturbed during zero-g maneuvers. Experiments in the chamber were manually operated by a seated operator at the aft of the cabin, using a video feed to the interior of the chamber to assess experiment performance.

1.1.2 Demonstration Experiment: Magnetic Grapples for Regolith Manipulation

Asteroid regolith is frequently ferromagnetic. We can exploit this property to enable multiple modes of interaction with asteroid surfaces, providing improved anchoring, mobility, and sample collection. To demonstrate the potential of using magnetic means to manipulate regolith in the vacuum and microgravity conditions on asteroid surfaces, we implemented a simple experimental procedure in our demonstration chamber. The regolith bed was filled with a high-fidelity CI chondrite simulant provided by the CLASS SSERVI node. Once the aircraft entered the reduced gravity portion of a parabola, a single 1 cm diameter N42 grade neodymium sampling magnet was lowered into the regolith bed by means of a servo-actuated slide rail, then retracted by the same servo before the end of the reduced gravity phase. The magnet was suspended by a Kapton ring spring hung from a 500 gram strain gauge, Project ESPRESSO demonstrated magnetic sample collection of asteroid regolith under vacuum and microgravity conditions, paving the way for nano-lander sample return missions

providing a means of measuring required extraction force and an extremely low-k coupling to the servo rail and any vibration or impulses transmitted from the chamber exterior. Typically, a ~15 gram, ~3 cm sphere of material was extracted from the surface during a sampling experiment. An example sequence is illustrated in Figure 1.

1.1.2.1 Mission Concept and Future Development

Project ESPRESSO team members are now developing a concept mission utilizing magnetic means of sample collection. We are exploiting a "switchable" permanent magnet architecture that requires no power outside of transitioning from an "on" and "off" state. Additionally, this architecture produces no significant external field in its "off" state, reducing potential for interference with other spacecraft systems. As the sampling mechanism is small, low mass, and low power, it can be embedded within nano-landers that may be carried to a target body in large numbers by a parent spacecraft. By passively deploying many small samplers over the entire surface of a target body, site selection is vastly simplified and overall mission risk is reduced compared to current touch-and-go sample return architectures. Additionally, samples of from multiple sites of the highly heterogeneous surfaces of

Figure 1: October 2018 reduced gravity flight campaign. Top left and center: Airborne Space Environment Chamber demonstration experiment, mounted to the floor of the NRC-CNRC Falcon 20 reduced gravity research aircraft. Top right: A contingent of Project PoSSUM flight crew and Project ESPRESSO PI Parker. Bottom panels: Sequence of sample extraction of CI Chondrite simulant material using a magnetic grapple under vacuum and microgravity conditions.

Figure 2: April 2018 field campaign. Left: Transect planning through layered ash deposits. Center: Project ESPRESSO postdoc Marcella Yant performs LIBS measurement of a basalt boulder near Kilbourne Hole. Right: Layered ash transect with LIBS and XRF sample sites marked; vertical extent approximately 6.5 meters.

near-Earth objects ensures that a representative sample of surface materials are returned. We intend to develop free-flying demonstrators to test in our full-scale Airborne Space Environment Chamber in future flight campaigns.

1.2 Field LIBS and Raman Campaigns

Project ESPRESSO team members joined a 2018 SSERVI field campaign led the RIS^{4}E team. Team members executed a survey of layered ash deposits using a handheld SciAps LIBS Z300 instrument in concert with a RIS^{4}E XRF instrument. Scenes from the field campaign are illustrated in Figure 2.

1.2.1 Potrillo Volcanic Field Campaign

1. At Kilbourne Hole, team members defined two transects of the layered ash deposits produced by the sequence of eruptions. Two LIBS instruments and one XRF instrument were deployed to densely sample the elemental chemistry of the sediment along these transects, seeking evidence of temporal evolution of the chemistry of the magma chamber driving the eruptions. Results were cross-compared between the instruments, generally revealing broad agreement for most elements considered. Trends were revealed in some elements, including aluminum, potassium, sodium, calcium, and magnesium. Ongoing analysis is seeking to confirm these trends and determine if they are a product of differential weathering effects or magma chamber evolution.

1.2.2 Instrument Calibration Efforts

Project ESPRESSO Postdoc Marcella Yant travelled to Mount Holyoke University to perform calibration of a field LIBS unit in collaboration with Prof. Darby Dyar's group. There, she collected Z300 LIBS spectra of thousands of rock targets with known composition to develop an instrument calibration model tuned to the types of field analog compositions of most value for understanding instrument performance in future lunar exploration. Team members are now in the process of implementing an updated on-board instrument calibration, as well as exploring new analysis approaches to deliver higher precision results with post-processing.

1.3 Quantitative Spectroscopy

Project ESPRESSO is developing two laboratories for measuring the optical constants of materials relevant to the surfaces of asteroids and the Moon over wavelengths spanning 170 nm to 28 microns. In addition, the team is developing new analytical techniques for estimating optical constants from archival spectroscopic data. These techniques and measurements will enable accurate quantitative estimates of surface composition of asteroids and lunar terrains from remote and in-situ spectroscopy.

New analytical techniques will vastly speed the production of optical constants measurements, enabling quantitative analysis of lunar and near-Earth object composition

1.3.1 Laboratory Implementation

At Johns Hopkins University, the spectroscopic facility has been enhanced to include a cryostat enabling investigations of optical properties of materials at temperatures as low as 10 Kelvin and as high as 800 Kelvin. Team members were trained by the vendor on the primary instrument, and data collection has begun. Reflection and transmission spectra, shown in Figure 3 have been collected for a set of canonical calibration materials, and new materials are in progress. SwRI Boulder is also implementing a new spectroscopic facility that will further enhance the capabilities of Project ESPRESSO

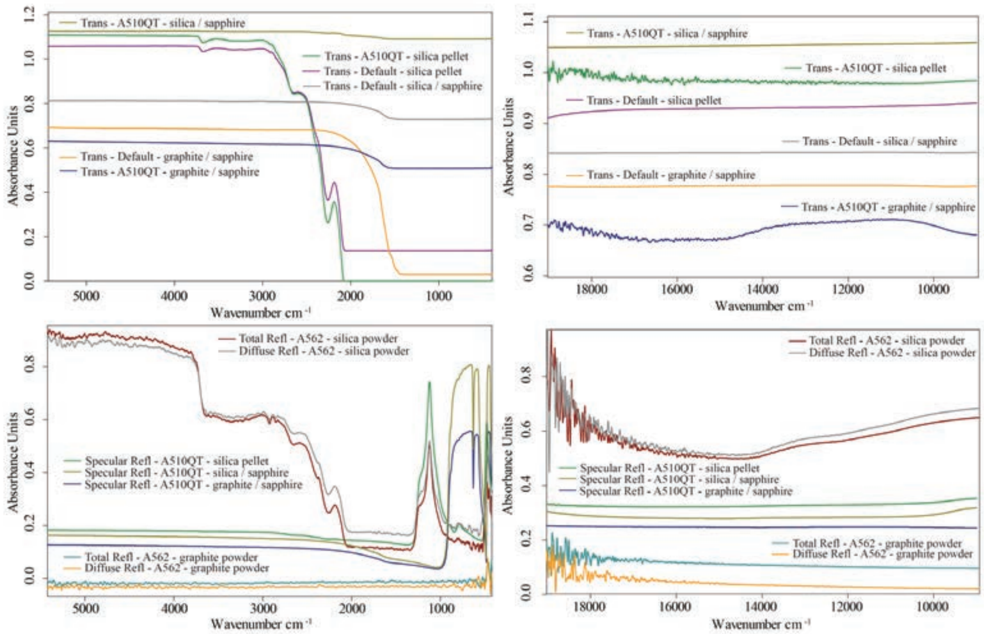


Figure 3: Example spectra collected in a variety of modes of transmission and reflectance for silica and graphite, preparing for determination of optical constants n and k.

optical constants determination efforts. A new laboratory led by Co-I Protopapa is under construction and will go into operation in early 2019.

1.3.2 Analytical Methods for Approximating Optical Constants

Project ESPRESSO Co-I Protopapa has begun development of a radiative transfer model designed to convert laboratory bidirectional reflectance and directional hemispherical reflectance measurements of surface analog materials (such as those already available in the RELAB database) directly into estimates of their real and imaginary indices of refraction. This approach will allow the conversion of a large number of existing archival laboratory spectra into model-dependent optical constants within a calibratable framework. Once this database of optical constants is built in a coherent and self-consistent way, the determination of the composition of target bodies can be performed in a quantitative manner. Ongoing efforts to mature this technique include validation of optical constants estimated by this method against those determined by more observationally-challenging existing techniques at our own facilities. Even in the case of uncertain estimates of optical constants from this technique, the modeling framework will enable quantitative relative comparison between targets and terrains analyzed within this framework. Team members are currently investigating the laboratory requirements for accurate optical constants retrieval (including the range of particle sizes and observational geometries) using this method. At present, several analog materials (including Illite and ammonium chloride) have been investigated using this approach.

1.3.3 Laboratory Investigations of LIBS and Raman Instrument Design

Project ESPRESSO team members at the Boulder Laser Ablation of Standoff Targets for Exploration Research Laboratory (BLASTER Lab) have continued to develop our facilities for long-range LIBS and Raman instrument development. The primary ablation laser (500 mJ / pulse, 750 MW peak power) has been installed and tested, and the primary tunable dye laser is in place and being commissioned. The LIBS vacuum test chamber and integrated mass spectrometer is also on site and undergoing refurbishment. Co-I Nowicki has begun development and testing of a compact, high-throughput spatial heterodyne spectrometer for future laboratory experiments and eventual incorporation into an airborne Raman system.

1.4 Statistical Methods in Planetary Science and Exploration

Rock abundance data from the LRO Diviner instrument can be used to estimate the ages of lunar craters, giving us a means to estimate the variation in the cratering rate over time. Project ESPRESSO's PI Parker developed a statistical model to determine the evidence in favor of an increased rate of impacts in the last 290 Myr as published in Science (Mazrouei et al. 2019).

1.4.1 Bayesian Model Selection and Approximate Bayesian Computation

Model selection is one of the primary tasks of science, and the Bayesian statistical framework provides a sound footing on which to do it. The relative evidence in favor of a particular model (or hypothesis) with respect to any other model or set of models can be determined through the use of evidence integrals and Bayes factors. Typically, the computation of an evidence integral requires the definition of a formal likelihood, which can be challenging or intractable in many situations in planetary science. Population synthesis problems, like inferring the intrinsic properties of a population of craters from their observed properties, can often be treated in a forward-modeling framework where the observational selection effects and physical processes that act to mask the intrinsic properties are modeled as Monte Carlo processes, resulting in the generation of synthetic samples of observations given a set of input parameters for the population model and the obscuring effects. The challenge is finding a way to take a synthetic sample and a real sample and compare them in a rigorous way that allows (a) the determination of model parameters and their credible intervals, and (b) the computation of an evidence integral for model selection. In cases where an analytical likelihood is intractable, the Approximate Bayesian Computation framework can often be applied. This approach only requires that a distance defined on a set of summary statistics be determined to compare a synthetic and real set of observations. An example script that applies this methodology can be found in the repository associated with Mazrouei et al. (2019) . This technique has broad promise for improving statistical analyses across all domains of planetary science.

2. Project ESPRESSO Inter-team/ International Collaborations

In 2018, Project ESPRESSO collaborated with many other SSERVI teams and international partners on a variety of projects. The virtual institute architecture of SSERVI proved invaluable in enabling these interactions and the results that emerged from them.

2.1 RIS⁴E and LIBS Field Campaign

As previously described in this report, Project ESPRESSO joined RIS⁴E in a spring 2018 field campaign to New Mexico. Team interactions enabled cross-comparison of instrumental performance in a common environment, and the logistical challenge of accessing the field site was reduced with the concerted effort spread across multiple teams.

2.2 CLSE and Lunar Atmosphere Dynamics

After the publication of Needham & Kring (2017), CLSE team members sought expertise in atmospheric dynamics to understand the detailed properties and dynamics of an early transient lunar atmosphere. In response, Project ESPRESSO Co-I Soto initiated the development of a lunar atmosphere GCM. Research is ongoing across both teams using this model.

2.3 ISET and Statistical Methods in Planetary Science

Rock abundance data from the LRO Diviner instrument can be used to estimate the ages of lunar craters, giving us a means to estimate the variation in the cratering rate over time. ISET's PI Bottke and Project ESPRESSO's PI Parker contributed to the development of a statistical model to determine the evidence in favor of a changing rate of impacts in the last 290 Myr as published in Science (Mazrouei et al. 2019).

2.4 ISAS/JAXA and Nano-Landers

Project ESPRESSO team developing small impact probes to estimate surface mechanical properties have partnered with a team of ISAS/JAXA researchers to study a nano-lander mission concept called the Mini Landers and Bounders Deployed for Exploration and Regolith Science (MARAUDERS).

2.5 NRC-CNRC and Reduced Gravity Flight Campaigns

Project ESPRESSO team members interacted closely with NRC-CNRC engineers to achieve our 2018 reduced gravity flight campaign. The NRC-CNRC team have expressed substantial support for the Airborne Space Environment Chamber concept and have provided invaluable input on design and operation planning.

2.6 CAN3 Team Support

As the SSERVI CAN3 was solicited in 2018, Project ESPRESSO interacted with seven proposing teams to identify areas of synergy between our ongoing efforts and their proposed efforts. This communication will help ensure a cohesive and collaborative virtual institute going forward as new teams are selected.

3. Project ESPRESSO Public Engagement Report

Project ESPRESSO team members have volunteered in variety of public engagement efforts. Co-I McKinnon has spoken at numerous events including Astronomy on Tap NYC, and conducted a Skype-A-Scientist online program. Online engagement efforts included live tweeting of our field campaign and reduced gravity flight campaign. In November, team members developed a strategy for funded public engagement activities that focuses on improving the accessibility of NASA planetary exploration. The Project ESPRESSO Accessible Exploration Initiative was proposed as an augmentation in December of 2018.

4. Student / Early Career Participation

Postdoctoral Fellows

1. Marcella Yant, Johns Hopkins University, Optical Constants and Field Instrumentation

New Faculty Members

2. Cristina Thomas, Northern Arizona University Assistant Professor, Spectroscopic Observations of Asteroids

3. Jennifer Hanley, Lowell Observatory Tenure Track Astronomer, Optical Constants and Regolith Properties

4. Jamie Molaro, Planetary Science Institute Research Scientist, Thermal Properties of Regoliths.

5. Kevin Walsh, Southwest Research Institute Principal Scientist, Regolith Dynamics

6. Silvia Protopapa, Southwest Research Institute Principal Scientist, Optical Constants

5. Mission Involvement

1. New Horizons, Alex Parker, Kuiper Belt Extended Mission, Co-Investigator

2. New Horizons, Silvia Protopapa, Kuiper Belt Extended Mission, Co-Investigator

3. New Horizons, Will Grundy, Kuiper Belt Extended Mission, Co-Investigator & COMP Team Lead

4. New Horizons, Kelsi Singer, Kuiper Belt Extended Mission, Co-Investigator

5. New Horizons, Silvia Protopapa, Kuiper Belt Extended Mission, Co-Investigator

6. OSIRIS-REx, Kevin Walsh, Regolith Development Working Group Lead, Co-Investigator

7. OSIRIS-REx, Jamie Molaro, Prime Mission, Participating Scientist

8. OSIRIS-REx, Cristina Tomas, Prime Mission, Collaborator

9. Curiosity/MSL, Kevin Lewis, Participating Scientist

10. Dragonfly, Sarah Horst, New Frontiers 4 Phase A, Co-Investigator

Jack Burns

University of Colorado in Boulder, CO

Network for Exploration and Space Science (NESS)

CAN 2 Team

1. NESS Team Project Report

1.1 Low Latency Surface Telerobotics

The Telerobotics group at CU Boulder is composed of undergraduate and graduate students conducting laboratory-based and Virtual/Augmented Reality (VR/AR) experiments to explore various aspects of low-latency telerobotic operations for exploration on the Moon's surface.

1.1.1 Laboratory-Based Experiments

For the first experiment, our research goal was to explore operational constraints of low-latency telerobotics in the context of geological exploration on the Moon. In particular, we ran two lunar rover simulations to quantify the impact of decreased video frame-rate and increased communication latency on human operator performance. **Our results indicate that a threshold video frame-rate exists at 5 frames per second, and dropping below this frame-rate significantly decreases performance. We also found that operating at increased communication latency (2.6 seconds round-trip) increases the time to complete tasks by 150% when compared to real-time operation.** The results of our experiments were published in the IEEE Aerospace conference and will appear in Acta Astronautica (2019, in press). In 2018, our students presented talks on the results of our telerobotic geological exploration experiments at the Deep Space Gateway workshop and the IEEE Aerospace conference.

For the second experiment, our Telerobotics group has shifted our efforts to explore human situation awareness and cognitive load when performing low-latency telerobotic assembly tasks. A COTS robotic arm was integrated with a robotic mobile platform to conduct hardware-based simulations of the telerobotic assembly of a lunar radio array. In June, two students showed the progress made on the robotic arm at the Exploration Science Forum at NASA Ames. We are now preparing for a pilot experiment in which we aim to establish baselines for human situation awareness and cognitive load when using telerobotics to assemble a radio array.

Co-I Fong assisted with review and planning for the low-latency telerobotic assembly experiments that will be conducted by CU Boulder students. In particular, for telerobotic assembly studies, Fong provided advice and guidance on performance metrics (operator, task, and system). These studies are not intended to investigate fundamental human factors or human-robot interaction issues, for which there is extensive existing literature. Rather, the studies will focus on identifying core operational issues associated with the potential use of low-latency telerobotics for future human exploration.

1.1.2 Virtual/Augmented Reality Simulations

To help inform future planetary surface telerobotic research and operations, our team has explored the use of novel interfaces that utilize virtual reality (VR) and augmented reality (AR) technology to leverage the increased bandwidth afforded by the Lunar Gateway outpost. This work has taken the form of two projects: (1) the design of a rover VR simulation testbed; (2) an AR stereo video pass-through camera interface implemented on a physical robot for evaluating interfaces for surface assembly tasks.

Our VR simulation testbed was created for prototyping rover designs and surface teleoperation interfaces without the requirement of physical hardware. A VR head-mounted display (HMD) allows users to use immersive first-person control of the robot to simulate teleoperation of the robot on the lunar surface from space. The testbed enables exploration into the design of robot autonomy algorithms and new interfaces that support ground control, and/or crew operation (teleoperation and/or supervisory control) of surface robots from the Gateway to significantly improve critical NASA lunar exploration missions and enable a more rapid and iterative development process for surface telerobotics.

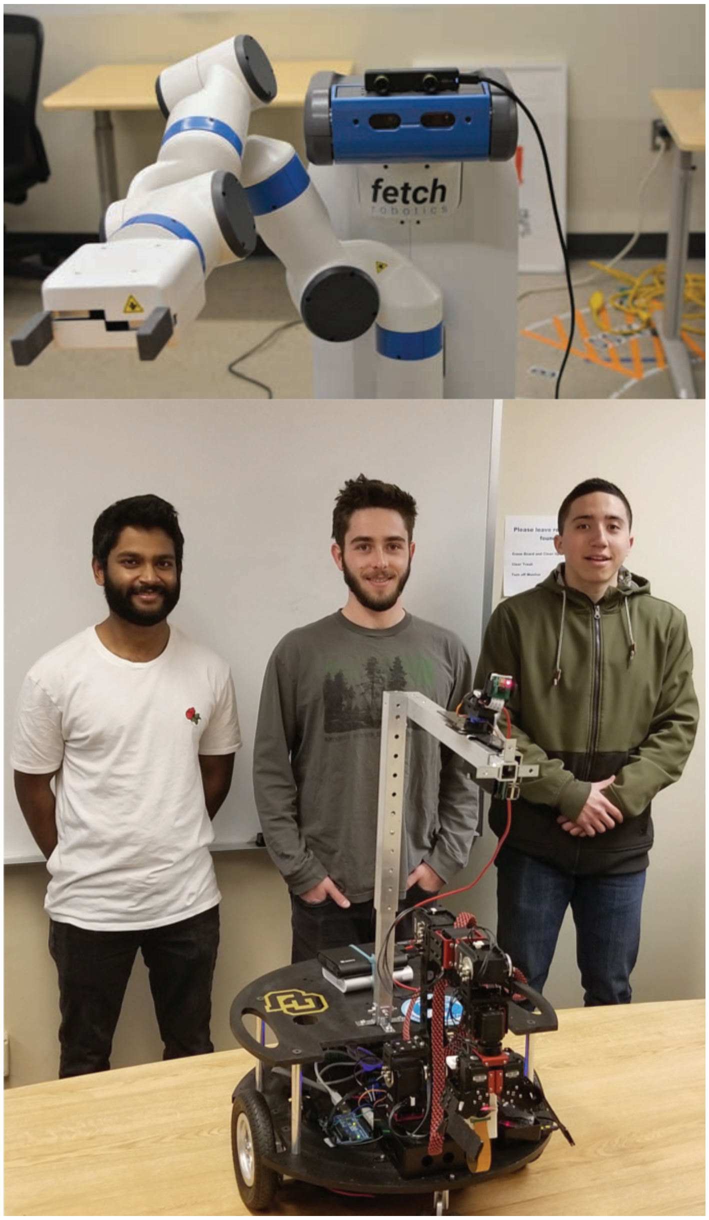


Figure 1: (top) A Fetch Mobile Manipulator robot with a 7-DOF arm used to simulate long-distance teleoperation assembly tasks. An AR stereo video pass-through camera is mounted to the head of the robot allowing the user to see from the robot's point-of-view while improving the remote user's depth perception with stereopsis. (bottom) Arun Kumar (left), Ben Mellinkoff (middle), and Alexander Sandoval (right) representing the Telerobotics group along with a mobile rover and robotic arm platform for conducting low-latency assembly tasks.

Additionally, to better inform interface design within the simulation testbed we implemented our own interface for the distal teleoperation of a real robot from within a VR HMD. As in the simulator, we provide the user with stereoscopic imagery that is streamed from an AR stereo video pass-through camera attached to the robot allowing the user to see from the robot's point-of-view. **Currently, we are evaluating the impact of depth perception on robot teleoperation assembly tasks, which is the first in a series of experiments aimed at informing future surface robot teleoperation tasks, such as radio relay assembly.** This work was done in collaboration with Jennifer Heldmann's and David Kring's SSERVI teams and with NESS Co-I Terry Fong at NASA ARC.

To support development of the rover VR simulation testbed, Co-I Fong provided CU Boulder with a synthetic lunar terrain model developed by the Intelligent Robotics Group at the NASA Ames Research Center. The digital elevation model (DEM) covers a 1 km x 1 km area near the Hermite A crater. The synthetic DEM is based on publicly available images and laser altimetry that were acquired with the Lunar Reconnaissance Orbiter (LRO). This source data was used to generate an initial DEM with 1 m resolution using photoclinometry. The initial DEM was then synthetically enhanced via fractal synthesis to create artificial, high-resolution surface detail, which is consistent with lunar terrain morphology. In addition, rocks and synthetic craters were inserted into the DEM using a parametric shape model and using size-frequency distributions to control density.

1.2 Hydrogen Cosmology: Dark Ages, Cosmic Dawn and Epoch of Reionization

1.2.1 Instrument Design and Data Analysis Pipeline

This year, the CU Boulder group has further developed a global 21-cm spectrum data analysis pipeline —which originated in the work from the first year with DARE (Dark Ages Radio Explorer)— for the SmallSat mission concept DAPPER (Dark Ages Polarimeter PathfindER) led by NESS PI Burns. **We proposed for DAPPER in July 2018 as**

Figure 2: Synthetic lunar digital elevation model of the terrain near Hermite A. The model has a resolution of approximately 4 cm/pixel (grid posting).

part of a new NASA Astrophysics Science SmallSat program and were awarded a NASA concept study in September. Progress towards the proposal before, and the corresponding report afterwards, has occupied an important part of our activities. A fundamental difference between DARE and DAPPER is that the latter focuses on the lower-frequency (earlier times), purely cosmological trough of the Dark Ages, even though we also plan to sparsely sample the Cosmic Dawn trough as well (that DARE aimed to at higher frequencies). Two key fronts for this research have been the continuous development of the data pipeline and work on the ground-based precursor for DAPPER, the Cosmic Twilight Polarimeter (CTP) led by NESS Co-I Bradley at NRAO. The CTP also employs our same pipeline and thus serves as a valuable testbed for it. In addition, we have also been applying our pipeline to another key 21-cm instrument, EDGES (Experiment to Detect the Global Epoch-of-Reionization Signature; led by NESS Co-I Bowman), that in the beginning of 2018 reported a ground-breaking absorption feature at a frequency consistent with Cosmic Dawn (Bowman et al. 2018).

The analysis code pylinex[1] (Tauscher, Rapetti, Burns & Switzer, 2018), which performs fits to data using Singular Value Decomposition (SVD) and Information Criteria, continues to be extended to incorporate goodness-of-fit tests, including our newly defined psi-squared statistic[2] (Tauscher, Rapetti & Burns, 2018). The latter is an extension of the traditional chi-squared statistic that takes into account not only the values of the residuals but also the correlations between them. This allows for an augmented sensitivity to unfitted broad features even well within the noise level. We are also investigating a novel methodology to determine the validity of the training sets employed in the analysis. Starting with only those for the signal and the foreground, we are able to e.g. detect fine differences between sets generated by the 21-cm code ares[3] (Mirocha et al. 2012, 2014) and a parametric scheme (tanh; Harker et al. 2016) made to reproduce similar 21-cm models. We are also completing the pipeline by implementing the ability to transform the initial signal SVD estimates

[1] https://bitbucket.org/ktausch/pylinex

[2] https://bitbucket.org/ktausch/psipy

[3] https://bitbucket.org/mirochaj/ares

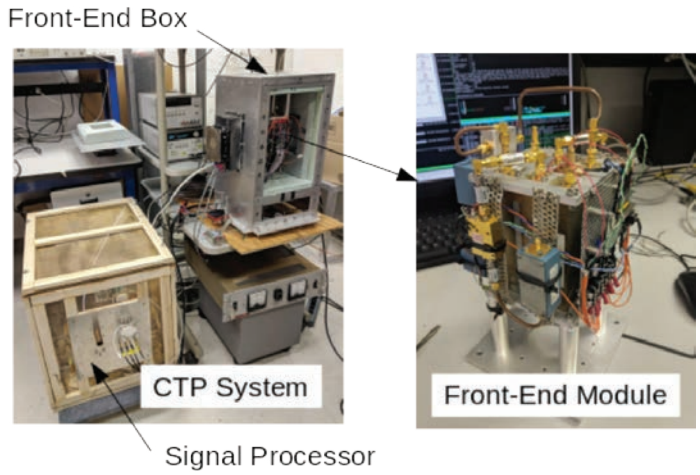


Figure 3: Photographs of the upgraded CTP. (Left) Components that make up the CTP electronics. (Right) Close-up of the front-end module.

into physical parameter constraints in a Bayesian, simultaneous fit of these parameters together with those from the other components (foreground and instrument), as is paramount for extracting science at the end of our advanced measurement procedure.

The ground-based Cosmic Twilight Polarimeter (CTP) led by NESS Co-I Bradley, a prototype for DAPPER, has undergone major upgrades this year. The electronics have undergone a battery of detailed laboratory measurements in an effort to understand the systematic issues limiting the sensitivity. The digital sampler and back-end signal processor were completely reworked, and are now capable of handling 50 MHz of bandwidth with 8192 channels at a cadence of 2 seconds. In addition to the FFTs stage, the processor generates the coherence vector, average, variance, and spectral kurtosis via parallel spectrograph threads. This system was then used to analyze the RF electronics where careful integration tests revealed drifting in the tone calibration system traced to the square-law detector (SLD). An improved SLD is currently under development.

Further tests of the tone system for the CTP uncovered very weak gain modulation that was traced to the one microvolt level fluctuations in the power supply. Significant rework of the electronics packaging has removed ground loops and interference coupling that was affecting the operating conditions of the RF amplifiers. Finally, the two-stage thermal control system was replaced by a single-stage system having over five times the heat flow capacity to mitigate thermal drifts in the front-end electronics. At present, the rms error is under 100 mK with further improvements expected in the future. Figure 3 shows the components of the improved system.

In a study led by Co-I Bradley in collaboration with the CU Boulder team (Bradley, Tauscher, Rapetti & Burns, submitted to ApJ), we analyzed the recent EDGES data set (Bowman et al. 2018; see further details on this measurement below) utilizing a reported model of a ground plane artifact that could explain the unexpected EDGES results via this systematic effect instead of attributing them to an astrophysical origin. We find that the available evidence is inconclusive on whether the reported absorption trough is due to a ground plane artifact or an astrophysical signal.

1.2.2 Low Radio Frequency Lunar Arrays

In Fall 2018, NASA Astrophysics funded NESS to undertake a Probe-class concept study for a low frequency lunar array (FARSIDE = Farside Array for Radio Science Investigation of the Dark ages and Exoplanets). We partnered with JPL's Team-X for this design study. As defined by Paul Hertz, a Probe instrument/observatory will have a cap of $1 billion. The P.I. for FARSIDE is Burns and Co-Is include NESS Co-Is G. Hallinan, J. Bowman, R. MacDowall, and R. Bradley.

As a start on this FARSIDE study, notional science traceability matrices (STMs) were developed for pathfinder and full-scale lunar arrays. Based on the STMs, preliminary steps for an array trade study were commenced. In order to inform the trade study, we began with an analysis of observing requirements for a shared-science objective array (heliophysics, exoplanets, cosmology) that established an allowed range of lunar farside latitudes for site selection. Over the last decade, the ground based 21-cm instrument community has advanced the requirements on array antenna design, particularly with respect to factors contributing to chromaticity in the response of the antennas. At the start of NESS, it was uncertain if dipole-based antennas placed directly on lunar regolith (such as the ROLSS concept) remained a viable antenna technology for the trade study. During this year, we began an investigation of the relevant antenna properties using the EDGES antenna as a reference design, but placed directly on lunar regolith. We found the efficiency of the antenna is only approximately 0.3 when placed on regolith, with a fractional bandwidth of about two, even for a relatively large dipole of approximately 2.5 x 4 meters. Slightly elevating the antenna above the regolith in a patch antenna-like design enabled the dipole size to be reduced to 1 x 1.5 meters while maintaining similar efficiency, but slightly smaller fractional bandwidth. We are presently investigating the chromatic beam patterns for pure regolith and other more-realistic trial conditions, including rocks mixed with regolith. We anticipate this work to be completed early in 2019.

1.2.3 Theoretical Predictions of the Global 21-cm Spectrum of Neutral Hydrogen

During this year, the UCLA team (led by Co-I Furlanetto) focused on developing the science case for highly-redshifted 21-cm observations from the lunar environment. Furlanetto's group has been building machinery to understand the signal both on its own and in the context of other measurements of the high-redshift universe. In Mebane et al. (2018), we built a new semi-analytic model of the very first "Population III" luminous sources to form in the Universe. This flexible, fast model allows us to predict the signatures of these stars and black holes under a wide variety of assumptions. In Mirocha et al. (2018), we examined whether these populations leave clear signatures on the 21-cm signals. **We found that, for some ranges of the parameters governing the formation of the first sources, they left a characteristic asymmetry in the 21-cm signal. Such a signature provides a clear target for future lunar radio arrays.**

The first claimed detection of the 21-cm signal by NESS Co-I J. Bowman (Bowman et al. 2018) has enormous implications for lunar instruments - and for the formation of the first stars. Mirocha & Furlanetto (2019) considered the implications of the EDGES measurement for galaxy formation, showing that it provided the first evidence that star formation in small, early galaxies must have been governed by different physics than local galaxies. We are currently continuing this investigation. Graduate student Mebane is applying our framework for the Population III sources to the EDGES signal, while undergraduate student Fu is considering globular clusters as a source population for the EDGES signal.

1.3 Extrasolar Space Weather

In the last year, the Caltech team (led by Co-I Hallinan) has focused on detection of planetary mass bodies at radio frequencies, as a proof of concept for a future lunar-based effort, while simultaneously constraining the science traceability matrix and associated design constraints for a lunar-based array. For the former, in a rather spectacular turn of events, one of our target brown dwarfs, which act as proxies for large exoplanets, the T2.5 dwarf SIMP J013656.5+093347.3, has recently been classified as a member of the Carina Near moving group, with a corresponding age of only 200 Myr (Gagné et al. 2017). This results in a mass of 12.7 ± 1 M_{Jup}, classifying the object as a possible free floating planet. Meanwhile the maximum magnetic field near the polar regions is at least 3000 G, based on constraints from our latest paper. By comparison, Jupiter's magnetic field is only 14 G at the poles. **This now becomes a critical new benchmark for dynamo theory, as well as the strongest candidate radio exoplanet to date.** Gaia DR2 should reveal other

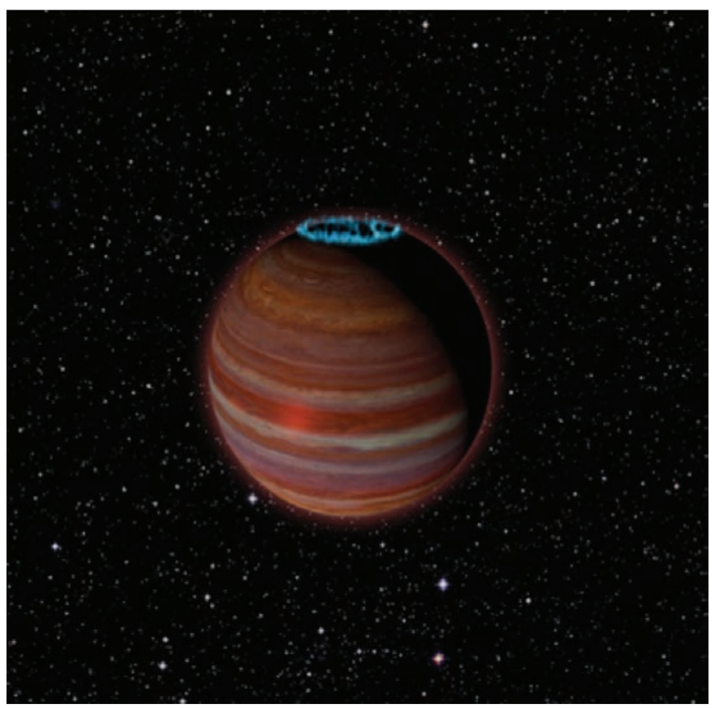


Figure 4: Artist's impression of the auroral emission from the 12.7+/-1 Jupiter-mass free-floating object, SIMP J013656.5+093347.3.

nearby free floating planet candidates via moving group association, so the next few years may be ripe for additional discoveries. Meanwhile, we have begun pushing into the Y dwarf regime with the VLA, initially with a small pilot sample (Kao et al. 2018a), followed by deep observations of 11 further objects in an ongoing observing program.

Simultaneously, we completed the first extrasolar space weather surveys searching for radio signatures of stellar coronal mass ejections (CMEs) and extrasolar planetary magnetic fields. This involves 31 hours of data, monitoring 4000 stellar/planetary systems. Graduate student, and NESS team member, Marin Anderson will lead this paper in early 2019. This will serve as the framework for designing a similar survey from the lunar surface.

1.4 Heliophysics

As part of the Heliophysics and Space Physics key project of NESS, we are working with the Astrophysics key project personnel to design a lunar radio array pathfinder. Our NESS science goals for heliophysics are solved primarily by the capability to produce images of solar radio bursts at frequencies below the imaging possible by ground-based arrays. Typically, they cannot image solar radio bursts below frequencies around 20 MHz, which corresponds to the terrestrial ionospheric "cutoff" frequency. The electron density in the ionosphere blocks electromagnetic waves below a certain frequency and distorts the waves at frequencies above the "cutoff" frequency. The frequency of 20 MHz corresponds to solar radio burst emissions only a couple of solar radii from the solar surface, so ground-based observatory imaging only covers a small fraction of the inner heliosphere. **An array on the lunar surface will allow imaging down to frequencies of a fraction of 1 MHz, permitting the tracking of solar radio bursts as they move through space.** This imaging will provide improved data for scientific understanding of the burst physics and evolution, provide indications of magnetic field and density structures in the inner heliosphere, and contribute to space weather prediction. If the radio observatory could be in place before the end of the Parker Solar Probe mission (2018-2026), there would be considerable scientific overlap between the two missions.

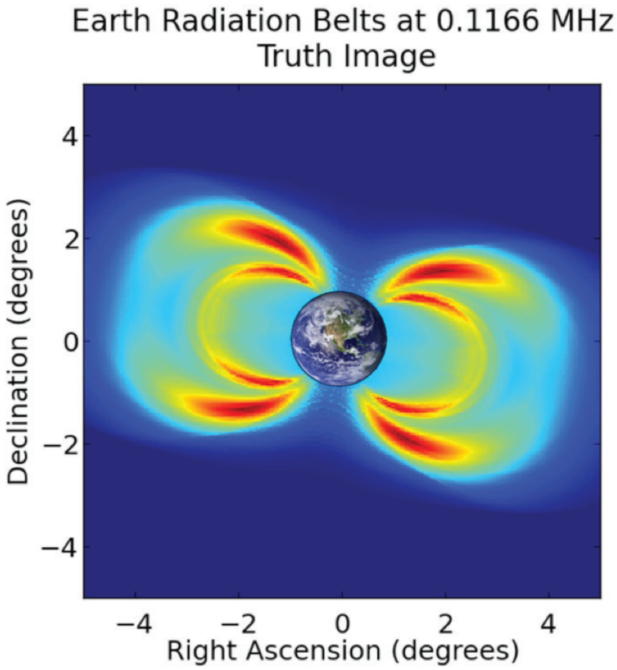
The array that could address these goals could be on either side (near-side or far-side) because the solar bursts are more intense than the signals from astrophysics sources. So, we have proposed placing a radio array for solar burst imaging on the near-side, because that is easier to implement sooner, and because it could serve as a pathfinder for the far-side astrophysics array. It should be noted that the far-side array would also contribute to solar radio burst astronomy. **The Lunar Gateway will likely play a key role in the deployment of a far-side lunar surface radio array, transferal of the far-side data back to earth, and other aspects of the radio array operation.**

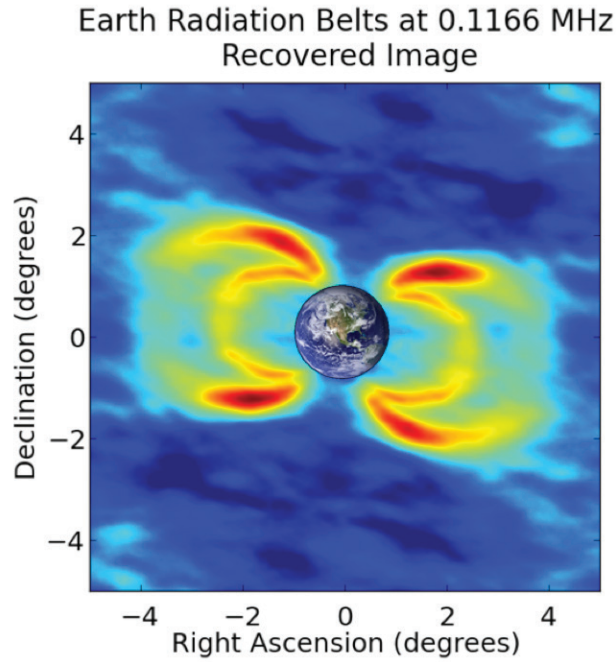
NESS Deputy and Co-I MacDowall led the submission of a response to the NASA Request for Information (RFI) for lunar-surface science payloads addressing "Low Frequency Radio Observations from the Near Side Lunar Surface." Related to this RFI response, he has led the submission of a NASA GSFC Center proposal to deliver a radio astronomy instrument to be carried to the lunar surface by a commercial lander. We have initiated various efforts to obtain NASA funding to advance the TRL of the low-frequency radio observatories to be built on the near-side and far-side lunar surface.

Co-I Kasper and his graduate student Alex Hegedus collaborated with members of the NOIRE team on a paper in preparation that takes simulations of the radiation belts and runs them through simulations of a lunar radio array. This work will end up in a sequence of papers exploring the range of radiation belt physics that could be detected by a Lunar nearside radio array. The figures above are a step towards this, showing the brightness of the radiation belts during a normal period (~10 Jy total from Lunar distances), and a dirty image recovered from a radio array centered on the sub-Earth point on the Lunar nearside.

2. Inter-team/ International Collaborations

P.I. Burns and Assistant Director Rapetti are collaborating with NESS International Collaborators Falcke and Klein-Wolt towards employing an RFI analysis based on neural networks and the 21-cm data analysis pipeline being developed at the University of Colorado (CU) Boulder on data from the Netherlands-China Low-Frequency Explorer (NCLE). The latter is a low-frequency radio antenna





developed in the Netherlands at Radboud University & ASTRON launched in the Chinese Chang'e 4 mission last May, 2018, and currently orbiting around the Earth-Moon L2 point. The neural network RFI analysis is also being developed at CU Boulder in collaboration with researchers at INAF-Bologna, Julian Merten (also at Oxford University) and Massimo Meneghetti (also at the University of Bologna). We (the CU Boulder team) plan to then work with the Dutch collaborators to adapt both analyses (the pattern recognition pipeline and the neural network RFI removal procedure), primarily under construction for DAPPER, for the study of NCLE data. We intend to build training sets for uncalibrated beam and receiver systematics based on NCLE instrument and spacecraft information, as well as sets for RFI removal based on the expected characteristics of the internal and external RFI environment. In addition to the machine learning algorithms aforementioned, we will also utilize a number of novel statistical goodness-of-fit tools we have under development.

The code developed at UCLA by Co-I Furlanetto and his team will be used by the Hydrogen Epoch of Reionization Array (HERA) collaboration (PI: A. Parsons, University of California Berkeley), which includes South African, Canadian, and European collaborators, as part of their science interpretation program. Co-I Furlanetto is also a member of the Extragalactic Potential Observations (EXPO) Science Investigation Team for the WFIRST satellite project. As part of that project, Furlanetto is examining the synergies between galaxy surveys and low-frequency radio surveys, including those from the lunar environment.

Co-I Kasper visited the low frequency radio research groups at the Paris Observatory and Meudon, met with Baptist Cecconi (Paris Observatory, lead for the NOIRE low frequency mission concept study) and learned about the NOIRE mission concept study and simulation framework for radio emission from energetic electrons in the radiation belts that was developed by a research group in Toulouse. He also agreed to be informed about the status of the NOIRE project and concept study, and to work with them to determine if their framework could be used by him and his team instead of having to build separate simulations of the emission.

As described in section 1.1.2, CU Boulder NESS team members collaborated with Hellman's and Kring's SSERVI teams on robot teleoperation experiments within a VR HMD.

3. Public Engagement Report

We celebrated International Observe the Moon Night on October 20, 2018. International Observe the Moon Night is an annual worldwide public event that encourages observation, appreciation and understanding of our Moon and its connection to NASA planetary science and exploration. The annual event connects scientists, educators and lunar enthusiasts from around the world. The Network for Exploration and Space Science, Fiske Planetarium, and Sommers-Bausch Observatory had activities planned throughout the evening, including: a public lecture entitled "Our Future in Space: Humans, Robots, and Telescopes Exploring Together" by Dr. Jack Burns at Fiske Planetarium and Telescope Observations of the Moon at Sommers-Bausch Observatory.

Burns presented "*Our Future in Space*" at Fiske Planetarium to 45 high school STEM students participating in the national Summer Science Program (SSP) at CU-Boulder on July 24, 2018. Burns, along with Scott Pace (Executive Director of the National Space Council), conducted a panel on Space Policy for the 60th anniversary alumni symposium of the SSP at CU-Boulder on July 28, 2018. Burns also presented "*Our Future in Space: Humans, Robots, & Telescopes Exploring Together*" at the Institute for Human & Machine Cognition 2018 conference in Pensacola, FL on February 22, 2018.

Harrison "Jack" Schmitt, an Apollo-era astronaut and the last person to set foot on the Moon, gave a group of CU Boulder students the chance to see something rare: color on the lunar surface. Schmitt, who flew on Apollo 17 in 1972, visited the university on Monday, October 29, 2018. He spoke to an undergraduate class focusing on space science and policy and later delivered a public talk at the Fiske Planetarium that can be watched online.

NASA's Chief Scientist Dr. J. Green visited CU Boulder (11/28/2018) to lecture in Burns' Space Policy class, interacted with the local NESS team, and presented a seminar at LASP: "*Space weather at Earth and Mars: How Bad Can it Get?*". NASA ARC Director Dr. Eugene Tu visited CU (12/12/2018) to lecture in Burns' Space Policy class and met with the CU DAPPER team and other CU NESS members.

Early in the year, the breakthrough announced by EDGES (led by NESS Co-I Bowman), of an absorption trough at 78 MHz consistent with Cosmic Dawn but with an amplitude larger than possible in standard cosmology/astrophysics (suggesting exotic physics in the early Universe), generated abundant media attention. Find several links in the news section of the NESS website.

News stories about the telerobotics work led by Burns at CU Boulder appeared in the Boulder Daily Camera and CU Boulder Today at the end of January, 2018, featuring undergraduate students B. Mellinkoff and M. Spydell.

4. Student/Early Career Participation

Undergraduate Students

1. Benjamin Mellinkoff (graduated during the year; now a masters student), University of Colorado Boulder, Surface telerobotics - Instrumentation.

2. Matthew Spydell (member only through the first part of the year), University of Colorado Boulder, Surface telerobotics - Instrumentation.

3. Alex Sandoval, University of Colorado Boulder, Surface telerobotics - Instrumentation.

4. Arun Kumar, University of Colorado Boulder, Surface telerobotics - Instrumentation.

5. Krista Fu (beginning 6/18), University of California Los Angeles, Astrophysics, Cosmic Dawn -Theory.

Graduate Students

6. Keith Tauscher, University of Colorado Boulder, Physics/Astrophysics, Cosmic Dawn – Theory / Data.

7. Bang Nhan (only through the first part of the year as student; afterwards as postdoc), University of Colorado Boulder, Astrophysics, Cosmic Dawn - Experiment.

6. Neil Bassett (from 6/18), University of Colorado Boulder, Physics/Astrophysics, Cosmic Dawn – Theory / Data.

8. Richard Mebane, University of California Los Angeles, Astrophysics, Cosmic Dawn -Theory.

9. Adam Trapp (beginning 10/18), University of

California Los Angeles, Astrophysics, Cosmic Dawn -Theory.

10. Marin Anderson, California Institute of Technology, Astrophysics, Cosmic Dawn – Theory / Data.

11. Alex Hegedus, University of Michigan, Astrophysics, Heliophysics.

12. David Bordenave, University of Virginia, Astrophysics, Cosmic Dawn - Experiment.

13. Nivedita Mahesh, Arizona State University, Astrophysics, Cosmic Dawn - Experiment.

14. Michael Walker, University of Colorado Boulder, Surface telerobotics - Virtual Reality Telerobotics simulations.

Postdoctoral Fellows

15. Jordan Mirocha, University of California Los Angeles (through 8/18)/McGill University, Astrophysics, Cosmic Dawn - Theory.

16. Raul Monsalve, University of Colorado Boulder, Astrophysics, Cosmic Dawn – Experiment / Data.

17. Bang Nhan (second part of the year as postdoc), University of Virginia, Astrophysics, Cosmic Dawn - Experiment.

18. David Rapetti, University of Colorado Boulder / NASA Ames Research Center, Astrophysics, Cosmic Dawn – Theory/Data.

New Faculty Members

19. Jonathan Pober, Brown University, Astrophysics, Cosmic Dawn - Experiment / Theory.

5. Mission Involvement

DAPPER: In September 2018, NASA announced the selections for its first-ever competition for Astrophysics Science SmallSats. Among the missions funded for a concept study is one that the NESS team developed in collaboration with NASA Ames called the Dark Ages Polarimeter PathfindER (DAPPER). J. Burns is the P.I., R. Bradley is a Co-I, and a number of senior researchers, postdocs, and students from NESS are collaborators. DAPPER resulted in part from SSERVI-funded DARE (Dark Ages Radio Explorer) research.

DAPPER will explore, for the first time, the Dark Ages of the early Universe. After the Cosmic Microwave Background photons decoupled from baryons, the Dark Ages epoch began: density fluctuations imprinted from earlier times grew under the influence of gravity, eventually collapsing into the first stars and galaxies during the subsequent Cosmic Dawn. Exploring these early unobserved epochs, a key science goal of NASA, was demonstrated to be achievable by recent observations by the Experiment to Detect the Global Epoch of Reionization (EoR) Signature (EDGES).

In the early universe, most of the baryonic matter was in the form of neutral hydrogen (HI), detectable via its ground state's "spin-flip" transition. This line's rest frame frequency (wavelength) of 1420 MHz (21-cm) arrives today highly redshifted to low radio frequencies (<200 MHz) due to cosmic expansion. A measurement of the 21-cm spectrum maps the history of the HI gas through the Dark ages and Cosmic Dawn and up to EoR, when ionization of HI extinguished the signal. EDGES recently reported a 78 MHz (redshift z~17) absorption trough roughly consistent with that expected from Cosmic Dawn, but 3 times deeper than was thought possible from standard cosmology and adiabatic cooling of HI. Interactions between baryons and slightly-charged Dark Matter particles with a proton-like mass provide a potential explanation of this difference but other cooling mechanisms are also being investigated to explain these results.

The Cosmic Dawn trough is affected by cosmology and the complex astrophysical history of the first luminous objects. A trough representing the Dark Ages, predicted to occur at lower frequencies (higher z), however, is determined entirely by cosmological phenomena (including Dark Matter) that took place before star formation began. **DAPPER, acquiring data from low lunar orbit above the farside, will observe this pristine epoch (17-30 MHz; z~83-46), which is inaccessible from Earth due to ionospheric opacity.** DAPPER will measure the amplitude of the 21-cm spectrum to the level required to distinguish (at >5) the standard cosmological model from that of additional cooling derived from current EDGES results. In addition to Dark Matter properties such as annihilation, decay, temperature, and interactions, the low-frequency background radiation level can significantly modify this trough. Hence, this observation constitutes a powerful, clean probe of exotic physics in the Dark Ages. A secondary objective for DAPPER will be to verify the recent EDGES results for Cosmic Dawn, in the uncontaminated environment above the lunar farside, with sparse frequency sampling from 30-100 MHz (z~46-13).

The main challenge of this measurement is the removal of bright foregrounds. DAPPER is designed to overcome this by using two pioneering techniques: (1) a polarimeter to measure both intrinsically polarized emission and polarization induced by the anisotropic foregrounds and large antenna beam to aid in the separation of the foregrounds from the isotropic, unpolarized global signal, and (2) a pattern recognition analysis pipeline based on well-characterized training sets of foregrounds from sky observations, instrument systematics from simulations and laboratory measurements, and signals from theoretical predictions. DAPPER team members recently demonstrated the effectiveness of dynamic polarimetry to measure foregrounds using the prototype Cosmic Twilight Polarimeter. Simulations using the DAPPER pattern recognition pipeline illustrate separation and detection of the standard signal, which has a minimal amplitude. Non-standard cooling would increase this amplitude, improving this measurement and pointing to new physics.

DAPPER's science instrument consists of dual orthogonal dipole antennas and a tone-injection receiver based on high TRL components from the Parker Solar Probe/FIELDS, CURIE, and WIND/WAVES. DAPPER will be deployed from NASA's Lunar Gateway and transfer to a stable 50x125 km lunar orbit to provide 5000 hrs of radio-quiet integration over a 2 year mission lifetime. Proximity to the Gateway offers a number of advantages such as regular ride-share transport, a fast communication system, a launch facility, and on-board data storage and computational equipment. DAPPER is a collaboration between the universities of Colorado-Boulder and California-Berkeley, the National Radio Astronomy Observatory, and the NASA Ames Research Center.

The concept study for DAPPER will be submitted to NASA on May 28, 2019. We expect to also submit a proposal on DAPPER to the Astrophysics Mission of Opportunity AO that will be due in August 2019.

SunRISE: The Sun Radio Interferometer Space Experiment (SunRISE) is a proposed NASA Heliophysics Explorer Mission of Opportunity that finished Phase A last year. **SunRISE will provide an entirely new view on particle acceleration and transport in the inner heliosphere by creating the first low radio frequency interferometer in space to localize heliospheric radio emissions.** Six small spacecraft (S/C) will fly in a supersynchronous geosynchronous Earth orbit (GEO) within about 10 km of each other and image the Sun in a portion of the spectrum that is blocked by the ionosphere and cannot be observed from Earth. Mission-enabling advances in software-defined radios and GPS navigation and timing, developed and flown over the past few years on the Mars Cube One (MarCO) and DARPA High Frequency Research (DHFR) missions, have finally made this concept affordable and low-risk. By determining the location of decametrichectometric (DH) radio bursts from 0.1 MHz–25 MHz, SunRISE provides key information on particle acceleration mechanisms associated with coronal mass ejections (CMEs) and the magnetic field topology from active regions into interplanetary space. SunRISE is highly complementary to current missions, such as the Parker Solar Probe and Solar Orbiter, and to the ground-based Daniel K. Inouye Solar Telescope (DKIST).

SunRISE shows that an Explorer Mission of Opportunity can answer fundamental questions in heliophysics, with implications for space weather prediction, and serve as a pathfinder for small satellite missions that have the potential to revolutionize space science. **SunRISE will help us understand the particle acceleration that occurs throughout the cosmos and leads to solar flares, solar energetic particles (SEPs), anomalous cosmic rays, and Galactic cosmic rays (GCRs).** SEPs and GCRs can damage satellites and lead to radiation sickness (Schwadron et al. 2014). Without new measurement methods (Cucinotta et al. 2010; Schwadron et al. 2015), heliophysics is missing a cornerstone for understanding particle acceleration. Parker Solar Probe (Fox et al. 2016;

Kasper et al. 2015) will fly within 10 RS but will not measure particles as they are first accelerated (~ 3 RS). SunRISE offers the solution: localize radio emission from acceleration source regions and by energetic particles as they travel interplanetary space, laying the observational foundation for understanding particle acceleration and transport physics at the nearest star.

The SunRISE investigation uses well-studied classes of DH radio bursts: Type II associated with CMEs and Type III from electrons escaping from active regions into the solar wind along open magnetic field lines. SunRISE measures the 3D location of source emission and its evolution in time by determining the emission frequency and angular location of the burst on the sky. SunRISE discriminates between competing hypotheses for the source mechanism of CME-associated SEPs by measuring the location of Type II emission relative to expanding CMEs over distances from 2 RS–20 RS (Objective 1), where the most intense acceleration occurs. Every major SEP event seen at Earth is associated with a Type II DH radio burst. Imaging a Type II burst constrains which major features of a CME are associated with SEP acceleration. SunRISE also determines if a broad magnetic connection between active regions and interplanetary space accounts for the longitudinal extent of flare and CME SEPs by imaging Type III bursts as they traverse the corona (Objective 2). SunRISE traces magnetic field topology from the corona into interplanetary space for the first time.

The theory and implementation of aperture synthesis is well developed for ground-based telescopes. The SunRISE observatory has three mission-enabling features: *Knowledge not Control*: The S/C positions do not need to be controlled to better than 1 km as long as they are known to ~ 1 m accuracy. *Integrated Solar DH Global Navigation Satellite System (GNSS) Receiver*: A Solar DH signal chain measures radio emission at the location of the S/C while a GNSS signal chain records signals from GNSS satellites in view. The GNSS signals are used on board to synchronize DH data collection and in ground-based precision orbit determination to provide accurate S/C location and time. There is no requirement for communication between S/C, which operate independently. *Correlator Architecture*: The DH-GNSS receiver transforms the received DH signals to the spectral domain. On the ground, the individual S/C data are combined to form SunRISE's synthetic aperture. This approach provides robustness against interference, reduces on-board computational complexity, and requires only modest downlink data volume. Implementation follows the proven approach of starting from well-defined, verifiable Level 1 science requirements that flow to Level 2 project requirements. A passive formation of six independent and identical S/C, SunRISE drifts in supersynchronous GEO orbit, high above the disruptive effects of the Earth's ionosphere.

The SunRISE baseline science mission requires five S/C. An extra S/C provides redundancy. Their orbits are designed to keep the formation within a maximum separation of about 10 km, while providing the interferometer baselines needed to sample a range of angular scales. Nearly all hardware and software designs have been used before in space. SunRISE integrates them into a 6U form factor, using a standard small satellite design to accommodate the DH-GNSS receiver, GNSS antennas and deployable dipole antennas.

A multi-channel polyphase filter bank processes the full spectrum from 0.1 MHz–25 MHz, allowing dynamic selection of a sufficient number of channels free from S/C generated or terrestrial interference to track radio emission over distances from 2 RS–20 RS. The P/L's 4-channel GNSS receiver can process up to 42 GNSS signals simultaneously, providing sub-meter position knowledge (λ/15 at the highest DH frequency) and time knowledge better than a few nanoseconds. In post-processing conducted on the ground, these GNSS observables precisely determine the position and time when the DH data were recorded, which are used to cross-multiply the signals coherently, forming a synthetic aperture with the required localization capability.

SunRISE is operated by JPL during its 12-month mission lifetime, employing existing tools that have been used for dozens of missions. Operations consist of regular data collection and orbit maintenance sequences occurring on a 2-week cycle. The science observing profile, with an observing availability greater than 90%, is sufficient to capture the typical duration of Type II bursts. Science data are accumulated continuously, with only brief interruptions for telecommunications, orbital correction maneuvers and reaction wheel desaturation. During data downlink, small orbital corrections are uplinked, if needed, to maintain the formation without risk of collision. SunRISE data flow from the S/C to the Deep Space Network to the JPL Mission Operations Center (MOC) to the University of Michigan (UM) Science Operations Center (SOC), and finally to the Space Physics Data Facility.

SunRISE will find out in the coming weeks if it is to be fully funded, and will launch in 2022 if it is.

Thomas Orlando

Georgia Institute of Technology in Atlanta, GA

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)

CAN 2 Team

1. Team Project Report

1.1 In Situ Formation of Molecular Water on Airless Bodies

A chemical kinetic model that simulates the progression of solar wind-implanted hydrogen and the formation of molecular water on airless bodies was developed. This model is built on two fundamental assumptions: i) chemically stable and bound hydroxyls (-OH) are formed via solar wind proton implantation and ii) gas phase water is produced thermally through recombinative desorption (i.e. M-OH + M-OH -> M-O-M + H_2O). Our model was applied to the lunar surface and the results are generally consistent with the overall latitudinal trends (Figure 1) in the observed 2.8 μm absorption. In addition, our results also indicate that a persistent 2.8 μm feature in the equatorial region should be present as the M-OH defects formed via solar wind implantation are chemically stable until the defect concentration is high enough for recombinative desorption to transpire. This results in a saturation limit through a dynamic equilibrium process between formation (proton implantation) and loss (recombinative desorption).

The model was upgraded by adapting a kinetic Monte Carlo algorithm that incorporates diffusion of the implanted

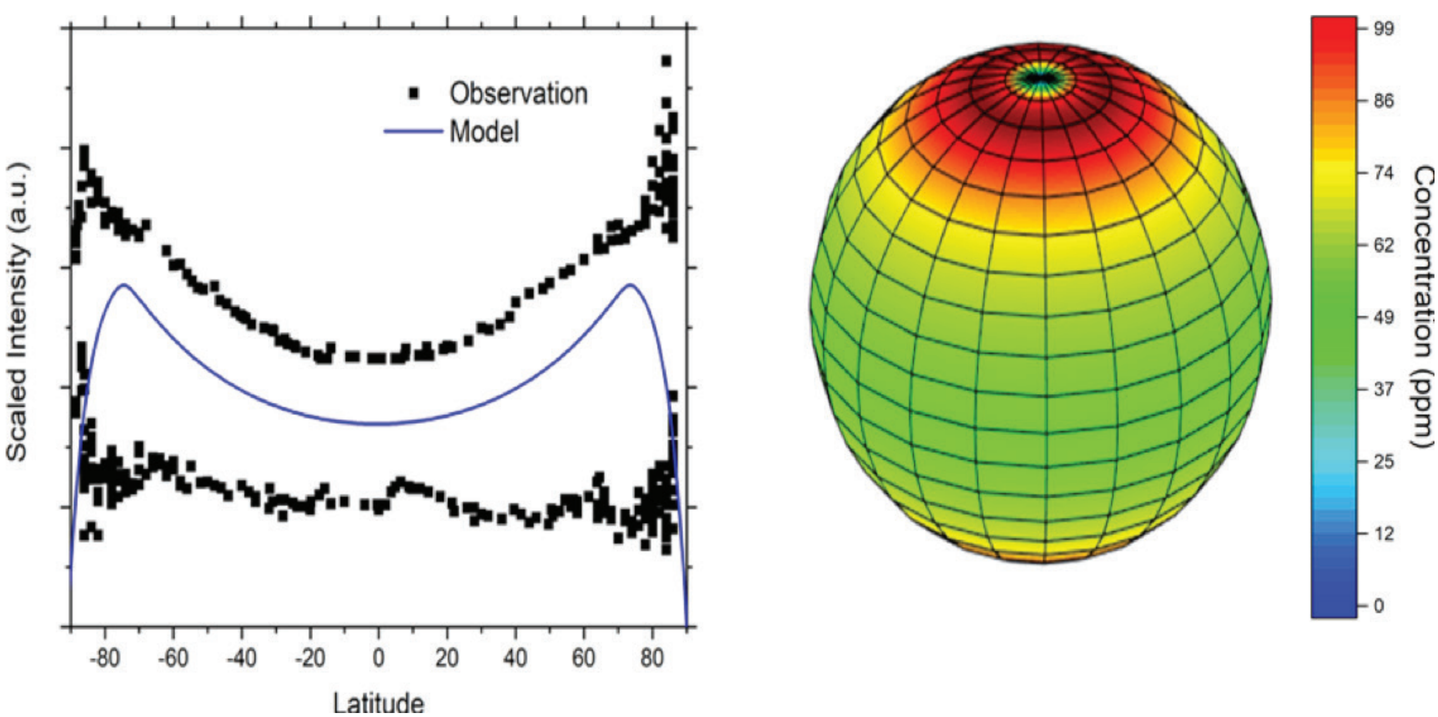


Figure 1: Comparison of the simulated OH concentration (left) after 3600 Lunar days as a function of latitude with upper and lower bounds of the 2.8 μm IR feature data digitized from (McCord, Taylor et al. 2011). The predicted hydroxyl signal (left: solid blues lines and right spherical map) overlaps with observation except for the polar areas. Note that over time the polar areas reach saturation and will match the observational data. The lack of signal is a consequence of the computational time necessary to see these effects. Figure adapted from (Jones, Aleksandrov et al. 2018).

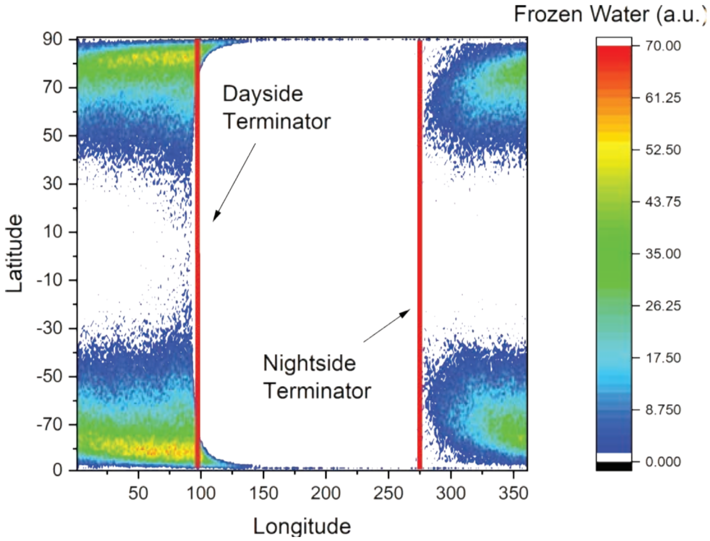


Figure 2: Location of molecular water on the surface of Mercury after simulating solar wind implantation and kinetics of recombinative desorption after six complete orbits. Red lines designate day and night side terminators. Note this simulation was done assuming the surface lacks any permanently shadowed regions.

> The atomistic model correctly simulates the latitude dependent 2.8 μ band on the Moon that has been attributed to surficial OH/H2O. The model is applicable to asteroids and Mercury, and shows that the solar wind can be a significant source of water on the poles of Mercury. This provides an alternative explanation for polar water that does not require cometary impact.

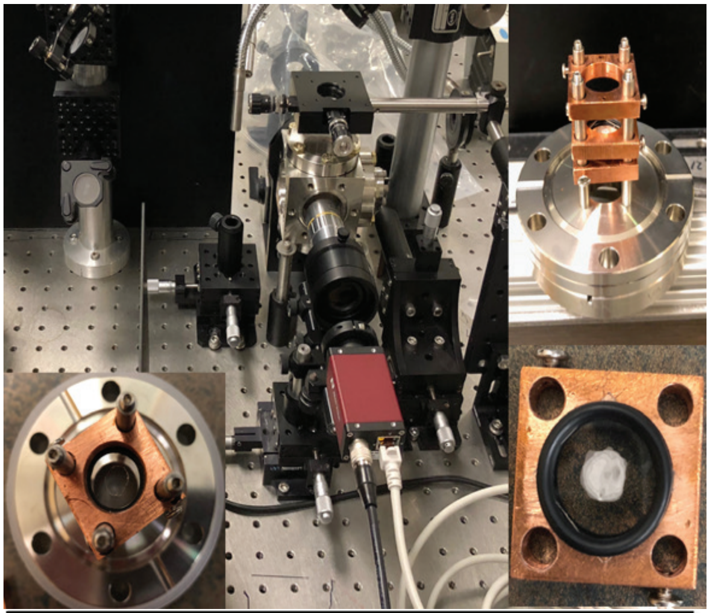
hydroxyl defect, a molecular hydrogen formation channel, and surface hopping of molecular water. The upgraded model has been applied to the surface of Mercury. For the activation energies associated with the surface of Mercury, we used compositional ratio maps available through the Planetary Data System. The rather unique distribution of precipitating protons due to the relatively weak magnetic field of Mercury was also taken into consideration. Figure 2 shows that molecular water is easily formed at Mercury relevant temperatures where protons are impinging onto the surface. As expected, the water adsorbed on the night side will sublimate upon reaching the dayside terminator where it will hop until it reacts with the surface via dissociative adsorption (i.e. H2O + M -> MOH + H) or physisorbs at a cold site--i.e. night side, poles, or permanently shadowed regions. Gas phase water will ultimately succumb to photo-dissociation, dissociative adsorption or molecular re-adsorption on cold portions of the surface. Consequently, though water is expected in permanently shadowed regions and near/on the poles, a significant amount of exospheric water is not expected.

1.2 Laser Induced Micro-Particle Accelerator

A laser induced micro-particle accelerator (LIMA) has been constructed to directly examine the chemistry and subsequent optical alteration that occurs due to micro-particle impact events on the Moon. The system (Figure 3A) has been used to launch 2 μm spherical silicate grains with expected velocity distributions up to 3-5 km/sec. The central image shows the optical layout, camera imaging system, and the copper particle holder and launch pad that is inserted into the laser (not shown) impact cube (center). We have observed particles imbedded into a polymer matrix (Figure 3B). The optical images indicate an implantation depth range so we are presently correlating the implantation depth with launched particle velocity distributions. The system is also being adopted to test the mechanical and elastic properties of the polymers being developed in REVEALS for applications in new spacesuits (see section 1.5).

1.3 Single Crystal Regolith Simulants

Single-crystalline aluminosilicate (AlxSi1-xO2) ultrathin-films have been grown as model-regolith simulants for use in experiments to unravel the atomistic details leading to interfacial volatile formation and evolution under simulated space weathering conditions. These films will be available to all REVEALS co-Is and other groups within SSERVI. Previous work done by Infrared Reflection-Absorption Spectroscopy suggests hydroxyl groups forming at Al-O-Si sites, which are detectable



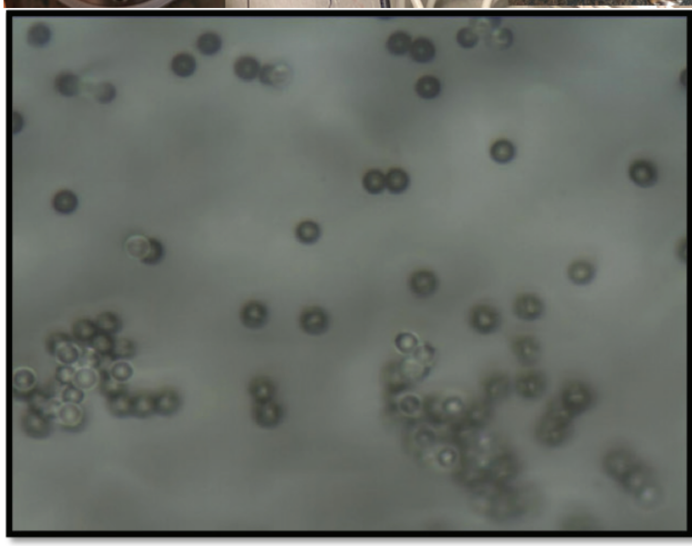
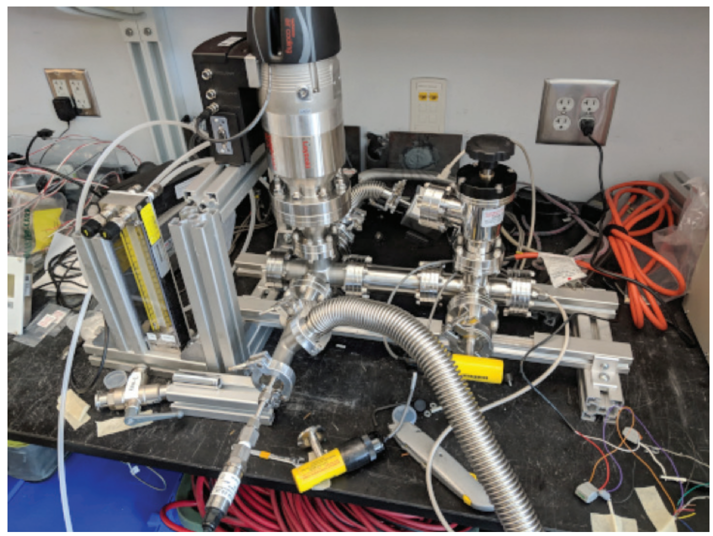


Figure 3A (top): Experimental setup of the LIMA showing the optical set-up and particle launching platform. Upper and lower right is the full launch and impact stage.
Figure 3B (bottom): Deposition of silicate beads approximately 100 nm in diameter into a polymer target.

at low temperatures, may form water at temperatures above 350K. This is the temperature range expected for recombinative desorption used in the model calculations. The control of these experiments will allow us to model the process with rigorous first principles ab initio quantum-chemistry methods in the next year.

1.4 Gas Transport Within Regolith and In Situ Resource Utilization

A basic understanding of gas transport within regolith enables predictive modeling and provides the foundation for examining different scenarios for in situ resource utilization (ISRU) for extended missions to near Earth destinations such as the Moon. The design of thermal H2O extraction devices using solar collection and focusing arrays (parabolic dishes and heliostat fields) requires a fundamental understanding of gas transport within regolith, at pressures not yet studied. An experimental apparatus was constructed to directly measure volatile diffusion constants and transport properties in regolith simulants (Figure 4). The transport properties of Ar and N2 through the regolith simulant JSC-1A were determined for Knudsen numbers between 0.01 and 10 (pressures of 100 to 25,000 Pa) in a packed bed of JSC-1A regolith simulant at ambient temperature. The results revealed behavior similar to microchannel flow and provide a foundation to study more complex volatiles such as H_2O.



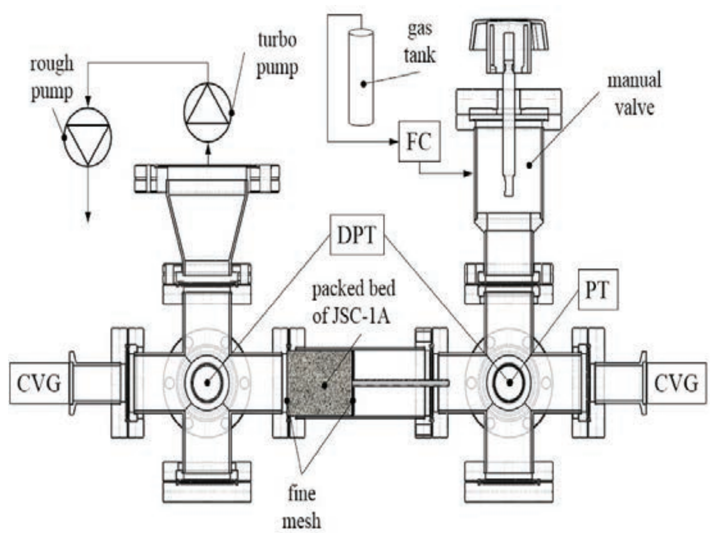


Figure 4A (top): Newly constructed system to measure transport properties of gases through regolith under controlled temperature, pressure and flow conditions that are relevant to ISRU applications.
Figure 4B (bottom). Schematic of the important system components.

Preliminary modeling and experimental work was also performed to understand and predict the extraction and thus feasibility of using volatiles from lunar regolith at temperatures up to 1500 °C. This high temperature corresponds to what is attainable using concentrated solar irradiation. Gibb's free energy minimization was used to predict chemical equilibrium compositions of the lunar regolith JSC-1A simulant from 0 to 2000 C at 3·10-13 bar, the pressure at the surface of the Moon. Other lunar and asteroid simulates from the CLASS Team are currently being analyzed for comparison.

1.5 Development and Testing of Reduced Graphene-oxide/High Density Polyethylene Composites for Spacesuit and EVA Applications

Nanocomposites that directly incorporate reduced graphene oxide (rGO) into high density polyethylene (HDPE) polymers for spacesuit applications have been synthesized. The mechanical strength and electrical properties of the "first and second generation" rGO/HDPE polymer samples have been tested. We have determined that the second generation chemical synthesis and "grafting" process allows rGO nanoparticle inclusion without compromising the beneficial electrical and mechanical properties of the rGO. The processing strategy and importance in controlling rGO immiscibility is shown in Figure 5. The alkylated sample denoted A-rGO makes the best composite. (Note: Two GT provisional disclosures have been filed on the synthetic approach).

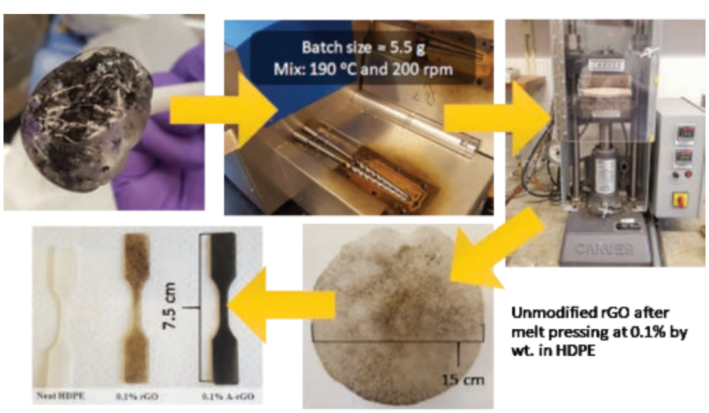


Figure 5: Processing strategy for producing rGO/HDPE polymer composites sheets. The samples for the strain tests are shown in the lower left portion. Note the alkylated sample denoted A-rGO makes the best composite.

> This allows for the production and processing of very strong and highly conductive polymer sheets that may be useful for spacesuits and EVA applications.

1.6 Examining Radiation Stability of Reduced Graphene-oxide/High Density Polyethylene Composites

HDPE has documented radiation resistance due to the presence of hydrogen. It is expected that the inclusion of rGO either maintains or increases the overall radiation stability. This is currently being examined using the irradiation facilities at the National Space Radiation Lab at Brookhaven National Laboratory (Figure 6). A series of Ar-GO/HDPE polymers with high mechanical strength and high electrical conductivity have been irradiated, and the chemical and physical stabilities are now being assessed. A proposal "Preliminary radiation attenuation measurements for effective shielding" in collaboration with CLASS and the Kennedy Space Center Utilization and Life Sciences group has been approved for future work.

1.7 Radiation Detector Two-dimensional Materials for Radiation Dosimeters

To address the need for individual radiation monitoring during astronaut EVAs, REVEALS has been working on

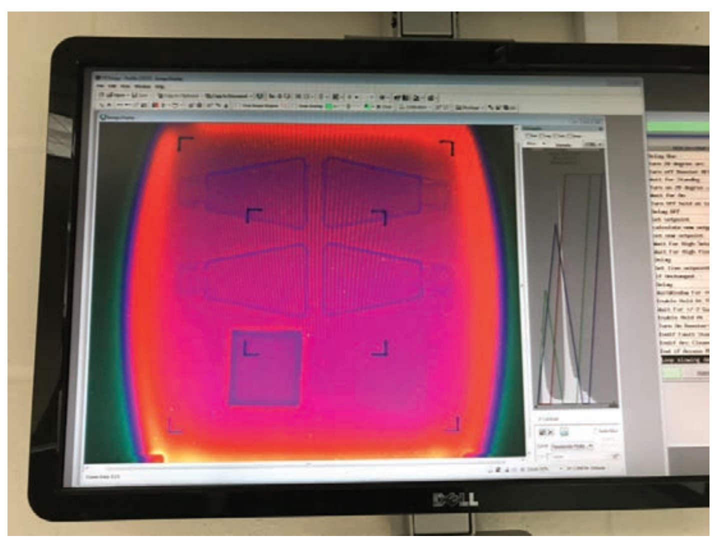


Figure 6: Irradiation tray for obtaining baseline attenuation of high LET radiation in ArGO_HDPE polymers at the National Space Radiation Lab at Brookhaven National Laboratory.

developing a new dosimetry platform for facile spacesuit integration. Radiation exposure will be correlated to alterations in the electronic properties of select topological insulators and 2D materials. Specifically, work has begun to construct a neutron dosimeter that leverages the conductivity of graphene and the superb neutron capture properties of hexagonal boron nitride (hBN). It has been hypothesized that hBN's neutron capture reaction can initiate a measurable change in the resistivity of an adjacent graphene layer, thus providing the means for quantifiable correlation between resistance change and neutron exposure. Second, because of the low thickness, high flexibility, and relatively low cost of the proposed dosimeter platform, multiple device placement over several biologically-critical spacesuit locations would be possible. To test these hypotheses, prototypes will be exposed to neutron sources of known fluence while being electronically monitored by four-point probing. (Note: A GT disclosure has been filed).

> Novel polymer composites and two dimensional meta-materials are being developed and tested as novel flexible materials and real-time passive radiation detectors. The materials and active dosimetry will be integrated into spacesuits and hardware for extra-vehicular and surface exploration activities.

1.8 Real-Time Radiation Dosimetry Reporting to an EVA Astronaut

Astronauts conducting surface Extravehicular Activities (EVA, or more commonly, "spacewalks") will be operating in a minimally-shielded environment at high risk of physiologically-damaging radiation exposure. To address this safety-critical operational need, REVEALS has also been working on integrating radiation sensors and display technology with current and anticipated spacesuit architectures. Display of information to an EVA astronaut is greatly complicated by complex constraints of a spacesuit. REVEALS began working on an "in-helmet" radiation-reporting display that minimizes operational risk to EVA astronauts (Figure 7). Specifically, we are working on mounting a thin-film electrochromic polymer display on the Extravehicular Mobility Unit manually-deployed pull-down sunshade.

2. Inter-team/International Collaborations

CLASS Collaborations: Regolith Shielding and Volatile Transport

Irradiation experiments at Brookhaven National Lab (BNL) are being carried out in collaboration with CLASS (Esther Beltran) and Ye Zhang at Kennedy Space Center, to evaluate several properties of polymers and regolith simulant T potential adoption in spacesuits and human habitats on the Moon, Mars and near-Earth. The program will speed up our understanding of chemical and mineralogical formulation by possibly adding or subtracting hydrated minerals found in regolith. Zhang, Beltran and La Saponara (REVEALS) successfully applied to BNL to run experiments in 2019 on the second generation of rGO polymers (grant titled "Preliminary radiation attenuation measurements for effective shielding").

In collaboration with Dan Britt (UCF), his graduate student Leos Pohl, Dr. Sudipta Seal (UCF), Chris Bennett (UCF), and Thom Orlando (REVEALS), we have been measuring the spectral changes in minerals and meteorites exposed to different temperature ramps during Differential Scanning Calorimetry (DCS), Thermo Gravimetric Analysis (TGA) and Temperature Programmed Desorption (TPD) experiments.

Figure 7. Extravehicular Mobility Unit manually-deployed pull-down sunshade where electrochromic polymer displays will be used.

D. Britt (CLASS-PI) also serves on the REVEALS advisory board.

VORTICES Collaborations: Temperature Programmed Desorption of Water from Regolith

The binding energies and transport properties of water on highland and mare lunar samples have been measured under ultrahigh vacuum conditions in collaboration with VORTICES team members K. Hibbitts and Dyar. The modeling effort of water formation on Mercury also involves VORTICES collaborators Hibbitts, Dyar and Klima. A. Rivkin (VORTICES-PI) also serves on the REVEALS advisory board.

DREAM2 and IMPACT Collaborations: Health Effects of Charged Dust Grains

Dr. Micah Schiable has been appointed a NASA Postdoctoral Fellow working on understanding the interaction of charged regolith grains with lung surfactants and the interaction of x-rays with DNA. Both efforts are geared toward understanding and mitigating health risks associated with human exploration of the Moon. W. Farrell (DREAM2-PI) is also a member of the REVEALS advisory board.

Germany/ESA

Dr. Katerina Fiege is supported by ESA to continue the SSERVI/REVEALS collaboration with N. Altobelli (ESA), R. Srama and M. Trieloff (University of Heidelberg) on understanding the optical and chemical signatures of interstellar dust particle impact events on lunar surfaces. The effort involves both modeling and experimental components.

Sapienza University- Italy

V. La Saponara (UC-Davis), S. Laurenzi and M.G. Santonicola (Sapienza University) are continuing their collaboration on the characterization of a sensor composed of graphene/DNA dispersed in a polymeric matrix as a UV-C radiation detector. This technique is related to the 2D topological material approach that also deals with measuring changes in resistivity or conductance.

3. Public Engagement (including EPO)

Robotics Competitions

The REVEALS team has supported and mentored two Middle School Robotics competition teams: The Freebots from Freedom Middle School and the GroveBots from Oak Grove Elementary School.

The Freebots team is primarily a group of refugee students from the Dekalb School District near metro Atlanta. The team was primarily mentored by Carla Kawabatha (a Freedom Middle School teacher in Figure 8 top panel far right), Thomas Orlando (REVEALS) and

Figure 8 (top): Freebots from the Freedom Middle School award presentation. (bottom) GroveBots from Oak Grove Elementary School award presentation.

Carol Paty (REVEALS). Their topical theme was "The Radiation Transformation: Decreasing Barriers to Long Term Space Travel." The team obtained a PERFECT score in the Research Project component, and won the First Place Champion's Award in the First Lego League's (FLL) Regional Tournament in December, 2018. The Freebots advanced to the Super Regional competition and won the overall First Place Champions award and the Robot Game Award for having the highest score. They also attended the Georgia Space Summit meeting at Georgia Tech in November, 2018, and won third place among all the poster contributions.

The GroveBots team (right panel in Figure 8) is mentored by Dr. Ester Beltran (REVEALS). This was also a major award winning team at the FLL Super Regional Competition, and qualified for the next stage to National Competition. Their topical theme was: "Improvisation for Space Missions, a Tool for Expediting Lengthy Astronaut Training."

V. La Saponara's Lab at UC-Davis hosted two demos (Discover Engineering organized by the Early Academic Outreach Program and the Arthur S. Dudley Elementary Visit to UC-Davis) on metal and composite materials performance, using the Tower of Death--an 8 ft. tall drop-weight tower built for outreach purposes in 2008 (Figure 9). A presentation on composite materials included the discussion of the REVEALS project.

W. Kaden and C. Bennett (UCF Physics Department) participated in the "Space Game" football game. Several thousand spectators spanning all ages and backgrounds interacted with their exhibits/interactive activities.

Figure 9: Demonstration to a group of middle school students from Sacramento on material properties at UC-Davis.

4. Student / Early Career Participation

Undergraduate Students

1. Hannah Lyons, University of Florida, Microbiology Worked on casting the regolith shielding for BNL testing. REVEALS summer intern

2. Zac Eller, University of Central Florida, Aerospace Engineering. Worked on casting the regolith shielding for BNL testing. REVEALS summer intern

3. Joshua Pollack, University of Central Florida, water formation of thin film samples

4. Adriana Henriquez, University of California at Davis, worked on polymer mechanical testing properties and scale effects in polymer

5. Shreya Rastogi, UC Davis, worked on polymer mechanical testing properties and electrical impedance tomography for electrically conductive materials

6. Linda Wu, UC Davis, volunteer, worked on polymer mechanical testing properties and electrical impedance tomography for electrically conductive materials

7. Bruno Matsui, UC Davis, volunteer, worked on polymer mechanical testing properties

8. Taner Dubie, UC Davis, volunteer, assisted with polymer mechanical testing properties

9. Richard Bramble, UC Davis, volunteer, assisted with polymer mechanical testing properties

10. Stephen Foster, UC Davis, volunteer, assisted with upgrade of environmental tests for polymers

11. Ghufran Alkhamis, Stanford, intern at UC Davis, volunteer, polymer mechanical testing properties

Graduate Students

12. Reilly Brennan, Georgia Institute of Technology, developing laser induced micro-particle accelerator

13. Garrett Scheiber, Georgia Institute of Technology, measuring volatile transport properties of regolith

14. Ashley Clendenen, Georgia Institute of Technology,

developing in situ resource utilization strategy based on solar energy

15. Elliot Frey, Georgia Institute of Technology, developing 2D meta-material radiation detectors

16. Cody Schultz, University of Central Florida, Aerospace Engineering. Assembled the regolith simulant and created all the samples sent to BNL. Research Assistant at CLASS

17. Faris Almatouq, Georgia Institute of Technology, Physics

18. Bijoya Dhar, University of Central Florida, synthesizing and characterizing single crystal regolith simulants

19. Matthew Gabel, UC Davis, worked on polymer manufacturing and testing

20. Austin Pastrnak, UC Davis, worked on polymer testing and scale effects

Postdoctoral Fellows

21. Zach Seibers, Georgia Institute of Technology, developing novel polymer composites for spacesuits

22. Nelson Martinez, UC Davis, studying radiation effects on material properties

23. Katerina Fiege, University of Heidelberg, particle impact studies with the Cassini Dust Analyzer Group

24. Micah Schiable, NASA, Postdoctoral Program Appointee, working on dust grain charging and health effects with REVEALS, IMPACT and DREAM2

5. Mission Involvement

1. Europa Clipper, C. Paty, PIMS, Co-I

2. Europa Clipper, C. Paty, REASON, Co-I

3. Europa Clipper, C. Paty, Interior Working Group, Co-Chair

4. JUICE, C. Paty, Science C

Amanda Hendrix

Planetary Science Institute in Tucson, AZ

Toolbox for Research and Exploration (TREX)

CAN 2 Team

1. TREX Project Report

The TREX team is based at the Planetary Science Institute (PSI). Roughly two-thirds of TREX's 33 Co-Investigators (Co-Is) are with PSI, distributed at locations across the country and Europe, with additional Co-Is and collaborators at Goddard Space Flight Center, Columbia University, Carnegie Mellon, Lunar and Planetary Institute, Univ. Colorado, Univ. Winnipeg, Univ. Illinois, The German Aerospace Center (DLR), Johns Hopkins University Applied Physics Lab, Smithsonian Institute and Fibernetics. TREX (trex.psi.edu) aims to decrease risk to future missions, specifically to the Moon, the Martian moons, and near-Earth asteroids, by improving mission success and assuring the safety of astronauts, their instruments, and spacecraft. TREX studies focus on characteristics of the fine particles that cover the surfaces of these target bodies - their spectral characteristics and the potential resources (such as H2O) they may harbor. Here, we review TREX activities in the January – December 2018 timeframe.

TREX Science and Exploration Themes

TREX studies are grouped into four Themes (lab studies, Moon studies, small bodies studies, and field work). The tasks and products of each Theme within TREX are connected. The Laboratory Studies Theme's products are inputs to the photometric and spectral studies of the Small Bodies and Moon Themes. The laboratory data will be used to validate models and as direct inputs for modeling spacecraft observations of surfaces. The models and lab data will in turn be inputs to the Field Studies Theme for use in creating autonomous decision-making software packages. PI Hendrix gave an overview of TREX activities in an invited talk at the COSPAR meeting in June 2018. At the 2018 LPSC meeting, each Theme group presented a poster to draw the attention of the community to TREX activities and results:

- Toolbox for Research and Exploration (TREX): Investigations of Fine Particulate Materials on the Lunar Surface (Banks et al., poster #517)
- Toolbox for Research and Exploration (TREX): Investigations of Fine-Grained Materials on Small Bodies (Domingue et al., poster #518)
- Toolbox for Research and Exploration (TREX): Robotic Decision Making in a Fine-Grained Environment (Noe Dobrea et al., poster #519)
- Toolbox for Research and Exploration (TREX): The Fine-Particle Spectral Library (Lane et al., poster #520)

1.1 The TREX Fine-Particle Spectral Library

Laboratory spectral measurements are ongoing, with the aim of completing work on terrestrial samples by mid-2019. All terrestrial samples have been obtained and prepared, and nearly all ~31 samples have been measured in all of the TREX labs. An important aspect of the TREX lab measurements is that we focus on measuring samples with particles of <10 microns. Some samples were purchased as fine reagents (hematite, pyrite, graphite, Fe metal). Others were pulverized in shatter-boxes by Co-I Dyar's group. We have also confirmed the grain size distribution of all terrestrial samples by sending them to Particle Technology Labs and/or to Wendy Roth at Univ. Colorado for particle size analysis. Once grain sizes are confirmed (Fig. 1), Co-I Dyar coordinates the shipment of samples to all TREX labs. Co-I Lane traveled to Berlin

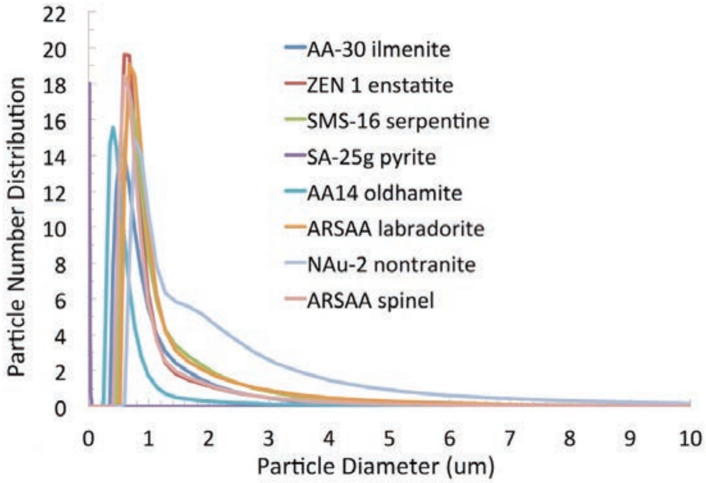
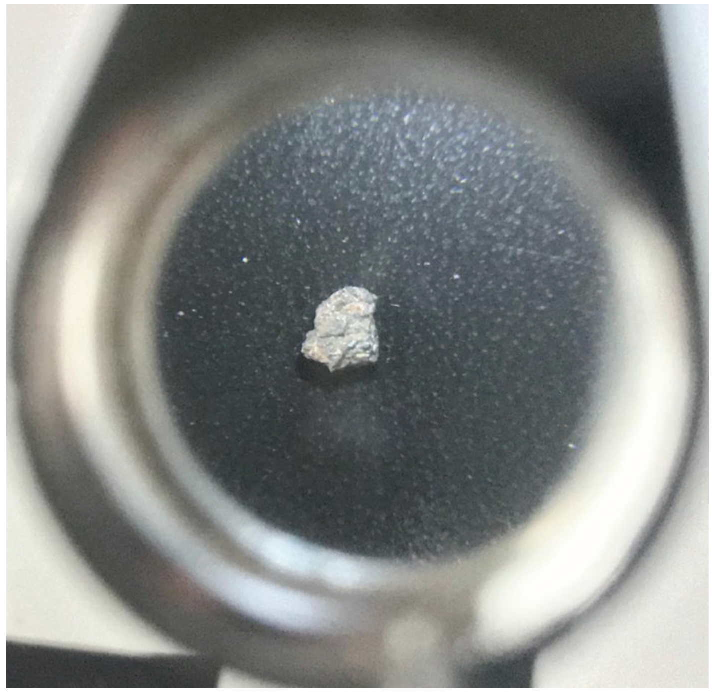


Figure 1. Grain size distributions of some of the TREX terrestrial samples.

(DLR) in April to run measurements on the 20 samples that were ready at that time. Measurements included FIR reflectance (ambient P, T), MIR emissivity (ambient P, 80 °C), MIR emissivity (vacuum) at 150° & 300° C, VNIR (vacuum, ambient T) reflectance, UV (vacuum, ambient T) reflectance, and VNIR (ambient P, T) reflectance. We held a TREX lab working group meeting (Feb 20-21, 2019) to review the terrestrial sample measurements completed to date in all the labs; the next phase of measurements will be meteorites, and those samples have been requested from the Meteorite Working Group.

In addition to the terrestrial samples, we are characterizing the Hamburg Meteorite that fell in Michigan (Fig. 2) (observed fall in January 2018). Spectral measurements of the Hamburg Meteorite have been done at PSI (UV, VNIR), Mt. Holyoke (MB and Raman), RELAB (biconical), and MIR emissivity (Stony Brook U.; Tim Glotch). Co-I Dyar is leading a paper discussing the analyses.

TREX labs continue to improve their capabilities. Setup of the TREX UV lab at LASP/CU is proceeding. In November, Co-I's Osterloo and Holsclaw visited McPherson (near Boston) for 2-day spectrometer training session on their new vacuum UV-VIS (115-600 nm) reflectance system. This system is now installed at LASP, and initial measurements of terrestrial samples have begun. PSI lab manager Neil Pearson continues to develop hardware in the PSI lab, including: installing a new pressure gauge on the main vacuum chamber; ordering a new deuterium



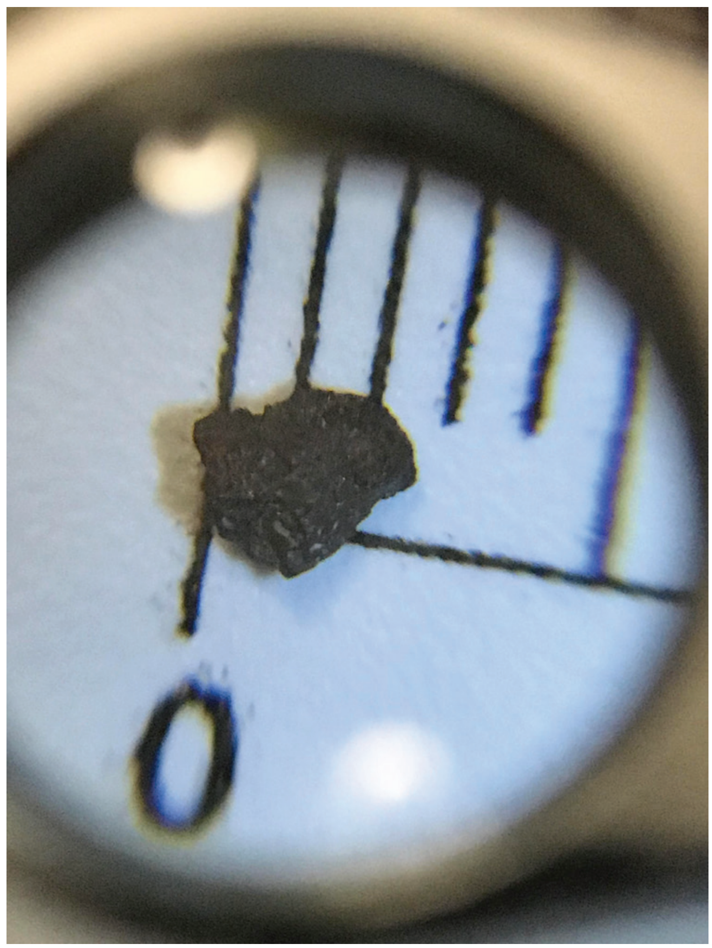


Figure 2. Michigan-based PSI scientist Jordan Steckloff acquired two pieces of the Hamburg meteorite (likely an L chondrite) from the Jan 16 2018 fall. UV through IR spectra are being measured in TREX labs and a paper discussing the analyses is in progress.

lamp; modifying a separate deuterium-halogen lamp for brightness and boosting SNR, possibly up to 80-100%; and proto-typing stray light absorbing baffles for the spectrometers using the 3D printer at PSI. Co-I Cloutis is working on lab upgrades to the FTIR in his lab at Univ. Winnipeg to boost signal for the MIR optical constants work. They recently received a new InSb detector for better SNR and are working on its installation. Teams at Univ. Illinois, PSI and LASP are working on a vacuum suitcase to transport some samples; this will allow samples prepared in a glove box at Univ. Illinois to be measured in the UV at LASP and PSI without exposure to atmosphere.

1.2 Lunar and Small Bodies Studies

TREX Co-I Watkins has been working with Dan Moriarty (GSFC) on a project to integrate Lunar Prospector (LP) measurements of the thorium (Th) abundance across South Pole Aitken Basin (SPA) with Moon Mineralogy Mapper (M3) hyperspectral data, Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) images, and Lunar Orbiter Laser Altimeter (LOLA) topography to assess the mineralogy and geology of Th-bearing lithologies across SPA (Fig. 3). SPA exhibits an unusual enhancement in thorium abundance, the origin of which is debated within the community, and is theorized to have excavated and melted large volumes of mantle materials. Thorium is a key elemental tracer of igneous processes, including crystallization of the lunar mantle. Thus, these analyses will inform our understanding of the structure and evolution of the lunar mantle, and have important implications for planning future sample return missions.

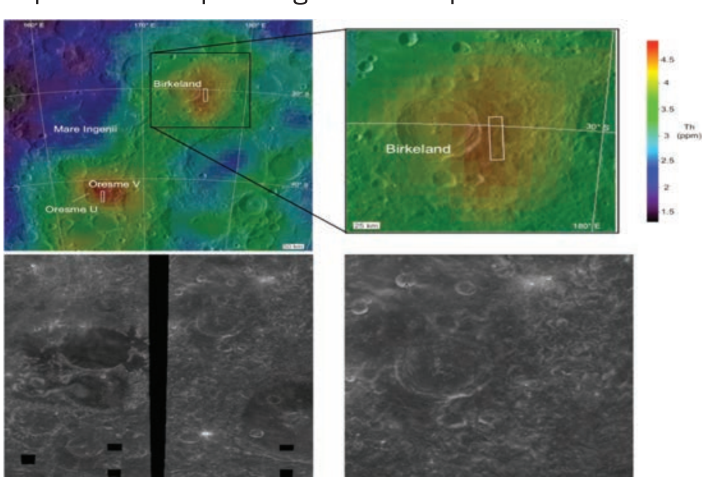


Figure 3. SPA Th hotspots viewed in LROC WAC overlain with Lunar Prospector thorium data (top), and OMAT images (bottom). From Watkins et al., 2018.

Additionally, TREX Co-I Grier is creating OMAT (optical maturity) profiles in the SPA area as defined by Watkins (ideally ~5 craters with similar OMAT values, and similar size in the ~5 km range). Watkins, Grier and Co-I Banks have selected the SPA Th hotspots to investigate using M3 data, OMAT data and NAC photometry (perhaps LP as well), combining them to determine thorium origin. Furthermore, Banks, Grier, Watkins and collaborators have initiated a study of lunar lobate scarps, doing a comparison of multiple data sets to analyze the photometric and optical maturity of surfaces surrounding the lobate scarp thrust faults. The study aims to understand if photometric and OMAT investigations will reveal distinctive results for the surfaces disturbed by ground motion from seismic slip events during scarp formation, and if such analyses can provide further insight regarding whether or not these surfaces contain materials that might inform and benefit future exploration.

TREX Co-I Banks was involved in a 2018 published paper with lunar science and exploration implications, “How old are lunar lobate scarps? Seismic resetting of crater size-frequency distributions (van der Bogert et al.).” Lunar lobate scarps are tectonic landforms similar to thrust faults on Earth. They are among the youngest landforms on the surface of the Moon. Some are likely to be still active today. In this study, absolute model ages were estimated using the size-frequency of impact craters (Fig. 4). Results showed not only that all studied scarps were active in the late Copernican, but also that fault activity causes surface renewal and disturbance kilometers distant from the lobate scarp thrust fault. This has important implications for future human or robotic exploration as potential locations of resources brought up to or exposed near the surface, in addition to being potential hazards.

TREX Co-I Domingue completed and published a study of the photometric properties in Tsilokovsky crater (Domingue et al. (2018) Characterization of lunar surface within Tsilokovsky crater: Photometric properties, Icarus 312, 61 – 99, doi:10.1016/j.icarus.2018.02.034). This study is part of work being done by PSI scientist Eric Palmer. The photometric properties are used to better determine Bond albedos that are in turn used to

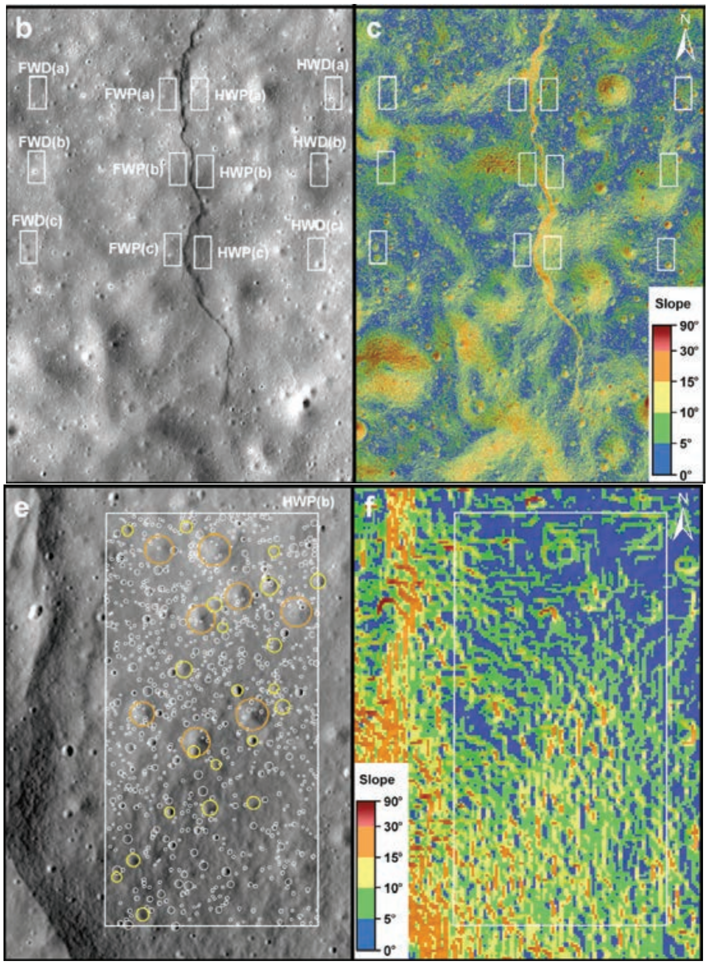


Figure 4. (Upper left) Mandel'shtam-3 scarp and locations of crater count areas (white boxes). (upper right) LROC NAC digital terrain model-derived slope map. (Lower) Close up view of a count area with identified and measured craters (circles) and (right) the slope map. The steeper slopes in the southern portion of the count area are associated with a lower density of craters. Modified from van der Bogert et al., 2018.

determine thermal emission properties for correcting M3 data sets. The goal is to examine the M3 thermal infrared for hydration signals. TREX Co-I Domingue completed the photometric analysis of a swirl region in Ingeni as part of this project (presented at LPSC 2019) and a publication is underway.

Co-I Prettyman completed a study, partially funded by SSERVI and in collaboration with SSERVI's SEEED team, comparing mineralogy and elemental data at Ceres; a paper is now published in Icarus ("Elemental composition and mineralogy of Vesta and Ceres: Distribution and origins of hydrogen-bearing species"). In this work, the surface elemental and mineral composition constrains the origin of H-bearing species. Compositional data acquired by Dawn's Visible to Infrared Mapping Spectrometer (VIR) and Gamma Ray and Neutron Detector (GRaND) are sensitive to different depths and spatial scales; physics-based smoothing enabled direct comparison of the elemental and mineral maps. On Vesta, similar H and OH patterns support exogenic origins for hydrated minerals (Fig. 5, panels B and C), while on Ceres, different patterns of H and hydrated minerals unveil a global ice table. Ceres' chemistry reveals internal aqueous alteration and ice-rock fractionation.

TREX Co-Is Deborah Domingue and Faith Vilas, science Co-Investigators on Hayabusa2, were involved in that spacecraft's approach with the near-Earth asteroid Ryugu (Fig. 6). Domingue modeled Ryugu's surface photometrically, with results that were used as inputs in landing site selection; she participated in the Hayabusa2 press conference at the DPS meeting in October. The photometric studies are important for characterizing surface roughness.

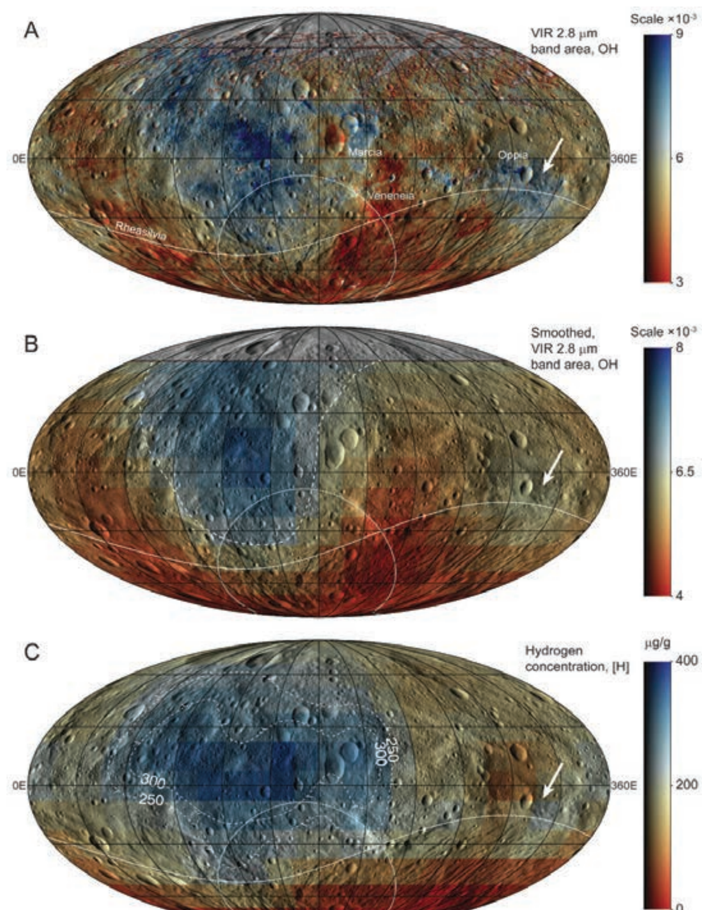


Figure 5. On Vesta, similar H and OH patterns support exogenic origins for hydrated minerals. Map data are superimposed on shaded relief. From Prettyman et al., 2018.

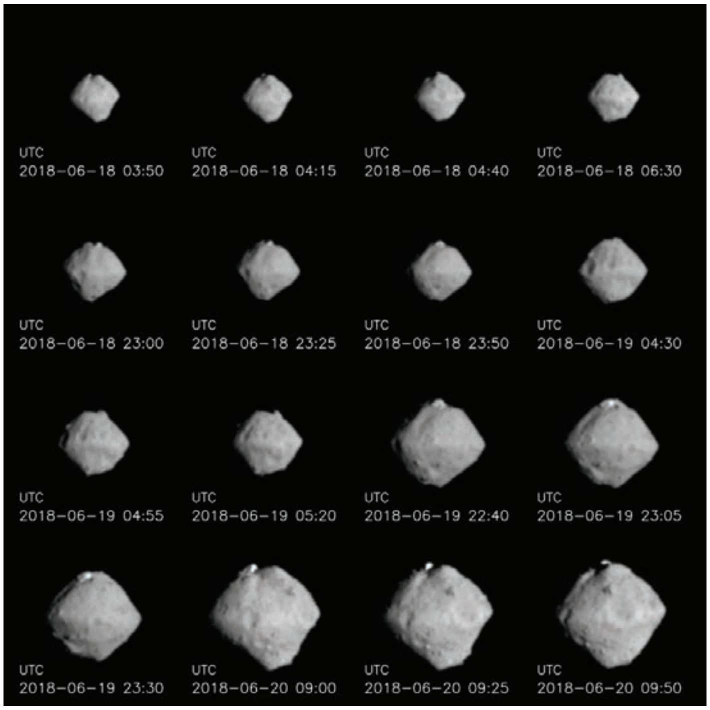


Figure 6. Approach images of asteroid Ryugu from Hyabusa-2.

1.3 Preparations for Fieldwork

The TREX team is planning for fieldwork activities beginning in ~February 2020. To prepare, we purchased the 4300 hand-held FTIR from Agilent for field use. Co-I Clark continues work on spectroscopic analysis software to facilitate integration onto the rover. The goal is to improve accuracy in spectroscopic analysis in general but to increase success in application within the rover environment. Co-I Prettyman continues progress on the development of a gamma ray spectrometer (GRS) for field testing with the rover. The GRS will acquire a time series of gamma ray spectra, which can be spatially registered to the rover path, providing a time series of the concentration of radioelements along the traverse. From an operations perspective, we must decide whether the information would be used in real time or analyzed once operations are complete. Co-I Wettergreen (Carnegie Mellon Univ.) updated the control software and verified automated pointing and data collection with the VNIR spectrometer on our rover. His team tested a new localization and navigation component that uses LIDAR, and is in the midst of updating the power system; they are also working on automated mineral classification in remote sensing data, with some promising initial results.

1.4 Carbon in the Solar System Workshops

TREX PI Hendrix and Deputy PI Vilas, along with SSERVI Chief Scientist Yvonne Pendleton, organized a series of three Carbon in the Solar System workshops in 2018. The first, held in April, was a 2-day workshop-without-walls. Twenty-five presenters, plus some 10-15 attendees, participated in lively discussions on topics ranging from carbon in/on Mercury, the Moon, asteroids, and the ISM, among others. The workshop-without-walls was followed by a panel discussion at the DPS meeting (October) with 3 expert panelists (Fig. 7). An additional panel discussion, with 10 presentations, was held during the AGU meeting and was widely attended. Interest in these workshops is wide-ranging. Recent results ranging from the Pluto system, the Saturn system, other locations beyond ~5 AU, all the way to Mercury in the inner Solar System, and nearly all points in between, raise questions abut the state of carbon in the Solar System: how do carbonaceous compounds become weathered in response to thermal processes and irradiation? How do we recognize carbon

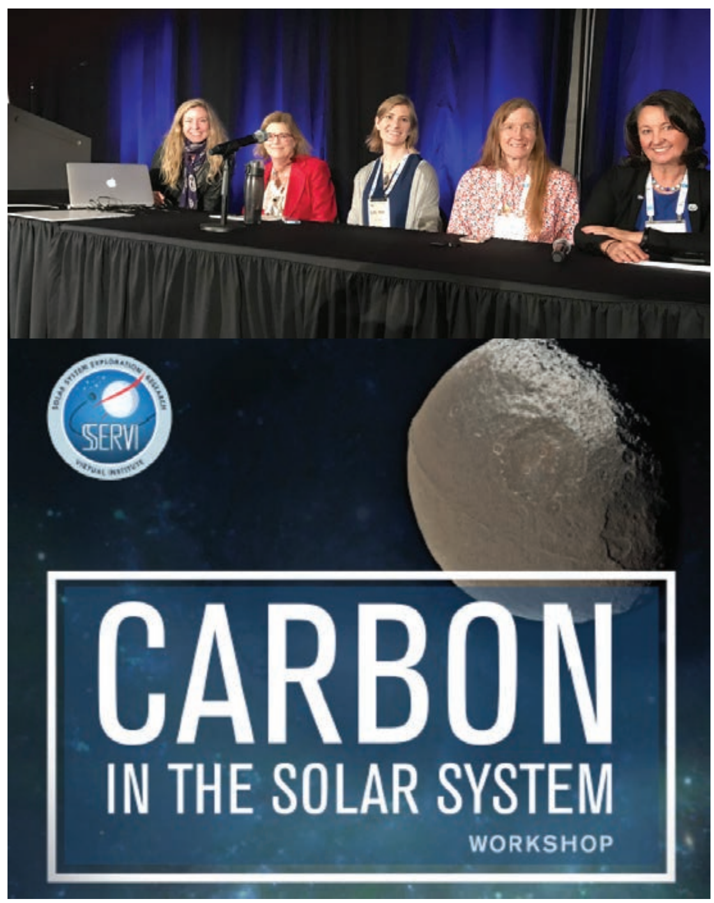


Figure 7. The SSERVI-sponsored "Carbon in the Solar System" panel discussion was held at the DPS meeting with panelists Kelly Miller, Diane Wooden and SSERVI Chief Scientist Yvonne Pendleton (shown with conveners TREX PI Hendrix and TREX DPI Vilas)

compounds and their various weathering products? The synthesis of these results improves our scientific understanding of the role of carbon in the Solar System, how it evolves and how to recognize it. The carbonaceous near-Earth asteroids 162173 Ryugu and 101955 Bennu will be sampled in the next few years; the analyses of these samples will provide context for the presence of carbon. We intend to organize additional workshops in 2019, beginning with a lunchtime discussion at LPSC.

2. TREX Inter-team/ International Collaborations

TREX Co-I Quick is collaborating with OJ Tucker (NASA GSFC, DREAM2 team) on a project to better constrain the types of volatiles (e.g., water vapor, CO2, CO, etc) and respective quantities, outgassed during volcanic eruptions on the Moon.

Spectral measurements of the Michigan Meteorite were done at Stony Brook U. (MIR emissivity, Tim Glotch, RIS^{4}E), along with measurements at various TREX labs, and the RIS^{4}E data will be included in the paper led by TREX/RIS^{4}E Co-I Dyar.

TREX Co-I Allain (Univ. Illinois) will be using some lab simulants produced by the CLASS group.

TREX Co-I Prettyman's paper with TREX-SEEED connection has been published in Icarus ("Elemental composition and mineralogy of Vesta and Ceres: Distribution and origins of hydrogen-bearing species").

The TREX Small Bodies Photometry and Spectroscopy groups held meetings at APL with VORTICES support, April 17 and May 16, 2018.

TREX Co-I Wright participated in field work (Potrillo Volcanic Field) with the RIS^{4}E team in April, 2018.

TREX Co-I Grier is partnering with VORTICES team member Angela Stickle, using Stickle's IDL code to obtain OMAT profiles of impact craters.

The TREX team is collaborating with Dr. Susan Lederer (JSC), who has conducted impact experiments at JSC on various minerals (primarily phyllosilicates), similar to what TREX will do as part of small bodies space weathering simulations; Dr. Lederer has offered the samples to TREX for characterization in our labs before and after impact. This collaboration will expand the number of samples we can study under impact situations. PSI lab manager Neil Pearson has sent select samples to Lederer in Houston, including Na-montmorillonite (SWy-3), Ca-mont. (STx-1b), Serpentine (UB-N), and Serpentine (SMS-16).

3. Public Engagement Report

The TREX team, under the guidance of Public Outreach Lead Sanlyn Buxner, submitted a Public Engagement proposal in December 2018. The TREX Public Engagement program will leverage the geographic breadth and content diversity of the subject matter experts on the TREX team. In total, the project will directly engage fourteen team members across the country to raise awareness and help inspire both the general public and next generation of subject matter experts. Additionally, the program will leverage both the outreach expertise and resources of the Planetary Science Institute. The overall goals are to further develop the expertise of subject matter experts on the team, collaborate with other SSERVI teams and SMD science teams as appropriate, and to inspire and engage the public in the exciting science of TREX and SSERVI.

TREX Co-I harpist Maria Banks played the national anthem on May 30, 2018 for the Red Sox game at Fenway Park, as part of the "NASA at Fenway" event! The event, organized by the Lunar Reconnaissance Orbiter outreach team, emphasized the Moon and lunar studies; Banks also participated in the outreach part of the event and talked with school children about TREX and other lunar projects. TREX Co-I Petro spearheaded this outreach event and led many activities and talks.

4. Student / Early Career Participation

Our volunteer Maryland high school students are wrapping up interviews of TREX scientists; interviews will be posted on the TREX webpage in 2019.

High School Students

1. Jack Brink, Bel Air High School

2. Trevor Lorin, Bel Air High School

3. Brett Weeks, Edgewood High School (International Baccalaureate Magnet Program)

4. Emma Gabel, Edgewood High School (International Baccalaureate Magnet Program)

5. Savanah Hofftein, Edgewood High School (International Baccalaureate Magnet Program)

6. Gabriella Postlehwait, Edgewood High School (International Baccalaureate Magnet Program)

7. Kristina Holsapple, Edgewood High School (International Baccalaureate Magnet Program)

8. Lydia Potowski, Edgewood High School (International Baccalaureate Magnet Program)

9. Grace Martino, Edgewood High School (International Baccalaureate Magnet Program)

10. Riley Johnson, Edgewood High School (International Baccalaureate Magnet Program)

11. Xandi Matu, Edgewood High School (International Baccalaureate Magnet Program)

12. Ave Bonwit, Edgewood High School (International Baccalaureate Magnet Program)

13. Andrew Grad, Edgewood High School (International Baccalaureate Magnet Program)

14. Emily Logue, Edgewood High School (International Baccalaureate Magnet Program)

15. Julia Clifton, Edgewood High School (International Baccalaureate Magnet Program)

16. Matthew Brandenburg, Edgewood High School (International Baccalaureate Magnet Program)

17. Mary Richardson, Edgewood High School (International Baccalaureate Magnet Program)

18. Alexander Chapman, Edgewood High School (International Baccalaureate Magnet Program)

19. Stacy Ramos, Edgewood High School (International Baccalaureate Magnet Program)

Undergraduate Students

20. Christopher Nguyen, Univ. Hawaii

Graduate Students

21. Alberto Candela, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.

22. Himanshi Yadav, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.

23. Srinivas Vijayarangan, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.

24. Suhit Kodgule, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.

25. Kevin Edelson, Ph.D. Candidate, Robotics Institute,

School of Computer Science, Carnegie Mellon Univ.

26. Camilo Jaramillo, Nuclear, Plasma, and Radiological Engineering Department, Univ. Illinois at Urbana-Champaign

27. Heather Sandefur, Nuclear, Plasma, and Radiological Engineering Department, Univ. Illinois at Urbana-Champaign

5. Mission Involvement

TREX team members are involved at some level with numerous NASA missions, along with missions from other space agencies and the United Arab Emirates.

1. **Cassini,** Amanda Hendrix, UVIS Co-I, Deputy Project Scientist; Roger Clark, VIMS Co-I; Chuck Wood, Radar; Greg Holsclaw, UVIS Instrument Scientist; Andrea Jones, Public Engagement Lead

2. **Lunar Reconnaissance Mission (LRO)**, Noah Petro, Deputy Project Scientist, LROC, Diviner, LOLA; Amanda Hendrix LAMP Co-I; Maria Banks, LROC; Rebecca Ghent, Diviner; Ryan Clegg-Watkins, LROC; Faith Vilas, LAMP

3. **Hayabusa**, Faith Vilas

4. **Hayabusa 2**, Faith Vilas, Deborah Domingue, Jorn Helbert

5. **Chandrayaan-1**, Roger Clark, Moon Mineralogy Mapper; Noah Petro

6. **Europa Clipper**, Amy Barr-Mlinar, EIS, REASON; Roger Clark, MISE; Lynnae Quick, EIS

7. **MESSENGER**, Maria Banks; Deborah Domingue, Deputy Project Scientist; Jorn Helbert; Greg Holsclaw; Karen Stockstill-Cahill; Faith Vilas

8. **Mars Reconnaissance Orbiter (MRO)**, Maria Banks, HiRISE; Roger Clark, CRISM; Eldar Noe Dobrea, CRISM

9. **Mars Global Surveyor (MGS)**, Roger Clark, TES; Karen Stockstill-Cahill, TES

10. **Mars Odyssey**, Melissa Lane, THEMIS; Roger Clark; Karen Stockstill-Cahill, THEMIS

11. **MSL/Curiosity**, Darby Dyar; Andrea Jones, SAM Public Engagement co-lead

12. **Mars Exploration Rovers (MER)**, Karen Stockstill-Cahill; Shawn Wright

13. **Dawn**, Tom Prettyman, GRAND PI; Ed Cloutis; Amara Graps; Jian-Yang Li; Lynnae Quick; Norbert Schorghofer

14. **OSIRIS-REx**, Ed Cloutis; Rebecca Ghent; Jian-Yang Li

15. **Deep Impact/DIXI**, Jian-Yang Li

16. **Stardust-NExT**, Jian-Yang Li

17. **New Horizons**, Amara Graps

18. **BepiColombo**, Jorn Helbert, MERTIS Co-PI

19. **Venus Express**, Jorn Helbert

20. **Mars Express**, Jorn Helbert

21. **MAVEN**, Greg Holsclaw IUVS Co-I; Andrea Jones, E/PO

22. **Emirates Mars Mission (EMM)**, Greg Holsclaw, EMUS Instrument Scientist

23. **ExoMars**, Ed Rivera-Valentin, HABIT

SSERVI International Partners

SUMMARY OF INTERNATIONAL ACTIVITIES

SSERVI's International Partnerships Program provides collaboration opportunities for researchers within the global planetary science and human exploration community, working both on development of new science and technical approaches and communicating this science to the public. International partners are invited to participate in all aspects of the Institute's activities and programs on a no-exchange-of-funds basis. In addition, SSERVI's Solar System Treks Project (SSTP) has played a significant role in the institute's international partnerships, and collaborative efforts are outlined in the sections below.

Non-U.S. science organizations can propose to become either Associate or Affiliate partners of SSERVI on a no-exchange-of-funds basis. Affiliate partnerships are with non-government institutions (e.g., universities and other research institutions); the majority of existing SSERVI international partnerships are Affiliate. Associate partnerships are government-to-government agreements including those between NASA and international space agencies.

Presently, SSERVI International Partners include: Australia, Canada, France, Germany, Israel, Italy, Netherlands, Saudi Arabia, South Korea, and the United Kingdom. During 2018, SSERVI received a proposal for partnership from the Japan Aerospace Exploration Agency (JAXA) Institute, which was submitted for review and signing in 2019. Discussions have also continued with representatives from the Mexican Space Agencies on development of a proposal for membership. In addition, SSERVI participated in and/or accomplished the following activities:

European Lunar Symposium

The 6th European Lunar Symposium was held May 13-16, 2018, in Toulouse, France. This meeting built upon the success of previous European Lunar Symposiums (ELS) held in Berlin (2012), London (2014), Frascati (2015), Amsterdam (2016) and Muenster (2017). The meeting was held under the umbrella of the European SSERVI teams, supported by the local team at Toulouse and SSERVI colleagues.

The format was similar to previous European Lunar Symposiums and consisted of both oral and poster presentations divided into four broad themes of: "Science of the Moon," "Science on the Moon," "Science from the Moon," and "Future Lunar Missions." There was a total of 121 presentations made over two and a half days (68 orals + 53 posters). Approximately 150 participants, representing the global community of lunar scientists and explorers, made this a highly successful event.

SSERVI Group Photo ELS2018. Representatives from left to right: Mihaly Horanyi, Mahesh Anand, Yves Daydou, Carle Pieters, Brad Bailey, Patrick Pinet, Greg Schmidt, David Kring, Kristina Gibbs.


ELS2018 Group Photo. Credit: ELS organizers

Italy

SSERVI's Italian partner plays a leading role in laser retroreflector science and development. SSTP collaborated with the Istituto Nazionale di Fisica Nucleare to produce a planning tool within the Moon Trek portal to facilitate the planning of lunar laser retroreflector studies.

France

SSTP is in the early stages of a collaboration with SSERVI's French partner in characterizing multiple potential lunar traverse possibilities.

Korea

SSTP continues to work with the South Korean Space Agency (KARI) and its partner, the Korea Institute of Geoscience and Mineral Resources (KIGAM). This year, the joint efforts have largely focused on ingestion and integration of specialized maps developed by the lead for the gamma ray spectrometer that is being built for the Korea Pathfinder Lunar Orbiter (KPLO).

Australia

SSERVI's Australian partner, Curtin University, is in the process of expanding its Desert Fireball Network beyond the Australian Outback into new locations around the world. SSERVI's Central Office is working with Curtin to facilitate the expansion of the Desert Fireball Network into the Global Fireball Network (GFN). SSERVI Central has facilitated the expansion of the network into the states of California and Georgia this year. We also leveraged our developing relationship with the Mexican Space Agency (AEM) to facilitate agreements to locate new GFN stations on the site of Mexico's National Astronomical Observatory in Baja California and at several locations throughout the Sonoran Desert. We facilitated meetings with the University of Sonora, which has agreed to provide sites for new GFN stations being provided by Curtin, and to build additional stations based on Curtin's design.

As SSERVI Central works to help the expansion of our Australian partner's Desert Fireball Network to the Global Fireball Network, we are also assisting in dissemination and integration of their related outreach efforts. We highlighted the Fireballs in the Sky curricula developed through Curtin University at a variety of NASA booth venues including AGU and the American Library Association, and are integrating the Fireball Network's Fireballs in the Sky augmented reality app into NASA's citizen science program.

Development of new Partnerships:

Mexico

Looking forward to a SSERVI partnership and supporting SSERVI's Australian partnerships, SSERVI helped coordinate between National Observatory of Mexico, University of Sonora, and AEM (Mexican Space Agency) on behalf of the Desert Fireball Network and expansion into Mexico.

Mexico's Universidad Nacional Autónoma de México (UNAM) plays a key role in the Mexican Space Agency's planned international partnership with SSERVI, and SSERVI continued its long-standing outreach with UNAM. In 2018, SSERVI arranged for Natalie Gallegos, a Latina engineer at JPL working on SSTP, to remotely deliver two seminars in Spanish through UNAM's Ciencia a Distancia program to students in Mexico City and across the country.

JAXA

NASA's Science Mission Directorate and the Japanese Space Agency JAXA jointly requested that SSTP develop a data visualization and analysis portal for Mars' moon Phobos to be used for Japan's upcoming Martian Moons eXploration (MMX) mission. We produced and demonstrated a prototype portal and are working with the international Phobos/Deimos working group to identify and integrate data desired to support this mission.

After demonstrations of SSTP capabilities at the 2018 JpGU Conference in Chiba, Japan, we were approached by the project scientist for the JAXA/ESA BepiColombo mission to Mercury and asked if we could develop a portal using Messenger data for use in BepiColombo mission planning. We were also approached by members of the Hyabusa2 mission and asked if we could develop a portal for visualization and analysis of data returned from Ryugu. These questions were referred to the NASA Chief Scientist and the Director General of JAXA, both in attendance at the conference, and a joint decision by both agencies was made to proceed with collaborations for both missions. We have since produced a prototype for the Mercury portal and are working with JAXA in the gathering of data for the Ryugu portal.

In addition, another area of collaboration with JAXA is through public engagement. In 2018 we conducted SSTP student and teacher workshops at Japan Geophysic Union meeting as well as created and presented new public programs on NASA's hyperwall at the meeting.

Because of these and other burgeoning collaborations with SSERVI, in 2018 JAXA submitted a proposal for Associate-level partnership with SSERVI. This proposal covers research aspects ranging from lunar science to the science of the moons of Mars, and also addresses potential collaborative activities in human exploration. The proposal is expected to be signed in mid-2019.

International Partner Reports

1. Canada Project Report

The Canadian Lunar Research Network (CLRN) has been a proud international node of the NASA Solar System Exploration Virtual Institute (SSERVI) since 2008. Recently, CLRN has begun a survey of the lunar research environment in Canada – with funding support from the Canadian Space Agency – in an effort to update our research themes to better reflect current trends in Canadian lunar research. We are excited to announce the inclusion of over 20 new researchers to our network including both faculty members from institutions across Canada, and members of private industry working to develop technologies that related to future lunar research and exploration. Several diverse examples of ongoing CLRN research are highlighted below.

1.1 Remote Sensing Studies

1.1.1 Lobate Melt Flows Around Pierazzo Crater (Dr. Catherine Neish)

Dr. Neish of Western University was recently involved in an international collaboration examining the occurrence of impact melt flows within the ejecta blanket surrounding Pierazzo crater on the lunar surface. Through the morphological mapping and the use of fractal analysis, the study noted the occurrence of distal impact melt flows from 9 to 40 km away from the center of the crater. As the fractal analysis was inconsistent with lunar dry granular flows and more similar to terrestrial basaltic lava flows, the authors used thermal modeling to argue that the melt was emplaced ballistically. The rarity of the impact melt rock is proposed to most likely be due to turbulent mixing with the solid ejecta blanket; however, in high crater-facing topography, the flow of ejecta is restricted liming the quenching that occurs through turbulent mixing. Additional information about this research can be found in the associated published article: V. J. Bray, C. Atwood-Stone, C. D. Neish, A. McEwen, N. Artemieva, J. N. McElwaine (2018) Lobate impact melt flows within the extended ejecta blanket of Pierazzo crater. Icarus, 301, 26-36. https://doi.org/10.1016/j.icarus.2017.10.002

1.1.2 Geomorphology of Lunar Wreaths (Dr. Phil Stooke)

Dr. Stooke, emeritus professor at Western University, has undertaken a study of a newly observed lunar landform, the lunar wreath. These features are circular to elliptical forms with a wrinkled texture. They measure approximately 1 to 2 km in diameter and, to date, have only been observed in Mare Imbrium and Mare Insularum. So far no systematic survey has been undertaken to determine the global distribution of these unique features or how commonly they occur on the lunar surface. Dr. Stooke has begun an analysis of four separate lunar wreaths, located at: 23.29° W; 48.87° N, 22.79° W; 3.52° S, 19.57° W; and 3.63° S, 19.62° W. Each of the observed wreaths possesses a raised outer rim, and topographically depressed interior region. These wreath features are interpreted by Dr. Stooke to not simply be degraded impact craters, but more likely the result of the outgassing of residual volcanic volatiles or radiogenic argon. This work will be presented in March 2019 at the 50th Lunar and Planetary Science Conference (LPSC) (Abstract number 1009).

1.2 Sample studies

At Western University, PhD Candidate Patrick Hill along with Drs. Osinski and Banerjee have been working on the petrographic analysis of lunar samples. In late 2018, Hill, Osinski, and Banerjee in collaboration with several others authors, published an article on the petrography and geochemistry of three lunar meteorites (Figure 1). This research looks at three feldspathic regolith breccias and examined the potential of the meteorites being paired. More information on this research can be found in the published work: Hill, Patrick J.A., et al. "Petrography and geochemistry of lunar meteorites Dhofar 1673, 1983, and 1984." Meteoritics & Planetary Science (2018). https://doi.org/10.1111/maps.13207

Additionally, Hill and Osinski recently began working on image analysis of impactites within the Apollo collection. By analyzing the morphology and geometry of the impact melt rock within fragmental breccias and comparing it to terrestrial analogues, they aim to provide insight into the formation of these impactites. Through this semi-

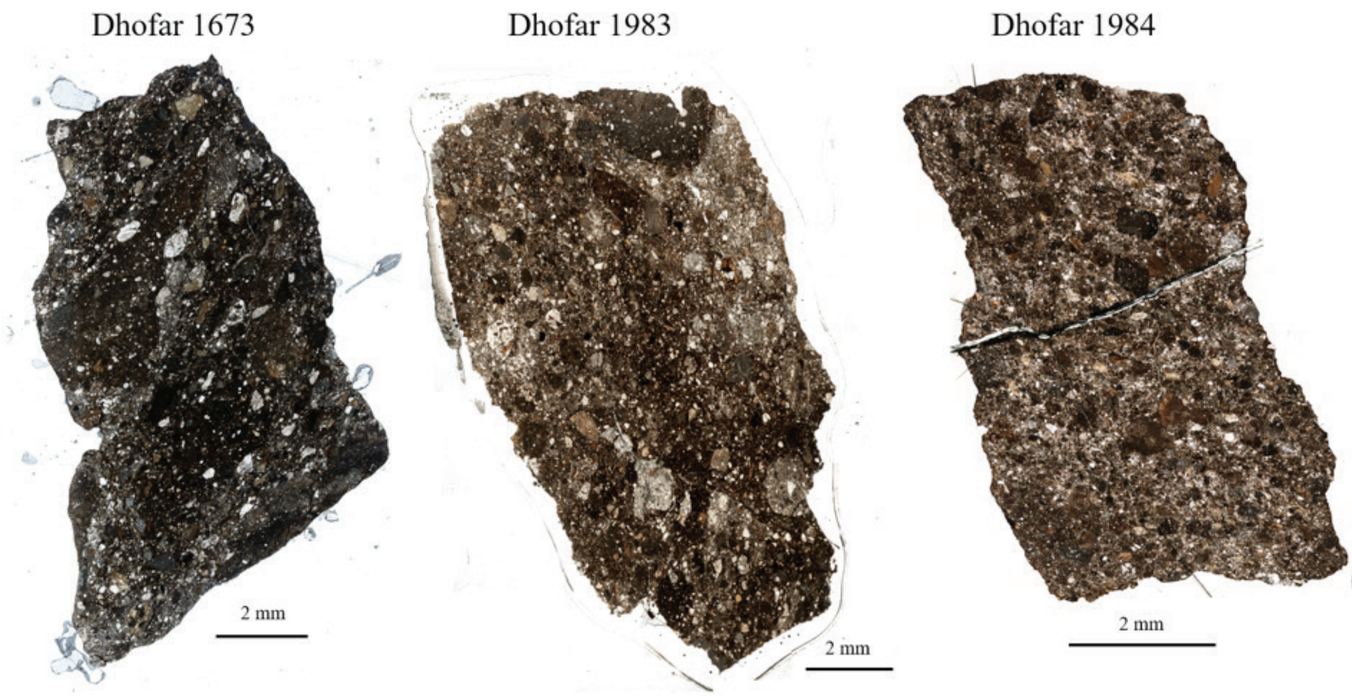


Figure 1 - Plain-polar images of a thin section for Dhofar 1673, Dhofar 1983, and Dhofar 1984.

automatic image classification technique, the clasts of impact melt rock can be isolated and quantified through several geometric parameters (Figure 2). In doing so they look to provide insight into the petrogenesis of this lunar material and implication for the formation of terrestrial breccias containing impact melt rock. After primarily results, the team looks to expand the current number of samples to include a range of breccia types and begin to take the first steps in unifying the nomenclature and terminology used within the impact cratering community with lunar community. As we return the Moon common language will be essential in order for the return of high-value science targets.

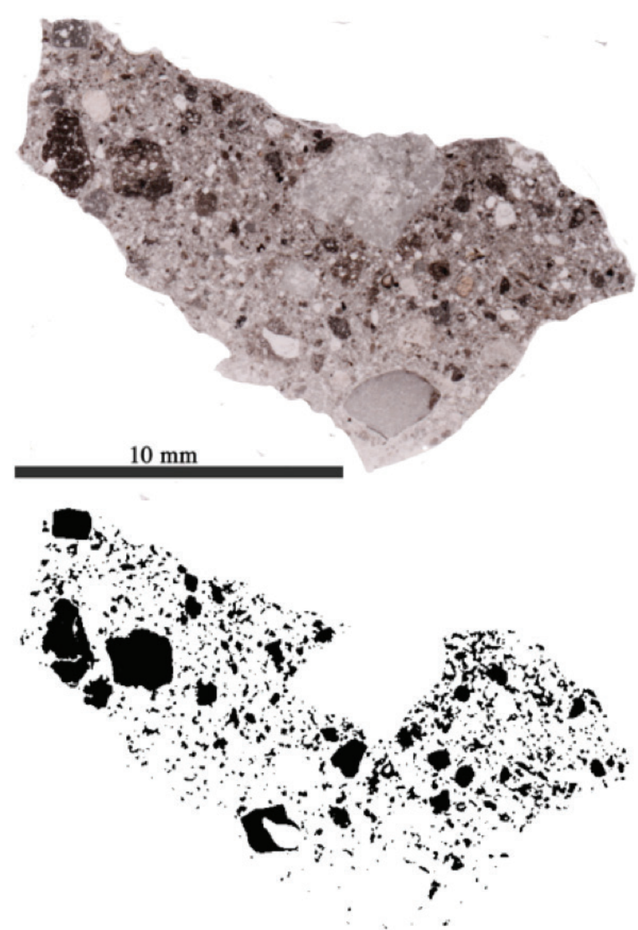


Figure 2 - (A) Apollo 16 sample (67016) in plain polarized light. (B) 67016 converted to an 8-bit greyscale image of impact melt-rock clasts present within the fragmental breccia.

1.3 Precursor to Humans And Scientific Rover (PHASR) Science Maturation Study

In 2018, a Canadian Space Agency (CSA) Science Maturation Study, led by Dr. Gordon Osinski was undertaken by Western University. The goal of this study was to provide significant scientific background for the planned PHASR (rover) as a component of the joint CSA, European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA) Heracles mission concept. The proposed rover would land on the lunar surface to test technologies such as a lunar night survival and would perform a 70-day sample return mission to return lunar samples back to Earth via the Lunar Gateway. Contributions to this study were provided by several members of the Canadian Lunar Research Network at Western including: Drs. Bourassa, Tornabene, Pilles, and Morse, and PhD Candidates Hill and Tolometti.

1.3.1 Maturation Study Science Goals

The results of this study produced 4 distinct science goals for the proposed rover mission. (1) Lunar Chronology: to return lunar samples to the Earth in order to constrain the early bombardment history of the solar system, characterize the lunar crust, and constrain the thermal evolution of the Moon. The specific objectives are to acquire chemical data and return samples of: clast-poor impact melt rock, ejected impact melt rock, peak ring material, and material from secondary craters. (2) Impact cratering: acquire samples and in-situ measurements of impactites to provide insight into peak ring basin formation, impact melting, and shock metamorphic processes, and to understand the provenance of uplifted and excavated lunar crustal material. The objectives are to acquire mineralogical/chemical data and return samples of impactites, peak ring material, and impact melt material, and to investigate shock effects and characterize geology of secondary craters. (3) Volcanism: acquire samples and in-situ measurements of mare and pyroclastic volcanic deposits to provide a clear view of the overall history of lunar volcanism and its relation to the Moon's thermal and compositional evolution. The objectives are to acquire chemical data and return samples of pyroclastic and mare deposits, and other volcanic material. (4) Human lunar exploration: to provide essential information for future human activity on the Moon. The science objectives are to measure the radiation and surface thermal environments, and to create geologic and terrain maps of the area.

1.3.2 Proposed Instrumentation

A further goal of this study was to select the suite of payloads that would satisfy the aforementioned science goals/objectives for PHASR. Two mast-mounted instruments have been proposed: an Integrated Vision System (IVS) and a combined Raman/LIBS/Zoom Camera (e.g., Supercam on Mars 2020). The IVS combines a science camera (e.g., Pancam on ExoMars) with a LiDAR and a spectral imager in the 1000 nm to 2500 nm range. It would provide high resolution panoramic colour images, 3D mapping, and textural information and spectral data to interpret mineralogy. The Raman/LIBS/Zoom camera collects spot data to identify chemical composition of rocks and soil and can also be used to interpret mineralogy. A radiation detector and thermopile are two body-mounted instruments used to measure a broad spectrum of radiation and to measure the lunar surface temperature. PHASR would also have two instruments mounted to a robotic arm: a microscopic imager and an in-situ geochemical spectrometer (e.g. APXS). The microscopic imager would provide images of grain sizes and small-scale textural information. The in-situ contact spectrometer would analyze the chemical elements in rocks and soils to a higher fidelity than capable by the mast-mounted instruments. A set of sampling tools were also selected for the rover to cover the range of expected samples desired by the scientific community. The reference design for PHASR used for this study assumed that up to16 kg of sample material could be collected. A simple scoop device would be included to collect regolith and any loose rock fragments. A sieve would be implemented to also collect loose rock fragments and chips, but that can discard the regolith. Finally, a percussive chisel would be used to break off in-situ samples from larger boulders or outcrops to ensure the source of the sample and collect the appropriate context data.

1.3.3 Proposed Traverse Plan

In order to best address the science goals for the PHASR mission concept, a proposed traverse plan was created which covers ~85 km across the floor of Schrödinger Basin, the target for the proposed HERACLES mission. This proposed traverse is situated between the prominent pyroclastic vent and the interior wall of the Schrödinger peak ring. The main target of this sample traverse is the prominent pyroclastic deposit located on the central basin floor. This material was determined to be the highest priority target for a mission to Schrödinger due to the potential inclusion of lunar mantle materials and possible presence of volatile-rich materials. The proposed traverse plan begins with a 100 m diameter landing ellipse, centered at (140.071° E, 75.235° S). From this landing point the rover would traverse approximately 1.4 km toward the rim of a near-by well-preserved unnamed 0.9 km diameter impact crater. The fist planned stop features abundant boulders and soft regolith for sampling. The rocks here were protected from the effects of space weathering in the subsurface, until they were excavated by the 0.9 km crater. Thus these rocks represent relatively fresh material excavated from depth, providing further insight into the depth and composition of the pyroclastic deposit. The proposed traverse then proceeds across the basin floor along a prominent graben feature, toward the peak ring. Near the peak ring the traverse includes several proposed stops near boulder falls visible in high-resolution LRO-NAC (Narrow Angle Camera) images, that would allow the rover to sample uplifted peak ring material without having to ascent steep slopes. The planned traverse then continues a counter-clockwise loop back across the breadth of the prominent pyroclastic deposit toward the main volcanic vent. Finally, the rover would return all collected samples to the lander at the landing site for return to Earth and additional laboratory-based analysis.

2. Inter-team/International Collaborations

CLRN is proud to be home to several inter-team collaborations. Dr. Cloutis is a collaborator on the SSERVI team Toolbox for Resources and Exploration (TREX; PI Amanda Hendrix of PSI). Cloutis is also a member of two other SSERVI teams: RIS^{4}E (PI: Glotch) and CLASS (PI: Britt). Dr. Osinski is a collaborator on the FINESSE (PI: Heldmann), Inner Solar System Impact Processes (PI: Kring), and SEEED (PI: Pieters) teams. As part of the FINESSE team he continues to work on the samples collected from the West Clearwater Lake impact structure in 2014 and work with Co-I Hodges of dating of the impact event. Kring and Osinski are collaborating on the investigation of the hydrothermal system of the Chicxulub impact structure, Mexico. With Pieters, he is collaborating on a combined UV-Vis-NIR spectroscopy and shock metamorphic study of Apollo samples. Dr. Brown is a member of the CLASS team (PI: Dan Britt), where the focus is on modelling bolide impacts to estimate ground damage. Drs. Brown and Osinski are also collaborating with the SSERVI associate team in Australia (Bland – PI) on expansion of the Desert fireball network to a global network of fireball cameras. As part of this collaboration this group is field testing several DFN cameras in Canada for eventual deployment across the country to augment the planned global fireball observatory. Additionally, several CLRN team members are involved in international space exploration missions as detailed in the following sections.

2.1 Dr. Gordon Osinski – CSA / ESA / JAXA HERACLES Mission Concept

Drs. Osinski (Western University), Dr. Bouvier (Western University), Dr. Gellert (University of Guelph), Dr. Moores (York University), and Dr. Tornabene (Western University) are members of the joint European-Canadian-Japanese international Science Definition Team (iSDT) for the HERACLES mission concept. Osinski is Chair of the Site Selection and Science Scenario Group.

2.2 Dr. Catherine Neish – NASA LRO Mini-RF Co-Investigator

Dr. Neish of Western University is a co-investigator on the Lunar Reconnaissance Orbiter (LRO) Mini-Radio Frequency (RF) instrument. Dr. Neish has used radar data from the Mini-RF instrument in her research of impact craters and impact melt flows on the lunar surface. Dr. Neish's role as a co-investigator on an active mission instrument facilitates international and inter-group collaboration with members of the NASA LRO team.

2.3 Dr. Ed Cloutis – JAXA Selene-2 & CNSA Chang'e 3

Dr. Cloutis of the University of Winnipeg has been involved in several international collaboration efforts. Recently Dr. Cloutis has worked as the Science Principle Investigator for the Japan Aerospace Exploration Agency (JAXA) Selene-2 mission. While this mission has been canceled, components of the former orbiter, lander, and rover mission may likely be incorporated into new future international collaborations. Dr. Cloutis has also worked with the Chinese National Space Administration (CNSA) as a collaborator on the Chang'e 3 mission. Dr. Cloutis lent his expertise to the analysis and interpretation of spectroscopic data collected on the lunar surface by the Chang'e 3 lander and Yutu rover. Additionally, Dr. Cloutis has been involved in a joint Canadian Space Agency

(CSA) / European Space Agency (ESA) effort to develop a 12U cubesat for use in volatile detection in permanently shadowed regions of the lunar surface.

3. Public Engagement (including EPO) Report

CLRN has continued its long-standing tradition of working alongside the Western CPSX outreach program to engage young future scientist and the general public. Several of these outreach events and activities specifically feature the theme of lunar science and exploration. CLRN has also worked with the CPSX outreach program to develop several new and exciting outreach activities detailed below.

3.1 International Observe the Moon Night

On the evening of October 20, 2018 CLRN co-hosted an International Observe the Moon Night event along with the Centre for Planetary Science and Exploration (CPSX), Department of Physics & Astronomy, Western University Engineers Rocketry Society, London chapter of the Planetary Society, and the Royal Astronomical Society of Canada (RASC). The celebration was held at the Hume Cronyn Memorial Observatory on the campus of Western University in London Ontario and was attended by just over 100 members of the public. This event marked the ninth annual celebration of International Observe the Moon Night at Western. The event featured lunar observation through the observatory's main 10-inch refractor telescope as well as several smaller telescopes provided by RASC. The event also featured two talks by Western CPSX graduate students: "To the Moon and Back" by PhD candidate Tolometti, and "Titan – an Earth-like Moon with the Potential for Life" by PhD student Hedgepeth.

3.2 Space Academy

This year, in collaboration with the CPSX Summer Space Academy, CLRN developed a day of activities that focused on exploring the lunar surface. Hill, a PhD candidate with CPSX and a member of CLRN, developed a day activity that focused on using remote sensing to develop an exploration program on the lunar surface. First, students were introduced to remote sensing as a science, particularly focusing on how scientist use the electromagnetic spectrum to gain information from planetary surfaces. The students were then introduced to various datasets utilized to study the lunar surface include LRO-NAC (Narrow Angle Camera) and LRO-WAC (Wide Angle Camera) imagery, Chandrayaab-1 Moon Mineralogy Mapper data, and FeO and Th abundance datasets derived from the Clementine mission. By using the LRO Quickmap website and Google Moon software, students were then left to find areas of interest on the lunar surface. The students had to develop a mission plan for a sample return lander or rover mission. Students then presented their mission to the class highlighting the motivations and objectives they wanted to see achieved. Students identified several targets of interest including: exploring the far side, exploring the polar regions, investigating central uplifts, and investigating regions for their resource potential (mainly focusing on potential ice or the use of rare earth element within the KREEP Terrane).

3.3 Developing New Outreach Activities

CLRN also worked alongside CPSX Outreach to develop new Moon-focused learning activities utilizing state of the art immersive Virtual Reality (VR) technology. The new outreach activity employs the use of Oculus Rift VR headsets to project an immersive virtual model of the lunar surface. A user can look around and navigate the virtual camera around the digital terrain as if they were position on the lunar surface itself. The goal of this new activity is to provide a first-hand perspective of lunar surface exploration and to present the possibility of future lunar surface exploration in a new, exciting, and immersive way that leaves a memorable imprint on young future scientists.

4. Student / Early Career Participation

Undergraduate Students

1. Damla Alper, Western University, Earth Science & Planetary Science.

2. Victoria, Barlow, Western University, Earth Science & Planetary Science.

3. Stephanie Connell, University of Winnpieg, Geography & Planetary Science.

4. Matthew Cuddy, Red River College, Geography & Planetary Science.

5. Adrienne Iannicca, Western University, Earth Science & Planetary Science.

6. Krista Kubanek, University of Winnpieg, Geography & Planetary Science.

7. Jesse Kuik, University of Winnpieg, Geography & Planetary Science.

8. Jean-Paul, Marin, Western University, Earth Science & Planetary Science.

9. Alexis Parkinson, University of Winnpieg, Geography & Planetary Science.

10. Mary Ramirez, University of Winnpieg, Geography & Planetary Science.

11. Evan Stanish, University of Winnpieg, Geography & Planetary Science.

12. Nathalie Turenne, University of Winnpieg, Geography & Planetary Science.

Graduate Students

13. Erin, Gibbons, McGill University, Instrumentation and Extraterrestrial Biosignatures

14. Patrick, Hill, Western University, Lunar Impactites and Stable Isotope Geochemistry.

15. Cassandra, Marion, Western University, Impact Cratering and Impactites.

16. Jennifer, Newman, Western University, Impact Cratering.

17. Gavin, Tolometti, Western University, Geochemistry and Petrography of Lunar Impact Melts.

Postdoctoral Fellows

18. Zachary, Morse, Western University, Impact Cratering and Lunar Geomorphology.

19. Eric Pilles, Western University, Remote Sensing of Planetary Surfaces.

New Faculty Members

20. Melissa Battler, Mission Control Space Services Inc., Planetary Geology and Robotic Mission Simulation.

21. Matthew, Bourassa, Western University, Rover Systems Engineering.

22. Scot Bryson, Orbital Farm, Closed Loop Farming Systems.

23. Martin Connors, Athabasca University, Planetary Magnetospheres, Asteroid Dynamics, an Impact Cratering.

24. Michele, Faragalli, Mission Control Space Services Inc. and Carleton University, Robotics, Terramechanics, and Artificial Intelligence.

25. Ian Fichtenbaum, Bradford Space, Spacecraft Design, Integration, and Communication.

26. Raymond, Francis, University of Western Ontario & NASA JPL, Planetary Surface Robotics, Operations, and Autonomous Science.

27. Jean-Francois Hamel, NGC Aerospace, Navigation and Control Systems for Orbiters, Landers, and Rovers.

28. Alan Fine, Dalhousie University Faculty of Medicine, Space Health Systems Development and Implementation.

29. Ralf Gellert, University of Guelph, Rover Instrumentation.

30. Paul Giovanni Graham, OpenLuna Foundation, Lunar Mission Infrastructure and ISRU Potential.

31. Jacques Giroux, ABB Canada, Instrumentation and Space Defense.

32. Laurence Harris, York University, Space Health and Perceptual Issues in Low Gravity Environments.

33. Jonathan Kelly, University of Toronto, Planetary Rover Navigation.

34. Roman V. Kruzelecky, MPB Communications Inc., Remote Sensing and Lunar ISRU Processing.

35. Catherine Neish, Western University, Remote Sensing of Planetary Surfaces and Impact Cratering Processes.

36. Joan Saary, University of Toronto, Space Health and Effects of Radiation.

37. Gordon Sarty, University of Saskatchewan, Space Health Systems Development and Implementation.

38. Nathalie Sleno, Leap Biosystems Inc., Space Medicine and Health Systems.

39. Isaac Smith, York University, Martian and Lunar Surface Ice.

40. Warren Soh, Magellan Aerospace, Lunar Rover Mobility, Power, and Thermal Systems.

41. Gordon Walker, University of British Columbia (Retired), Remote Sensing and Telescopic Spectroscopy.

42. Ruth Wilkins, Health Canada, Space Health and Effects of Radiation.

5. Mission Involvement

1. HERACLES (Mission Concept), Dr. Gordon Osinski, Chair, international Science Definition Team (iSDT) Site Selection and Science Scenario Group.

2. Lunar Reconnaissance Orbiter, Dr. Catherine Neish, Mini-RF, Co-investigator

3. Lunar Reconnaissance Orbiter, Dr. Ed Cloutis, Lunar Reconnaissance Orbiter Camera, Co-investigator

4. Super-SWEPT, Name, Instrument/experiment, Role

5. SWEPT-2, Name, Instrument/experiment, Role

6. VMMO lunar 12u Cubesat, Dr. Roman V Kruzelecky, Co-investigator

7. VMMO lunar 12u Cubesat, Dr. Ed Cloutis, Co-investigator

8. Selene-2 (JAXA), Dr. Ed Cloutis, Co-investigator

9. Chang’e 3, Dr. Ed Cloutis, Collaborator

10. OpenLuna (Mission Concept), Paul Graham, Project Director

11. CanMoon CSA Lunar Analogue Mission, Dr. Gordon Osinski, Co-PI

12. CanMoon CSA Lunar Analogue Mission, Dr. Ed Cloutis, Co-PI

13. CanMoon CSA Lunar Analogue Mission, Dr. Matthew Bourassa, Project Manager and Field Lead

14. CanMoon CSA Lunar Analogue Mission, Cassandra Marion, Mission Operations Manager

15. CanMoon CSA Lunar Analogue Mission, Dr. Eric Pilles, Simulation Assurance Manager

16. CanMoon CSA Lunar Analogue Mission, Jen Newman, Planning Lead

17. CanMoon CSA Lunar Analogue Mission, Dr. Zachary Morse, Science Lead

1. United Kingdom Project Report

https://www.facebook.com/uksservinode/

UK-SSERVI-NODE@JISCMAIL.AC.UK

Executive Summary

The UK-node of SSERVI is a voluntary group of individuals drawn from academia, industry and government departments in the UK who are passionate about lunar science and exploration. At present the group has over 100 members representing 25 institutions from across the UK. UK-SSERVI members are involved in a multitude of lunar science and exploration activities including world-leading research on Moon rocks and soil samples, returned by the Apollo and Luna missions, on lunar meteorites, remote sensing studies of the Moon, in-situ resource utilisation studies, and actively contributing to various upcoming lunar missions by providing payload instruments and scientific expertise. Another important activity of UK-SSERVI node involves dissemination of information and engagement of wider stakeholders (e.g. students, public, policy makers) in sharing the excitement of lunar science and exploration through various means (e.g., European Lunar Symposia, Virtual Microscope, Public engagement activities, media interviews etc.).

Below are a selection of highlights from the UK-SSERVI node for the year 2018.

Department of Earth and Planetary Sciences at Birkbeck, University of London

Key staff: Ian Crawford, Sam Halim

Sam Halim started his PhD research at Birkbeck in October 2018, investigating the survivability of meteorite projectiles impacting the Moon. There are two aspects: (i) survivability of terrestrial meteorites, with a view to assessing the survivability of biomarkers from the early Earth being preserved on the Moon; and (ii) survivability of carbonaceous impactors to assess the extent to which these may provide local enhancements of C and N on the lunar surface that might be useful resources for future exploration. Already this work has led to a 2019 LPSC abstract: https://www.hou.usra.edu/meetings/lpsc2019/pdf/1816.pdf. Sam is supervised by Ian Crawford (Birkbeck), Gareth Collins (Imperial) and Katherine Joy (Manchester).

Outreach:

In 2018, Ian gave 18 public talks on topics relating to

lunar exploration, astrobiology, and space exploration.

Relevant publications (2018):

• Schulze-Makuch, D., Crawford, I.A. (2018) 'Was there an early habitability window for Earth's Moon?', Astrobiology, 18, 985-988.

• Cousins, C.R., Fogel, M., Bowden, R., Crawford, I.A., Boyce, A., Cockell, C.S., Gunn, M. (2018) 'Biogeochemical probing of microbial communities in a basalt-hosted hot spring at Kverkfjöll volcano, Iceland', Geobiology, 16, 507-521.

• Crawford, I.A. (2018) 'Widening Perspectives: The Intellectual and Social Benefits of Astrobiology (Regardless of Whether Extraterrestrial Life is Discovered or Not)', Internat. J. Astrobiology, 17, 57-60.

Lancaster University, Lancaster Environment Centre

Key staff: Prof Lionel Wilson

Lunar research at Lancaster has continued to involve extensive collaboration with Brown University. We are working toward a detailed analysis of processes controlling volcanism on the Moon, from mantle melting to the various kinds of intrusive and extrusive features. Of particular interest this year has been the predicted variation with time in magma discharge rate (from ~106 to ~104 m3 s-1) and explosive eruption style (changing from hawaiian to strombolian) during the eruptions that formed major lava flows in the lunar maria (Wilson & Head, 2018a). At the other extreme, quite small-volume surface eruptions were commonly linked with the consequences of intrusions into the breccia lenses beneath impact crater (Wilson & Head, 2018b). The vacuum environment causes the vesicularity of lava on the Moon to be very different from that on Earth with consequences for surface morphology and apparent age of volcanic features (Qiao et al., 2018). We have a number of other papers on these issues in press or submitted.

2018 Journal Publications:

Qiao, L., Head, J.W., Xiao, L., Wilson, L. & Dufek, J.D. (2018) The role of substrate characteristics in producing anomalously young crater retention ages in volcanic deposits on the Moon: Morphology, topography, subresolution roughness and mode of emplacement of the Sosigenes lunar irregular mare patch. Meteoritics and Planetary Science 53(4), 778-812, doi:10.1111/maps.13003

Wilson, L. & Head, J.W. (2018a) Controls on lunar basaltic volcanic eruption structure and morphology: gas release patterns in sequential eruption phases. Geophysical Research Letters 45(12), 5852-5859, doi:10.1029/2018GL078327.

Wilson, L. & Head, J.W. (2018b) Lunar floor-fractured craters: modes of dike and sill emplacement and implications of gas production and intrusion cooling on surface morphology and structure. Icarus 305,105-122, doi:10.1016/j.icarus.2017.12.030

2018 LPSC abstracts:

Wilson, L. & Head, J.W. (2018) Lunar basaltic volcanic eruptions: gas release patterns and variations in lava vesicularity: 1. Lava ponds, shield volcanoes, foams, and Irregular Mare Patch (IMP) morphology. Lunar planet. Sci. XLIX, #1325.

Ji, J.Z., Head, J.W., Wilson, L., Pieters, C.M., Cassanelli, J. & Liu, J.Z. (2018) Impact basin melt seas: morphologic/morphometric evidence of geometry and cooling behavior from the lunar Orientale Basin Maunder Formation. Lunar planet. Sci. XLIX, #2520.

Wilson, L. & Head, J.W. (2018) Lunar basaltic volcanic eruptions: gas release patterns and variations in lava vesicularity: 2. Fissures, mare flows, and Ring Moat Dome Structure (RMDS) morphology. Lunar planet. Sci. XLIX, #1326.

Qiao, L., Head, J.W., Wilson, L. & Ling, Z. (2018) Lunar Irregular Mare Patch (IMP) sub-types: Linking their origin through hybrid relationships displayed at Cauchy 5 small shield volcano. Lunar planet. Sci. XLIX, #1390.

Qiao, L., Head, J.W., Ling, Z., Wilson, L., Xiao, L. & Dufek, J. (2018) A comprehensive geological characterization of the Ina Volcano summit pit crater on the Moon: extrusions of waning-stage lava lake magmatic foams produces anomalously young crater retention age. Lunar planet. Sci. XLIX, #1392.

Zhang, F., Wöhler, C., Head, J.W., Bugiolacchi, R., Wilson, L. & Grumpe, A. (2018) Ring-Moat Dome Structures (RMDSs) in the lunar maria: further statistical and morphological characterization. Lunar planet. Sci. XLIX, #1374.

Candidate mounds of very vesicular lava foam extruded from beneath the crust of a lava lake on the floor of the Sosigenes depression on the Moon. Figure 1 from Qiao et al. (2018).

The Open University

Group members: Feargus Abernathy, Mahesh Anand, James Bowen,Ana Cernok, Kevin Dewar, Samantha Faircloth, Ian Franchi, Monica Grady, Richard Greenwood, Tara Hayden, Martyna Hodges, Yachen Jiang, Pete Landsberg, M Leese, Vibha Levin-Prabhu, Sungwoo Lim, Geraint Morgan, Andrew Morse, James Mortimer, Judith Pillinger, David Rothery, Hannah Sarjeant, Ian Sheard, Simon Sheridan, Vibha Srivastava, Alice Stephant, Susanne Schwenzer, Andrew Tindle, Sasha Verchovsky, Ian Wright

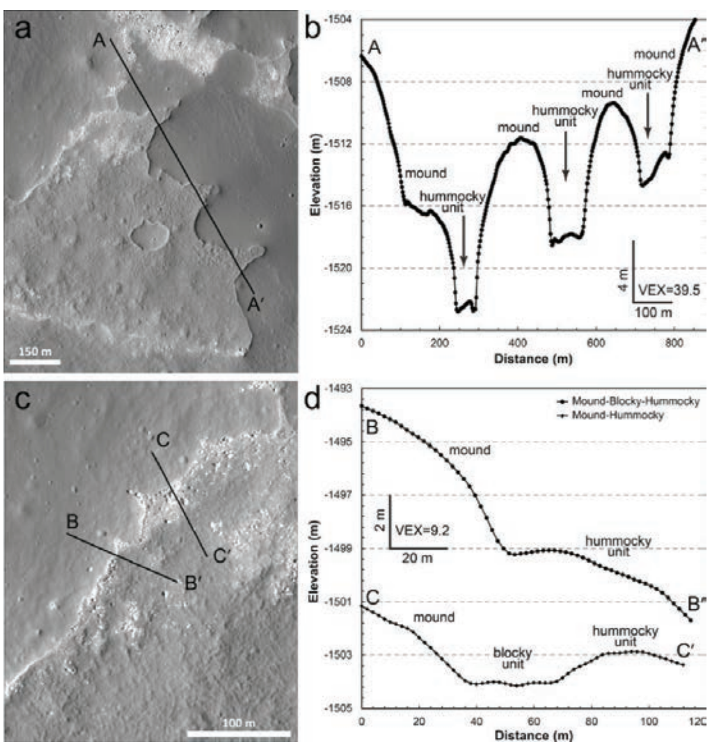


Fig. 1. (a) Contacts between mound and hummocky units near the center of Sosigenes, LROC NAC frame M177508146, 0.48 m/pixel. (b) Topographic profile across the mound and hummocky units shown in (a). Elevation is derived from NAC DTM data, 2 m/pixel. (c) Portion of LROC NAC frame M177508146R shows the contact between the mound and hummocky units, with some blocky materials present along the contact. (d) A NAC DTM-derived profile shows the topographic relief from mound, blocky to hummocky units (C-C′). For comparison, a profile directly crossing from the mound to the hummocky unit is also illustrated (B-B′).

Members of the Open University lunar group are currently involved in the following lunar activities:

1. PROSPECT package on ESA-Roscosmos Luna 27 mission

The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) is in development by Leonardo S.p.A. (Italy) under contract to the European Space Agency (ESA) for application at the lunar surface as part of international lunar exploration missions in the coming decade, including the Russian Luna-27 mission planned for 2024. PROSPECT will search for and characterize volatiles in the lunar polar regions to answer science questions and investigate the viability of these volatiles as resources.

The Open University is leading the development of ProSPA, the Sample Processing and Analysis element of PROSPECT, supported by RAL Space and Airbus Defence and Space (UK), Max Planck Institute for Solar System Research and Technical University of Munich (Germany) and Media Lario Technologies (Italy). ProSPA will receive samples extracted from the lunar sub-surface by the ProSEED drill and perform a suite of analytical experiments aimed at understanding the nature, source, evolution and utility of the volatiles therein. These functions are distributed across two physical units – a Solids Inlet System (SIS) comprising a series of single-use sample ovens on a rotary carousel together with a sample imager, and a miniature chemical analysis laboratory incorporating two mass spectrometers and associated ancillary and control systems. The science output is anticipated to be the identity, quantity and isotopic composition of volatiles as a function of depth within the first 1.2 m of the lunar surface. ProSPA completed Phase B+ and we are now embarking on Phase C, D, E and F activities.

2. Lunar science and exploration

We continue to build upon our strong track-record in lunar samples research by expanding our capability in making in-situ and bulk measurements for abundances and isotopic composition of H, C, N and other associated volatiles in lunar samples using NanoSIMS and stable mass spectrometric techniques. We welcomed two new PhD students in our group (Tara Hayden and Yachen Jiang) to work on lunar volatiles and ISRU projects, resp. We said good bye to Ana Cernok who completed her Marie Curie fellowship and moved to a research position at the Royal Ontario Museum, Canada. Ana's work at the OU was focussed on understanding the effect of shock on distribution of volatiles in lunar samples. PhD research by two of our students, Hannah Sargeant and Vibha Levin Prabhu are bridging the science and exploration topics by undertaking research in the areas of ISRU (oxygen production by ilmenite reduction and evaluating the potential of microwave sintering of lunar soil for 3D printing on the Moon, respectively). We continued our research funded by the UK Space Agency to analyse lunar soils for their volatile inventory in order to inform developments of instruments for lunar landed missions. Further lunar exploration related activities include Anand and Wright's role as members of ESA's PROSPECT user group.

Dr Mahesh Anand Co-chaired the 6th European Lunar Symposium (ELS) which was held at the Les Abattoirs, Toulouse, France, May 13-16, 2018. The program included a total of 125 presentations made over two days (68 orals + 57 posters). Over 150 participants, representing the global community of lunar scientists and explorers, made this a yet another successful ELS.

3. Scientific community engagement

Dr Mahesh Anand Co-chaired the 6th European Lunar Symposium (ELS) which was held at the Les Abattoirs, Toulouse, France, May 13-16, 2018. The program included a total of 125 presentations made over two days (68 orals + 57 posters). Over 150 participants, representing the global community of lunar scientists and explorers, made this a yet another successful ELS.

4. Public education and dissemination of knowledge

The Open University Moons MOOC, presented in partnership with FutureLearn https://www.futurelearn.com/courses/moons was presented for the 8th and 9th times in 2018, with start dates in February and October. A similar pattern is being followed in 2019. This offers free online learning spread over 8 weeks at a notional 3 hours of study per week. A few thousand learners participate in each presentation, and the keenest have formed a Facebook group https://www.facebook.com/groups/flmoons/ that has >700 members.

5. Virtual Microscope

In 2018, we continued our work on digitising Apollo samples as part of the collaborative project between SSERVI and the Open University. Work on over 550 Apollo thin sections have now been completed. The VM for Apollo rocks can be accessed at **http://www.virtualmicroscope.org/collections/apollo**

6. OU Moon Night: A celebration of the 45th Anniversary of Apollo 17 landing

7th December 2018, Open University, Milton Keynes, United Kingdom

We held our second annual Moon Night event on Friday,

7 Dec 2018 to showcase our research in lunar science and exploration with the local members of the public and staff members and families of the OU. About 200 people participated in a range of activities that included handling Moon rocks and meteorites, Virtual Reality involving driving a rover on the lunar surface, taking a voyage to the Moon in an inflatable planetarium, and demonstration of 3D printing which is being investigated as a future technology for building a future lunar base.

The participants were also treated to two live music performances by world renowned trumpeter, Yazz Ahmed, who collaborated with Dr Mahesh Anand to develop a piece of music which communicated the key themes of lunar science research being carried out at the OU.

The event closed with a special guest lecture by Dr Ioannis Baziotis from the Agricultural University of Athens who recounted his dream and personal journey of taking

On 20th of July 1969, Neil Armstrong was the first human to set foot on the Moon, followed by Edwin "Buzz" Aldrin.
Lunar regolith
9
Footprint

Wireless Zone

Wireless Zone

part in a NASA-funded international expedition to search for meteorites in Antarctica.

This year, we also trialled live casting of the Moon Night via Stadium and STEM's Facebook page to reach our OU students as well as the wider global community. Our Facebook live videos proved to be very popular- in total we had 20 videos spanning the whole event. We reached over 15,000 people and had nearly 5k views! The event page used to promote the event reached over 34 000 people. All videos will also be put on the OUSTEM YouTube's page.

Please reserve the date for the next Moon Night event in 2019, which will take place on Friday, 6 Dec during the 50th anniversary year celebrations for the Apollo 11 Moon Landing as well as that of the OU's founding. We look forward to seeing you then!

7. *Publications:*

• Barnes, J.J., Franchi, I.A., McCubbin, F.M., Anand, M. (2018) Multiple volatile reservoirs in the lunar interior revealed by the isotopic composition of chlorine in lunar basalts. Geochim Cosmochim Ac https://doi.org/10.1016/j.gca.2018.12.032

• Snape, J.F., Curran, N.M., Whitehouse, M.J., Nemchin, A.A., Joy, K.H., Hopkinson, T., Anand, M., Bellucci, J.J., Kenny, G.G. (2018) Ancient volcanism on the Moon: Insights from Pb isotopes in the MIL 13317 and Kalahari 009 lunar meteorites. Earth Planet Sc Lett 502, 84-95.

• Potts, N.J., Barnes, J.J., Tartèse, R., Franchi, I., Anand, M. (2018). Chlorine isotopic compositions of apatite in Apollo 14 rocks: Evidence for widespread vapor-phase metasomatism on the lunar nearside ~4 billion years ago. Geochim Cosmochim Ac 230, 46-59.

• Greenwood, R.C., Barrat, J-A., Miller, M.F., Anand, M., Dauphas, N., Franchi, I.A., Sillard, P., Starkey, N.A. (2018). Oxygen isotopic evidence for accretion of Earth's water before a high-energy Moon-forming giant impact. Sci Adv, 4(3), article no. eaao5928.

8. *Communication:*

1. Anand M. (2018) The Continuing Legacy and Major Scientific Advances Enabled By Returned Lunar Samples.

2nd Mars Sample Return Conference, Berlin, Germany (25-27 April, 2018) [#6118].

2. Greenwood, R. C.; Barrat, J.-A.; Miller, M. F.; Anand, M.; Dauphas, N.; Franchi, I. A.; Sillard, P.; Starkey, N. A. (2018) Oxygen Isotope Evidence for a High-Energy Moon-Forming Giant Impact and Early Delivery of Earth's Water. 81st Annual Meeting of the Meteoritical Society, held 22-27 July 2018 in Moscow, Russia. LPI Contribution No. 2067, 2018, id.6345

3. Černok, A.; White, L.; Darling, J.; Dunlop, J.; Fougerouse, D.; Rickard, W.; Reddy, S.; Saxey, D.; Quadir, Z.; Zhao, X.; Franchi, I.; Anand, M. (2018) Sub-Micron Chemical and Structural Complexities Within Shocked Lunar Apatite. 81st Annual Meeting of the Meteoritical Society, held 22-27 July 2018 in Moscow, Russia. LPI Contribution No. 2067, 2018, id.6292.

4. McCubbin, F. M.; Liu, Y.; Barnes, J. J.; Anand, M.; Boyce, J. W.; Burney, D.; Day, J. M. D.; Elardo, S. M.; Hui, H.; Klima, R. L.; Magna, T.; Ni, P.; Steenstra, E.; Tartèse, R.; Vander Kaaden, K. E. (2018) Endogenous Lunar Volatiles. New Views of the Moon 2 - Asia, Proceedings of the conference held 18-20 April, 2018 in Fukushima, Japan. LPI Contribution No. 2070, 2018, id.6030.

5. Barber, S. J.; Wright, I. P.; Abernethy, F.; Anand, M.; Dewar, K. R.; Hodges, M.; Landsberg, P.; Leese, M. R.; Morgan, G. H.; Morse, A. D.; Mortimer, J.; Sargeant, H. M.; Sheard, I.; Sheridan, S.; Verchovsky, A.; Goesmann, F.; Howe, C.; Morse, T.; Lillywhite, N.; Quinn, A.; Missaglia, N.; Pedrali, M.; Reiss, P.; Rizzi, F.; Rusconi, A.; Savoia, M.; Zamboni, A.; Merrifield, J. A.; Gibson, E. K.; Carpenter, J.; Fisackerly, R.; Houdou, B.; Sefton-Nash, E.; Trautner, R. (2018) ProSPA: Analysis of Lunar Polar Volatiles and ISRU Demonstration on the Moon. 49th Lunar and Planetary Science Conference 19-23 March, 2018, held at The Woodlands, Texas LPI Contribution No. 2083, id.2172.

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7. Gibson, E. K.; Tindle, A. G.; Schwenzer, S. P.; Kelley, S. P.; Morgan, G. H.; Anand, M.; Pillinger, J. M. (2018) The Apollo Virtual Microscope Collection: Lunar Mineralogy and Petrology of Apollo 11, 12, 14, 15, and 16 Rocks. 49th Lunar and Planetary Science Conference 19-23 March, 2018, held at The Woodlands, Texas LPI Contribution No. 2083, id.1087.

8. Lim, S.; Levin Prabhu, V.; Anand, M.; Bowen, J.; Morse, A. and Holland, A. (2018). Numerical modelling of microwave sintering of lunar simulants under near lunar atmospheric condition. In: European Lunar Symposium (ELS) 2018, 13-16 May 2018, Toulouse, France.

9. Prabhu, V. L.; Lim, S.; Bowen, J.; Cowley, A.; Katrib, J.; Dodds, C. and Anand, M. (2018). Microwave Heating of Lunar Simulants JSC-1A and NU-LHT-3M: Experimental And Theoretical Analysis. In: European Lunar Symposium (ELS), 13-16 May 2018, Toulouse, France.

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11. Anand, M., Tindle, A.G., Schwenzer, S.P., Kelley, S.P., Gibson, E.K. (2018) The lunar meteorite virtual microscope collection. 6th European Lunar Symposium, May, 13-16, 2018, Toulouse, France.

12. S. J. Barber, I. P. Wright, F. Abernethy, M. Anand, K. R. Dewar, M. Hodges, P. Landsberg, M. R. Leese, G. H. Morgan, A. D. Morse, J. Mortimer, H. M. Sargeant, I. Sheard, S. Sheridan, A. Verchovsky, F. Goesmann, C. Howe, T. Morse, N. Lillywhite, A. Quinn, N. Missaglia, M. Pedrali, P. Reiss, F. Rizzi, A. Rusconi, M. Savoia, A. Zamboni, J. A. Merrifield, E. K. Gibson Jr., J. Carpenter, R. Fisackerly, B. Houdou, E. Sefton-Nash and R. Trautner (2018) PROSPA: AN INSTRUMENT FOR LUNAR POLAR VOLATILES PROSPECTING AND IN SITU RESOURCE UTILIZATION PROOF OF CONCEPT. 6th European Lunar Symposium, May, 13-16, 2018, Toulouse, France.

13. A. Černok, X. Zhao, J. Darling, L. White, J.Dunlop, I. A. Franchi and M. Anand (2018) ABUNDANCE AND H ISOTOPIC COMPOSITION OF WATER IN SHOCKED LUNAR

APATITE FROM MG-SUITE ROCKS. 6th European Lunar Symposium, May, 13-16, 2018, Toulouse, France.

14. A. Černok, J. Darling, L. White, J.Dunlop, and M. Anand (2018) SHOCK-INDUCED MICROTEXTURES IN LUNAR APATITE AND MERRILLITE. 6th European Lunar Symposium, May, 13-16, 2018, Toulouse, France.

15. R. C. Greenwood, J-A Barrat, M. F. Miller, M. Anand, N. Dauphas, I. A. Franchi, P. Sillard, N. A. Starkey (2018) OXYGEN ISOTOPE EVIDENCE FOR A HIGH-ENERGY MOON-FORMING GIANT IMPACT AND EARLY DELIVERY OF EARTH'S WATER. 6th European Lunar Symposium, May, 13-16, 2018, Toulouse, France.

16. H.M. Sargeant, F. Abernethy, S. J. Barber, I. P. Wright, S. Sheridan, P. Landsberg, A. D. Morse, M. Anand and P. Reiss, (2018) HYDROGEN REDUCTION OF ILMENITE IN A STATIC SYSTEM FOR A LUNAR ISRU DEMONSTRATION. 6th European Lunar Symposium, May, 13-16, 2018, Toulouse, France.

Lunar Science in the Isotope Geochemistry and Cosmochemistry Group, University of Manchester

Group members involved with lunar science: Rickbir Bahia, Sam Bell, Ray Burgess, Patricia Clay, Sarah Crowther, Jamie Gilmour, Vera Fernandes, Margaret Hartley, Tom Harvey, Katherine Joy, Gunter Just, Marissa Lo, John Pernet-Fisher, Fran McDonald, Romain Tartèse. Visitors: Nian Wang

• Ongoing lunar sample analysis activities: Noble gas analysis of Apollo ferroan anorthosites are currently taking place at the University of Manchester to investigate lunar highlands geological records. Halogen concentrations of melt inclusions are being analysed using NI-NGMS (neutron irradiation noble gas mass spectrometry) techniques to investigate the volatile abundances of volcanic source regions. Water and volatile (abundances & isotopic compositions) are also being investigated in situ using secondary ion mass spectrometry (TOF-SIMS and NanoSIMS). Plumbing system processes of mare volcanics are being investigated through analysis of crystal size distributions, textures and compositions. Chemical studies of lunar meteorites have shed new light on current lunar crust formation hypotheses. Analysis of zircons using xenon isotopes are helping to understand impact processing of ancient magmatic deposits. Shock studies of lunar samples are being investigated using integrated ESEM, FTIR, and CL imaging techniques.

• Lunar science mission activities: Group members Tartèse and Joy involved with the ESA PROSPECT user group. Tartese is involved in ESA-CNSA Joint lab for sample analysis initiative.

• Public engagement: Group members publicise their research outputs on the group blog at https://earthandsolarsystem.wordpress.com/ and have been involved with public engagement events discussing lunar science at the Museum of Manchester, Jodrell Bank radiotelescope visitor centre at the Bluedot music festival and the Museum of Science and Industry.

• School of Earth and Environmental Sciences hosted the UK SSERVI network meeting. Many of us participated in the ESA Workshop: towards the use of lunar resources and the China-Europe workshop on lunar exploration.

Lunar science papers Jan - Dec 2018

Potts N.J, Barnes J.J, Tartèse R., Franchi I.A., Anand M. (2018) Chlorine isotopic compositions of apatite in Apollo 14 rocks: Evidence for widespread vapor-phase metasomatism on the lunar nearside ~4 billion years ago. Geochimica et Cosmochimica Acta 230, 46-59.

Snape J.F., Curran N. M., Whitehouse M. J., Nemchin A. A., Joy K. H., Hopkinson T., Anand M., Bellucci J. J., Kenny G. G. (2018) Ancient volcanism on the Moon: Insights from Pb isotopes in the MIL 13317 and Kalahari 009 lunar meteorites. Earth and Planetary Science Letters. In Press. Volume 502, Pages 84-95. DOI.org/10.1016/j.epsl.2018.08.035

Zeng X., Joy K. H.. Li S., Pernet-Fisher J. F., Li X ., Martin D. J.P., Li Y., Wang S. (2018) Multiple lithic clasts in lunar breccia Northwest Africa 7948 and implication for the lithologic components of lunar crust.Meteoritics and Planetary Science DOI: 10.1111/maps.13049

Communications

Tartèse, R. (2018) Recent advances and future challenges in lunar geochronology. CNSA (LESEC) - ESA Lunar Science Workshop 2018, Amsterdam, The Netherlands (16-18/07/18).

Tartèse, R. (2018) High resolution in situ dating of planetary materials. ISSI-Europlanet Workshop "Role of sample return missions in addressing outstanding science questions in the field of Planetary Sciences", Bern, Switzerland (5-9/02/18).

Martin, D.J.P., Joy, K.H., Morlok, A., Bagshaw, H., Wogelius, R.A. & Hiesinger, H. (2018) Modal Mineralogy and Maturity Estimates of Apollo 14, 15 and 16 Soils using FTIR and QUEMSCAN Techniques, Abstract #2123, 49th Lunar and Planetary Science Conference.

Martin, D.J.P., Leiva, A., Bell. S.K., Pernet-Fisher, J.F., Joy, K.H., Morlok, A., Wogelius, R.A. & Hiesinger, H. (2018) Investigating the Orientation of Minerals using FTIR Microspectroscopy, Abstract #2138, 49th Lunar and Planetary Science Conference.

Morlok, A., Hamann, C., Martin, D.J.P., Joy, K.H., Wogelius, R., Weber I., Stojic, A., Hiesinger, H. & Helbert, J. (2018) Mid-Infraded Spectroscopy of Laser-Produced Impact Melts, Abstract #2118, 49th Lunar and Planetary Science Conference.

Pernet-Fisher, J.F. & Joy, K.H. (2018) Noble-Gas Isotope Systematice of Lunar Anorthosites: Hunting for Indigenous Signatures, Abstract #1951, 49th Lunar and Planetary Science Conference.

Weber, I., Morlok, A., Grund, T., Bauch, K.E., Hiesinger, H., Stojic, A., Grumpe, A., Wöhler, C., Klemme, S., Sohn, M., Martin, D.J.P. & Joy, K.H. (2018) A Mid-Infrared Reflectance Database in Preparation for Space Missions, Abstract #1430, 49th Lunar and Planetary Science Conference.

S. K. Bell, M. E. Hartley, K. H. Joy, and J. F. Pernet-Fisher (2018) Understanding the Apollo 15 magmatic plumbing system using crystal size distribution analysis. European Lunar Symposium 2018, Abstract #84.

K. L. Donaldson Hanna, D. J. P. Martin, K. H. Joy, J. J. Gillis-Davis, J. D. Carpenter, E. Sefton-Nash, and N. E. Bowles (2018) Update on the characterization of lunar highlands regolith simulants in preparation for drilling and sampling into the polar regolith by ESA's prospect package. European Lunar Symposium 2018, Abstract #80.

J. Lasue , O. Gasnault , P. Pinet , P. Y. Meslin , K. H. Joy , O. Forni , S. Maurice , S. Chevrel , S. M. Clegg , D. T. Vaniman , R. C. Wiens (2018) Laser-induced breakdown spectroscopy (LIBS): A technique for lunar exploration. European Lunar Symposium 2018, Abstract #82.

1. Germany Project Report

Summary of the German Space Mission Activities by DLR

The German Aerospace Center (DLR) is the national aeronautics and space research center of the Federal Republic of Germany. Its extensive research and development work in aeronautics, space, energy, transport, security and digitalization is integrated into national and international cooperative ventures. In addition to its own research, as Germany's space agency, DLR has been given responsibility by the federal government for the planning and implementation of the German space programme. DLR is also the umbrella organization for one of the nation's largest project management agencies.

DLR has approximately 8000 employees at 20 locations in Germany: Cologne (headquarters), Augsburg, Berlin, Bonn, Braunschweig, Bremen, Bremerhaven, Dresden, Goettingen, Hamburg, Jena, Juelich, Lampoldshausen, Neustrelitz, Oberpfaffenhofen, Oldenburg, Stade, Stuttgart, Trauen, and Weilheim. DLR also has offices in Brussels, Paris, Tokyo and Washington D.C.

DLR's mission comprises the exploration of Earth and the Solar System and research for protecting the environment. This includes the development of environment-friendly technologies for energy supply and future mobility, as well as for communications and security. DLR's re- search portfolio ranges from fundamental research to the development of products for tomorrow. In this way, DLR contributes the scientific and technical expertise that it has acquired to the enhancement of Germany as a location for industry and technology. DLR operates major research facilities for its own projects and as a service for clients and partners. It also fosters the development of the next generation of researchers, provides expert advisory services to government and is a driving force in the regions where its facilities are located.

Global view of Mars extending from the North Pole (right) and the Northern Lowlands, across the large Tharsis volcanoes (center), to the equatorial graben system Valles Marineris (left). In addition to these surface features, thin clouds can be seen in the Martian atmosphere. This image was taken by the HRSC from a much higher orbital position than its usual images of the Martian surface. Image: ESA/DR/FU Berlin CC BY-SA 3.0 IGO

The German solar system exploration and research activities focus on origins and evolution of our solar system as well as by investigating and comparing with other planetary systems by observation of the Sun and its interaction with the Solar System and by the examination of fundamental physics laws. We have been exploring the solar system with a large number of missions and we will continue to do so, along with our exoplanet missions, as we understand that exploring the solar system and the galaxy is of outmost importance for understanding humanity's place in the universe. Germany is contributing to solar system and extrasolar research by investigating planets and dwarf planets, their moons, asteroids and comets and their significance for life by comparing the solar system to other planetary systems using the best tools of geosciences and astronomy. Therefore, Germany develops instruments, data processing methods and physical models as contribution to international space missions. The activities are conducted within cooperation that are complementary to the ESA Science Program as well as worldwide cooperation with main partners in the USA, France, Sweden, Norway, Italy, United Kingdom, Japan, and Spain. Cooperation range from Col-contributions to PI-experiments.

German solar system exploration and research activities are related to the following missions:

Mars Express was the first 'flexible' mission of ESA's long-term science exploration programme. The spacecraft was launched on 2 June 2003 and arrived on 25 December 2003 with the successful or- bit insertion. With its complement of seven instruments, Mars Express was de- signed to study all aspects of the Mars, including its atmosphere and climate, and the mineralogy and geology of the surface and subsurface. Since beginning science operations in 2004, the durable orbiter has given scientists an entirely new view of Earth's intriguing neighbor. The High Resolution Stereo Camera (HRSC) is designed to simultaneously map the morphology, topography, structure and geologic context of the surface of Mars as well as atmospheric phenomena. The HRSC directly addresses two of the main scientific goals of the Mars Express mission: High-resolution three-dimensional photogeological surface exploration and the investigation of surface-atmosphere interactions over time; and significantly supports: the study of atmospheric phenomena by multi-angle coverage and limb sounding as well as multispectral mapping by providing high-resolution three-dimensional color context information. In addition, the stereoscopic imagery will especially characterize landing sites and their geologic context. The HRSC surface resolution and the digital terrain models bridge the gap in scales between highest ground resolution images (e.g., HiRISE) and global coverage observations (e.g., Viking). The high-resolution image data, in stereo and color, form the basis for the global mapping of Mars and the creation of digital terrain models that reveal the planet's topography. The camera has pro- vided coverage of 80 percent of the Martian surface at high resolution (better than 20 meters per pixel). The science team consist of 52 co-investigators from 34 institutions and 11 countries including US universities and organization.


ESA's Trace Gas Orbiter (TGO) and ExoMars Rover Rosalind Franklin. Image: ESA/ATG medialab

ESA's **ExoMars** mission is a two-part project to search for evidence of life on Mars. The first part, launched in 2016, placed in- to Mars orbit and released the Schiaparelli technology demonstration lander (which crashed). The second part is planned to launch in 2020 and to land an ExoMars rover on the surface, that is expected to operate on the surface into 2022 or be- yond. The scientific objectives of the ExoMars rover are to answer several key questions in the search for life on Mars including search for past life on Mars, investigation of how the Martian water and geochemical environment varies and demonstration of the technologies for a future sample return mission. The ExoMars rover will be equipped with a drill to collect material from outcrops and at depth down to 2 m. This subsurface sampling capability will provide the best chance to gain access to chemical biosignatures. PanCam a UK/ German camera system will establish the surface geological and morphological con- text for the mission, working in collaboration with other instruments. The design of PanCam which includes a stereo pair of Wide Angle Cameras (WACs), each of which has an 11-position filter wheel and a High-Resolution Camera (HRC) for investigations of rock texture at a distance and drill samples. PanCam also includes a calibration target mounted on the rover deck for radiometric calibration, fiducial markers for geometric calibration, and a rover inspection mirror. ESA selected Oxia Planum at 18.20°N, 335.45°E as favored landing site selection. DLR is, besides of the HRC contribution, as part of its Co-I- ships responsible for defining camera observation sequences and support operations as well as for assigning high precision environment maps including digital terrain models, geological context and spectral analysis of rocks and samples. The operational and scientific tasks as for ExoMars are also part of contributions to the Mastcam-Z instrument of the NASA **Mars 2020** mission.

NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport **(InSight)** mission to Mars was launched on May 5th, 2018 and landed in Homestead Hollow in the Elysium Region on November 26th, 2018. InSight is the first geophysical observatory on Mars and will investigate the martian interior using its two primary instruments: The CNES built the seismometer SEIS and the DLR built the Heat Flow and Physical Properties Package HP3. The lander is also equipped with a suite of ancillary sensors to measure winds, atmospheric temperatures, magnetic fields, and surface temperatures. The latter is determined using the HP3 radiometer. The main scientific questions addressed by the InSight mission are: 1) How did terrestrial planets form? 2) What happened during their early development? And 3) How are they structured? DLR's heat flow probe will contribute to answering these questions by measuring the planet's heat flow directly. This will be the first time since Apollo 17 in 1972 that heat flow measurements are carried out on a celestial body other than the Earth. To this end, HP3 will penetrate the ground to a target depth of 5 m using a hammering mechanism termed 'the mole'. The mole will emplace a suite of temperature sensors into the subsurface and the temperature rise will be measured as a function of depth. In addition, the thermal conductivity will be measured at regular depth intervals.

ESA's BepiColombo mission was successfully launched on October 19th from the European Spaceport in Kourou, Oct 18th, marking the beginning of a 7-years trip to the closest planet to the Sun. The interplanetary cruise will include nine flybys for gravitational assists: 1 at Earth, 2 at Venus and 6 at Mercury. Once in Mercury orbit, BepiColombo's carrier spacecraft will release two orbiters, ESA's Mercury Planetary Orbiter (MPO), and JAXA's Mercury Magnetospheric Orbiter (MMO), for a one-year nominal science mission. The MPO will study the surface, interior, exosphere, and magnetosphere of the planet using a suite of 11 instruments. Two of the instruments, the BepiColombo Laser Altimeter BELA and the Mercury Thermal Infrared Spectrometer MERTIS were built and will be operated under responsibility of DLR-PF. BELA is designed to acquire laser range measurements up to a distance of 1050 km from Mercury's surface 10 times a second to acquire the global topography of the planet including altimetry measurements of the Southern Hemisphere for the first time. Combined with gravity field da- ta, this gives insight into the processes that have shaped the planet's crust and surface features. Measurements of Mercury's tidal deformation would further proof the presence of a liquid outer core and could constrain the size of the solid inner core. BELA commissioning was successfully performed on Nov 26, 2018. MERTIS will study the mineralogy and temperature distribution of Mercury's sur- face in unprecedented detail. MERTIS scientific objectives are the Study of Mercury's surface composition, the identification of rock-forming minerals, the mapping of surface mineralogy and the study of surface temperature and thermal inertia. MERTIS aims to capture data on the mineralogy whereas the radiometer surveys the thermal inertia of the planet. The MERTIS Team successfully completed the planned tests of the Near Earth Commissioning Phase (NECP) between 13 and 14 November, collecting thousands of measurements of its internal calibration bodies and deep space. **BepiColombo** is scheduled to arrive at Mercury in December 2025.

ESA's Jupiter Icy Moons Explorer (**JUICE**) is the first L-class mission within the Cosmic Vision Program. This mission will explore Jupiter, its magnetosphere and satellites first in orbit around Jupiter before going finally into orbit around Ganymede, the largest satellite in the solar system. JUICE will be the first or- biter around a moon (other than Earth's moon) in solar system exploration. Its launch is scheduled for June 2022 followed by an interplanetary cruise of 7.6 years. After arrival at Jupiter in 2029, the spacecraft will perform a 3-years Jupiter tour including two flybys of Europa at 400 km altitude and multiple flybys at Ganymede and Callisto. Finally, JUICE will go into orbit around Ganymede including a 5,000-km altitude circular orbit and a 500 km circular orbit for at least 132 days until end of nominal mission. DLR contributions consist of the GALA (Ganymede Laser Altimeter), the Italian/German JANUS (Jovis, Amorum ac Natorum Undique Scrutator) visible camera as well as defining instrument observation sequences and assigning high precision environment

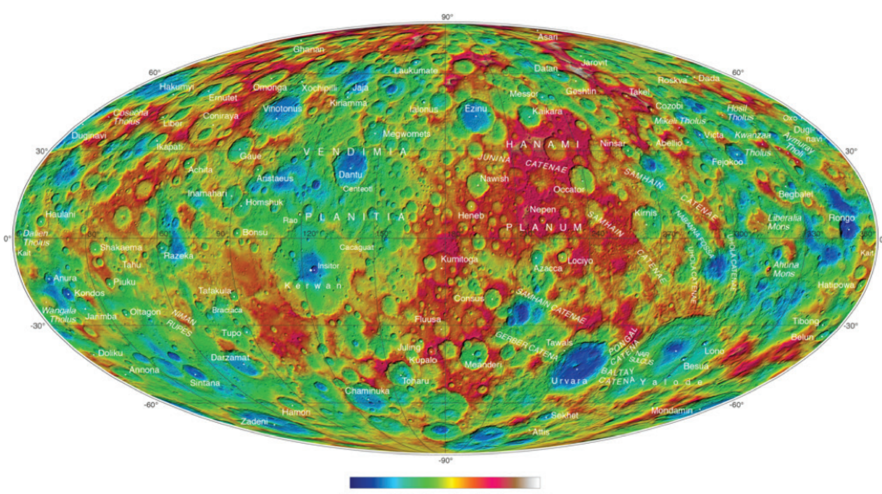
Rosetta and Philae over 67P Churyumov-Gerasimenko. Image: ESA/ATG medialab; Comet image: ESA/Rosetta/Navcam

maps including digital terrain models, geological context and spectral analysis of the surfaces of Jupiter’s moons.

The **Rosetta** mission, approved by the European Space Agency (ESA) in 1993 and launched in March 2004, was one of the most ambitious endeavors of European spaceflight. It carried 11 instruments and the Philae landing module with 10 experiments. On its route to comet 67P Churyumov-Gerasimenko, Rosetta came close to two asteroids. In 2008 it passed 2867 Šteins and two years later 21 Lutetia. The scientific objective was to determine the exact dimensions, shape, density and properties of both asteroids. During the early phase at 67P, in summer 2014, Rosetta orbited the cometary nucleus and mapped the surface. After a 3 months intensive campaign to characterize the surface and to select an appropriate landing site Philae touched down on November 12th 2014 and started the measurements. Rosetta followed the com- et all the way through the closest approach to the Sun and back out again. In 2016 Rosetta was running low on fuel and it was decided to finish the mission by landing the spacecraft on the surface of the comet on 30th of September. DLR was involved in several experiments on the spacecraft and on the lander including MUPUS (Multi-Purpose Sensors for Surface and Subsurface Science), ROLIS (Rosetta Lander Imaging System) and SESAME (Surface Electric Sounding and Acoustic Monitoring Experiment). The huge amount of scientific data brought us new knowledge about the chemical composition, mechanical and thermal properties of comets and about their origin and evolution. DLR also played a major role in the construction of the lander and operated the Lander Control Center (LCC), from where the difficult task of landing on the comet on 12 November 2014 – a feat never before accomplished – was designed and controlled.

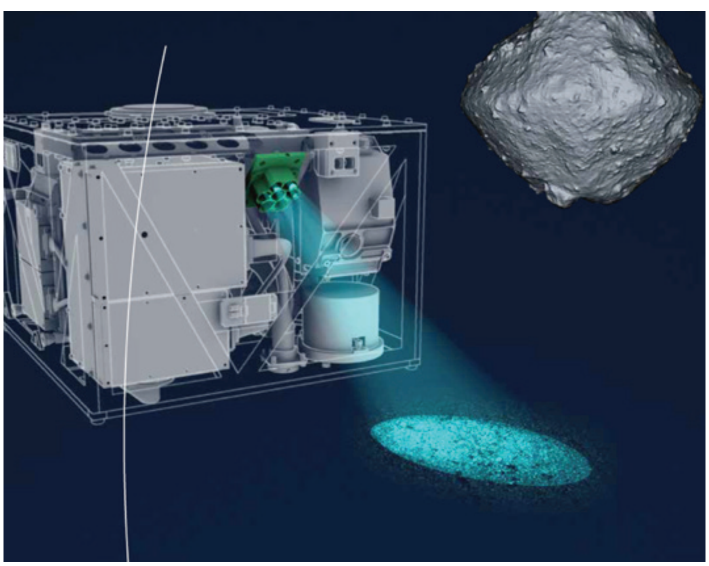
NASA’s **Dawn** mission was launched on 27 September 2007. The Dawn mission was designed to study two large bodies in the asteroid belt in order to answer questions about the formation of the Solar System. Ceres and Vesta were chosen as two contrasting protoplanets, the first one apparently “wet” (i.e. icy and cold) and the other “dry” (i.e. rocky), whose accretion was terminated by the formation of Jupiter.

The two bodies provide a bridge in scientific understanding between the formation of rock planets and the icy bodies of the Solar System, and under what conditions a rocky planet can hold water. Dawn entered Vesta’s orbit on July 16, 2011, and completed a 14-month survey mission be-



Digital Terrain Model of Ceres. Image credit: NASA/JPL/MPI/DLR fore leaving for Ceres in late 2012. It then entered Ceres' orbit on March 6, 2015. On 31. October 1, 2018, the Dawn space- craft had finally exhausted all of its hydrazine fuel, thus ending its mission. The satellite is currently in an uncontrolled state about Ceres. During Dawn's orbit its investigation confirmed that Vesta is the parent of the HED (howardites, eucrites, and diogenites) meteorites, which Dawn connected to Vesta's large south polar basin. Dawn also found hydrated and carbon rich material on Vesta's surface supplied by impactors, a result that was unexpected based on pre-Dawn telescopic observations. Dawn discovered that the inner so- lar system's only dwarf planet Ceres was an ocean world where water and ammonia reacted with silicate rocks. Dawn also found organics in several locations on Ceres' surface. On board Dawn are tow redundant German cameras for mapping and examining irregular and cratered sur- faces, and collects data at varying distances from Vesta and Ceres from various angle relative to the surface. As well as a panchromatic filter, a filter wheel also provides seven different color channels to investigate the composition and physical properties surface and was responsible for assigning precise coordinates to the Dawn image data and preparing high precision maps of Vesta and Ceres including digital terrain models.

Japan Aerospace Exploration Agency's (JAXA) **Hayabusa2** asteroid sample return mission has been launched to asteroid (162173) Ryugu on Dec 3rd, 2014. It arrived at Ryugu on June 27th 2018, and will return samples to Earth in 2020. The DLR developed the lander **MASCOT** in co- operation with the French CNES. Ryugu is classified as a probably volatile-rich C-type asteroid. Its visible geometric albedo is 0.07±0.01, its diameter 0.9 km. Remote sensing measurements indicated a cm- sized, gravel-dominated regolith surface layer. Ryugu rotates with a period of 7.63±0.01h, and spectral observations suggest iron-bearing phyllosilicates to be present on parts of its surface. MASCOT landed on the asteroid on October 3rd 2018. The main scientific objectives are to investigate: 1) the geological context of the surface; 2) the global magnetization and any local magnetization at the landing positions; 3) the mineralogical composition and physical properties of the sur- face and near-surface material including minerals and organics; 4) the surface temperature over the entire expected temperature range for a full day-night cycle; 5) the regolith emissivity and thermal inertia; 6) the local morphology and in-situ regolith structure and texture MASCOT operated on Ryugu until the battery ran out after 17 hours and 7 minutes, corresponding to three Ryugu days. MASCAM, the MASCOT Camera took images during decent and on the surface with resolutions down to 0.2 mm/pixel. These observations revealed a number of important properties of Ryugu, most of which were unexpected before landing. Although Ryugu has a very low albedo, two types of boulders could be clearly distinguished: brighter ones and darker ones. The boulder sizes range from a few decimeters to a few tens of meters. At the position of 22.30 ± 0.05°S and 317.13 ± 0.05°E high resolution images revealed the fine structure of a boulder. During the operations, MARA took continuous measurements of surface brightness temperatures, and measurements were found to be consistent with a thermal inertia much lower than anticipated based on measurements of chondritic meteorites. Low thermal inertia and thus thermal conductivity is likely caused by high intrinsic boulder porosity. Besides providing MASCOT and operating it, DLR provided two PI-Instruments, i.e., MASCAM and MARA. Furthermore, DLR was involved in geological and geophysical data analysis, including CoI contributions to the Hayabusa2 Orbiter instruments.



MASCOT on Ryugu. Image credit: JAXA/DLR/CNES

NASA **Psyche** is a Discovery-class mission to investigate a metal body. The Psyche investigation has three broad goals: Understand a previously unexplored building block of planet formation. Look inside the terrestrial planets, including Earth, by directly examining the interior of a differentiated body, which otherwise could not be seen. Explore a new type of world. For the first time, examine a world made not of rock, ice, or gas, but of metal. Psyche will meet its science objectives with three domestic high heritage instruments and radio science: Multispectral imager with clear and seven color filters map surface morphology and reveal the distribution of residual mantle silicates; a gamma-ray and neutron spectrometer determine elemental composition, particularly the concentrations of iron, nickel, silicon, and potassium; dual fluxgate magnetometers, in a gradiometer configuration, characterize the magnetic field. Radio science maps the gravity field sufficiently to differentiate among core-formation hypotheses. New models for magnetic dynamo generation and solidification of planetesimal cores make testable predictions for geophysical measurements, and lead as well to predictions about tectonics and surface compositions. The spacecraft launch is planned for 2022 with arrival at the asteroid in 2026 for 21 months of operations. As part of its contribution DLR will be responsible for assigning precise coordinates to the Psyche image data and preparing high precision maps of Psyche including digital terrain models and for planning stereo observation.

CHEOPS (CHaracterising ExOPlanet Satellite) – the first S-class ESA mission – is a relatively small space telescope (32 cm diameter) dedicated to the detailed characterization of extrasolar planets orbiting in known systems. It will provide the unique capability of determining accurate radii for a subset of planets for which the mass has already been estimated from ground-based spectroscopic surveys. It will also provide precision radii for new planets discovered by the next generation ground- based transits surveys. The project is organized as a partnership between the Swiss Space Office and ESA. The payload consortium includes 11 European countries and is led by the University of Bern.

PLATO is ESA's M3 mission of the Cosmic Vision Program 2015-2025. It will search for transiting extrasolar planets, down to the size of the Earth, orbiting solar-like stars with orbital periods up to 1 year. The orbit of these planets will be within the habitable zone, which is the region around a star in which a rocky planet with atmosphere can sustain liquid water on its surface. PLATO will obtain high precision light curves of tens of thousands of stars obtaining accurate measurements of their radii, masses, and ages. Transiting planets will be characterized for their radius, from the transit light curve, and mass, obtaining high precision spectroscopic measurements from ground. DLR is leading the international consortium building 26 cameras of 12 cm pupil size aperture that will constitute the pay- load. The PF institute hosts the PI of the mission and is responsible for the overall management of the payload, which involves more than 100 institutes across Europe. PF scientists lead the working packages responsible for the scientific definition of the planet search and planet characterization tools that will be used by the mission.

Student and next generation efforts:

DLR provides a student program which is open for international applications and also has a next generation program for research groups.

DLR also cooperates with the German academic exchange services (DAAD) and the Erasmus exchange program of the European Union.

1. France Project Report

Overall context:

IRAP has become a SSERVI partner, with the official signing on May, 24th, 2016 of its affiliation to SSERVI, in the presence of Gregory Schmidt (then SSERVI Deputy Director, Director of International Partnerships) and Doris Daou (then Associate Director), and representatives of the US consulate in Toulouse, as the result of the submission of the proposal 'SSMMAC-France' (Space Studies of the Moon, Mercury, Asteroids and Comets in France) by the Principal Investigator Patrick Pinet (IRAP, Toulouse).

Major events and facts:

IRAP attended Microsymposium 59th ('The Chinese Lunar and Deep Space Exploration Program') , LPSC 49th meetings held in Houston (March, 20th-24th, 2018) and COSPAR 42nd GA (July, 14th-22th , 2018 with an invited talk) .

IRAP met with the SSERVI partners and staff at the EC meeting held on March, 19th. IRAP also regularly interacted with SSERVI officers and staff in order to prepare and organize the ELS 6th meeting (~150 attendees) which took place in Toulouse on May, 13th-16th, 2018, with a special opening toward in situ resources utilization activities and the participation of private partners.

P. Pinet and S. Chevrel participated to a brainstorming workshop of the EuroMoon team held at ISSI (International Space Science Institute) in Bern (June, 13th-15th, 2018) focused on lunar surface composition and processes, and preparing for the future exploration of the Moon. The objectives were to investigate the nature and history of the lunar crust, the volcanism, the surface interactions with the space environment, and the water cycle on the Moon.

L. Margerin attended a workshop of the ISSI team on Moon seismology held in Beijing (June, 18th-23rd, 2018), with the production of two papers submitted to Space Science Reviews (Nunn et al.; Garcia et al.). Efforts in many countries indicate that an International Lunar Network of seismic stations could be deployed on the Moon by the mid 2020s. In Japan, there is a mission project to deploy one or more seismic penetrators. In China, there is the continuation of the China Lunar Exploration Program after Chang'e 6. In the USA, the Lunar Geophysical Network is one of the possible candidates for the New Frontiers 5 mission.

N. André has been appointed member of an ad hoc Science Team by the Human spaceflight and Exploration Science Advisory Committee (HESAC) of ESA in order to prepare a strategy for science at the Moon. P. Pinet is, at the request of ESA, a member of the international Science Definition Team for the Human-Enhanced Robotic Architecture Capability for Lunar Exploration and Science (HERACLES) project. In preparation of the scientific payload of the Deep Space Gateway, I. Dandouras is chairing at ESA a topical team recently formed to support the definition of payload studies in the field of space plasma physics.

Figure 1. "Let the fun begin!" The 6th European Lunar Symposium held in Toulouse, May 2018.

Outreach activities:

On the occasion of the 50th anniversary of the first man on the Moon (1969-2019), a book* on the Apollo Program has been published to commemorate this one-of-a-kind historical event, with S. Chevrel as the major contributor, with a number of related public conferences on the subject.

*Anfrol, M., Chevrel, S., De Closets, F., Dordain, J.-J., Gracieux, S., Sanguy, M.-A., Tromeur, D., 50éme Anniversaire Premier Homme sur la Lune (1969-2019), 316p., ed. EMPREINTE, Sept. 2018.

A few science and future projects highlights:

Lunar Orbital Imaging Spectroscopy and Geology: Given the wealth of the dataset acquired by the Moon Mineralogy Mapper imaging spectrometer (M3) onboard the Chandrayaan mission, advanced hyperspectral processing (MGM modeling) appears needed to fully explore the existing variability involving plagioclase and mafic crystal field absorptions, and to better constrain the lunar crust lithology and cratering process. Laboratory data are used to improve the capability of the MGM to realistically model complex mafic mineralogies when considering rock slab surfaces with coarse textures, involving plagioclase and mafic crystal field absorptions (Pinet et al., 2016). This strategy is tested on M3 spectra with the objective of documenting the petrology at Copernicus and Aristarchus craters through the characterization of exposed outcrops (e.g., central peaks, inner walls and rims) from plagioclase and mafic crystal field absorptions (Chevrel et al., 2018; Pinet et al., 2018a; 2018b).

ISRU: A new activity was recently started with experimental studies undertaken on lunar simulants to produce oxygen and metals from electrolysis (Berger and Turk, 2018).

Lunar Interior: new insights from Apollo data for the characterization of shallow moonquakes and the structure of the megaregolith:

Lunar seismic signals are notably different from usual terrestrial seismic records: the energy rise at the onset of the signal is gradual, the S-wave arrival is difficult (or impossible) to detect, the maximum of energy is broad, and the energy decay in the coda is very slow.

The signal can remain noticeably above the noise level for up to two hours, compared to a few minutes on Earth for an event of the same magnitude.

In 1974, Dainty et al. made the first attempt at modeling the scattering processes in the Moon using diffusion theory, and inferred a thickness of 25 km for the scattering layer but these modeling efforts were limited to the planar case. However, given the size of the Moon and the duration of lunar seismic signals, sphericity effects appear quite relevant. Accordingly, a radial stratification of scattering properties is here implemented for the first time in spherical geometry. The current approach considers for the first time the stratification of scattering properties and the spherical geometry (Gillet et al., 2017; Gillet, Toulouse University PhD Dissertation, dec. 2017).

With this new advanced modeling, the depth of shallow moonquakes is determined by inversion based on the observed variation of the time of arrival of the maximum of energy (tmax) with epicentral distance. Shallow moonquakes are now found to originate from a depth of about 50 km ± 20 km, likely resulting from the failure of deep faults in the brittle part of the moon. A significant discontinuity of seismic properties (with a huge diffusivity contrast) is found at 100 km depth, suggesting the existence of a 100 km thick megaregolith. These results point toward a highly fractured and heterogeneous crust, with the possibility of large lateral variations of scattering properties and are consistent with the findings from GRAIL observations and recent interpretations. The sharpness of this transition at 100km points toward a thermally activated mechanism such as viscous deformation annealing at depth the cracks and fractures. At global scale, the absorption properties which are derived also suggest quite an anhydrous lunar interior (Gillet et al., 2018).

Lunar Environmment / solar wind / interaction with the terrestrial magnetosphere:

The Moon, during most part of its orbit around the Earth is directly exposed to the solar wind. During 5–6 days every orbit, however, the Moon crosses the tail of the

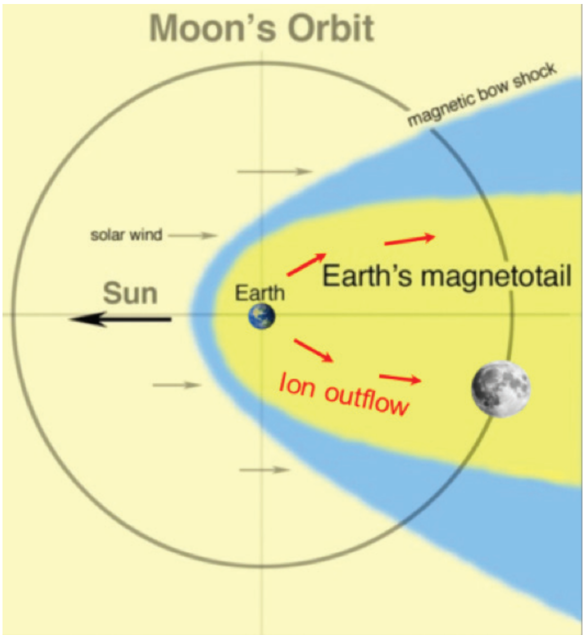


Figure 2. Moon's orbit with respect to the Earth's magnetosphere. Earth's and Moon's sizes not to scale.

terrestrial magnetosphere. It is then well situated to study atmospheric escape from the Earth into space, in the form of heavy ions upwelling from the ionosphere and then transported and lost into the deep magnetotail (Figure 2).

The ARTEMIS spacecrafts, which are in orbit around the Moon, have observed outflowing heavy ions in the terrestrial magnetotail, at lunar distances. Backward particle tracing indicated that these ions should originate from the terrestrial inner magnetosphere [Poppe et al., 2016]. In a recent study we examined Cluster spacecraft data acquired by the CIS-CODIF ion mass spectrometer, obtained in the terrestrial magnetosphere. Events were selected for which the orbital conditions were favorable and the Cluster spacecrafts were in the high-latitude inner magnetosphere a few hours before the ARTEMIS heavy ion detection, a time compatible with the transfer to lunar distances [Dandouras et al., 2019]. Analysis shows that the CIS-CODIF instrument detected, in upwelling ion beams and in the ring current, a series of ion species including O+ and a group of molecular ions around ~30 amu, which could include N2+, NO+, or O2+. Their density, when these molecular ions were present, was from a few % up to ~30% of the O+ density. The upwelling O+ fluxes, measured by Cluster in the inner magnetosphere, are consistent with the heavy ion fluxes measured by ARTEMIS around the Moon. The events occurred during active periods, with CME (Coronal Mass Ejections) arrivals followed by a northward rotation of the IMF (Interplanetary Magnetic Field). They show the existence of a direct pathway of plasma, upwelling from the ionosphere and then transported and lost into the deep magnetotail. Quantifying this atmospheric escape is important in order to understand the long-term evolution of the atmospheric composition, and in particular the evolution of the N/O ratio, which is essential for habitability. Future missions should investigate in detail the mechanisms of atomic and molecular ion acceleration and escape and their link to the solar and magnetospheric activity. Our observations suggest also that terrestrial heavy ions, transported to the Moon, may have preserved samples of the Earth's atmosphere from billions of years ago by their implantation in the near side lunar regolith.

Future lunar missions and instruments:

SELMA & SELPHIE:

IRAP has recently been involved in several missions proposals aimed at exploring the Moon. The SELMA and SELPHIE missions were proposed in response to ESA's Announcement of Opportunity for M-class in 2016 and F-class missions in 2018, respectively. They were unfortunately not selected. SELMA (Surface, Environment, and Lunar Magnetic Anomalies, Futaana et al., SELMA mission: How do airless bodies interact with space environment? The Moon as an accessible laboratory, Planetary and Space Science, Volume 156, p. 23-40, doi:10.1016/j.pss.2017.11.002, 2018) investigates the interaction of the neutral and plasma environment with the lunar surface and the impact of this interaction on the surface composition, in the first hand, on the presence of water.

SELMA focuses on four main subjects: water, volatiles cycle, mini-magnetospheres, and dust. SELMA comprises of the SELMA orbiter, SELMA impact probe for Magnetic Anomaly, passive impactor, and relay cubesat. To address its scientific objectives SELMA carries a highly focused suite of instruments including a lunar positive ion spectrometer for solar wind plasma and a lunar positive ion spectrometer for secondary ion mass spectrometry to be both provided by IRAP (Lead Co-Investigator: N. André).

The SELPHIE (Surface, Exosphere, and Lunar Pole Hydration with Impact Experiment) mission is designed to address the science of the delivery, production, transport and accumulation of lunar water comprehensively, by answering how the lunar surface water is delivered or produced, transported, and accumulated to cold traps or escaped to space. To address its scientific objectives SELPHIE carries in particular a solar wind monitor to be provided by IRAP (Lead Co-Investigator: N. André)).

SELPHIE has also been recently proposed to the ESA Request For Information on Lunar Exploration Campaign Science and Technology Payload (http://exploration.esa.int/moon/60923-request-for-information-lunar-exploration-campaign-science-and-technology-payloads) that could be contributed to a possible lunar mission campaign implemented within the framework of the European Space Exploration Envelope Programme (E3P). This mission campaign is currently in preparation and its implementation is subject to prending decisions at the ESA Council Meeting at Ministerial level planned for December 2019.

The campaign shall enable access to the Moon via missions that may be categorized as:

• Missions of Opportunity, where European payloads respond to flight opportunities made available by the private sector or international partners.

• Directed missions, where European payloads are selected for missions, which are defined and driven by ESA, alone or with international partners, to achieve a predefined set of objectives objectives.

DORN:

Since the early stages of the lunar exploration, radon-222 and its progeny (218Po, 214Po, 210Pb and 210Po) have been identified as key tracers of the present-day lunar seismic and venting activity. Long-term monitoring of the radon cycle on the surface of the Moon would thus provide valuable ground truth for orbital measurements and would help address several key issues related to the transport of lunar volatiles and dust, including the study of the transport of gases through the lunar regolith and of volatiles and dust in the lunar exosphere, the monitoring of the venting activity of the Moon and identification of active outgassing spots. A prototype for an in situ instrument called DORN (for “Detection of Outgassing

Radon”) aimed at measuring both radon and polonium atoms around the lander, and the subsurface flux of radon at the landing site is being developed at IRAP (Meslin et al., 2018).

LIBS:

Since 2012, LIBS (Laser-induced Breakdown Spectroscopy) has been successfully used under low atmospheric pressure for exploring the geology of Mars at Gale Crater with the Mars Science Laboratory rover’s ChemCam instrument. Laboratory studies performed at IRAP have also demonstrated that LIBS can give accurate and precise results under vacuum conditions. The potential of LIBS for rapid and accurate in situ elemental analysis of lunar materials and characterization of potential resources for future lunar exploration is currently under study (Lasue et al., 2018).

Small bodies:

ROSETTA:

Rosetta mission ended in late 2016 but IRAP is still involved in the work related to the data analysis and interpretation, with in particular, a significant participation in the dust working group of the mission dedicated to giving a multi-scale multi-instrument review of the properties of dust particles in the coma of 67P/Churyumov-Gerasimenko (Fulle et al. 2018; Levasseur-Regourd et al. 2018, 2019; Güttler et al. 2019; Lasue et al. 2019). We also developed laboratory simulations of light scattering to explore the link between cometary dust particles and the interplanetary dust medium (Hadamcik et al. 2018). Margaux Hoang defended successfully her PhD thesis on the results of the ROSINA/RTOF instrument at 67P (Hoang et al. 2018, 2019) and the team continued to participate in the ROSINA discoveries (Rubin et al. 2018; Bieler et al. 2019). Finally, J. Lasue participated in the review panel for the public release of the Rosetta end of mission data to the PSA and PDS. Further studies to apply radar technologies to the study of small bodies are on-going (Hérique et al. 2018).

IRAP is also involved in the development of new space cameras based on the CMOS technology. These cameras will equip the next NASA Mars Rover for 2020 and the SuperCam instrument on-board. These detectors are very versatile and find their use in many configurations. With an agreement with the Team Indus Google X-prize competitor, a set of CMOS detectors will be launched to the Moon in 2020. Another mission will also take advantage of this development : IRAP is involved in the phase D of the Eye-Sat nanosat dedicated to the study of interplanetary dust particles and their origin which will make use of the CMOS detectors as well and should be launched in the fall of 2019 (Levasseur-Regourd et al. 2014).

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1. Italy Project Report

Italian scientific community has a long dated partnership with SSERVI, since the establishment of the Italian Node at INFN Laboratori Nazionali di Frascati; recently, the Italian Space Agency took over as Associate agency, coordinating the initiatives of the domestic research centers and Universities. The interest of this national scientific community in Moon exploration have been confirmed by the applications and proposals issued both at the European Space Agency "Request for Information - Lunar Exploration Campaign Science and Technology Payloads" issued on November 2018 and at the "Joint Request for Information from the Chinese National Space Administration (CNSA) and the European Space Agency (ESA)" issued on November 2018. Italian researchers are also active part of the different Science teams and groups established by ESA in order to identify a common regional view on the role of the community in support of the Moon exploration plans as part of the Global Exploration Roadmap, whose last issue has been released at the beginning of 2018.

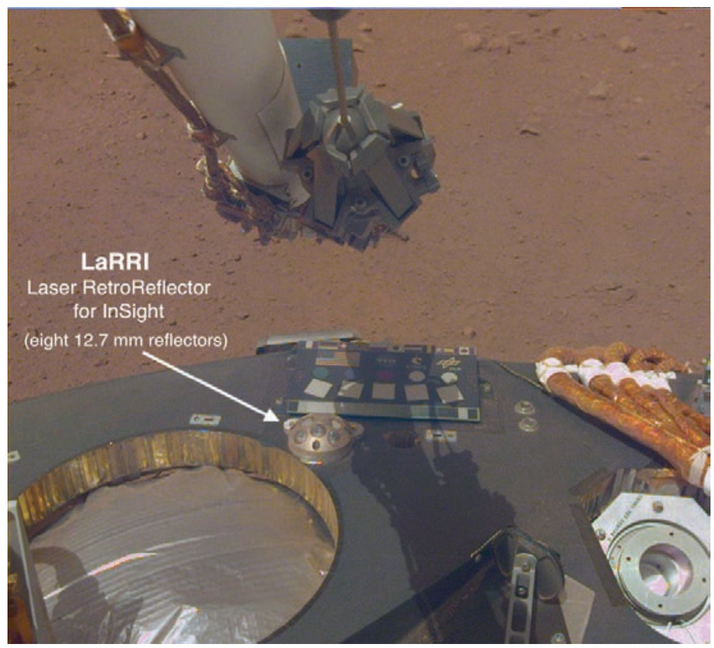
1.1 INFN-LNF

The SCF_Lab of INFN-LNF works jointly with the Matera Laser Ranging Observatory (MLRO) of the Italian Space Agency-CGS (Space Geodesy Center): INFN delivers laser retroreflectors, ASI laser-ranges to them in the Earth-Moon system. The SCF_Lab and MLRO (G. Bianco, director of ASI-CGS) participated in two proposals of lunar laser retroreflectors for the NASA ROSES-2018 Announcement "LSITP" (Lunar Surface Instrument and Technology Payloads):

- As Co-PI, proposing MoonLIGHT large reflectors for CLPS (Commercial Lunar Payload Services) landers, jointly with the University of Maryland (D. Currie PI). MoonLIGHT is a single, large retroreflector for lunar laser ranging from the MLRO or APOLLO stations for precision tests of general relativity, surface geodesy and to study the lunar interior structure.

- As Co-I, proposing a microreflector for a CLPS mini-rover, jointly with "Ceres Robotics Inc." (M. Sims PI, T. Colaprete, P. Willis). These microreflectors inherit from the design and goals of the one on InSight (LaRRI, see Figure), as well as from the three payloads delivered for the ExoMars/Mars 2020 ESA/NASA Rovers (and ExoMars Schiaparelli) [1] [2] [3].

In 2018 SCF_Lab and MLRO also proposed MoonLIGHT and a LaRRI-like microreflector for three ESA RFI on lunar exploration, science and technology.



Collaboration with B. Day (NASA-ARC) and the Team of E. Law (NASA-JPL)

A new method for seleno-location of lunar laser retroreflectors from orbit has been proposed by the SCF_Lab to E. Law and B. Day. The latter are developing a new, dedicated tool within MoonTrek to test this proposal.

Asteroids

Mars-inheriting microreflector prototypes have been developed for interplanetary missions to comets or to asteroids, like the ESA candidate Hera. The latter has a micro-lidar for time-of-flight measurements to our microreflectors if installed on the mission Cubesats or landed on Didymoon for its surface geodesy.

Phobos-Deimos

Retroreflector for Phobos-Deimos landings have been developed, for surface geodesy and tests of gravity in the Martian system. A prototype, PANDORA (Phobos ANd DeimOs laser Retroreflector Array), has been designed and built for a mission like the Japanese mission MMX (Martian Moons eXploration).

1.2 INAF

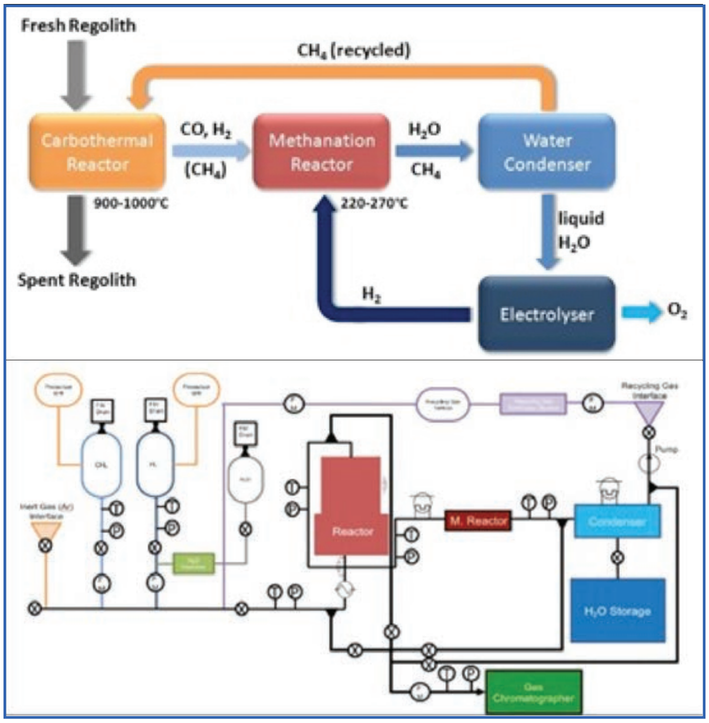
The INAF team is deeply involved in the lunar exploration preparatory activities, especially as part of the ESA PROSPECT user group. The Italian science team is composed by a wide group of scientists, all of them involved or with strong interest in the lunar science and exploration. The Prospect User Group members have been selected by ESA with the aim to define and ensure the scientific requirements of PROSPECT, to consolidate PROSPECT science objectives, to ensure PROSPECT is operated effectively at the lunar surface and to increase the scientific return of the expected data. The main purpose of PROSPECT is to support the identification of potential resources on the Moon and to assess the utilization of those resources. Water and other volatiles found at the surface of the Moon could provide a major potential assets for future exploration (e.g. Anand, 2010, Starukhina 2012, GER Global Exploration Roadmap (GER) white paper, 2018). They represent a vital consumable for human explorers and can also be the source of oxygen for life support systems. Moreover, hydrogen and oxygen as can be extracted from lunar soil and used as fuel. One of the key point is about the preservation of lunar volatiles and our team made some research work to address this issue. Numerical simulations have been used to establish if the volatiles will be preserved or not during the drilling phase and sample analysis. A 3-D thermophysical model, based on a finite element method (FEM), has been used to estimate the temperature of a lunar regolith sample and consequently the water ice sublimation rates.

Some members of the INAF Team are part of the ESA Lunar Science Team, that is in charge to write a plan that would be used as the basis of scientific investigations and payloads for ESA's future lunar exploration activities. This is intended to begin with the selection of a pool of payloads for potential flights in the period 2020-2025. The intention is that this plan will define the European science community's priorities lunar exploration and that that can be addressed by missions to the lunar surface in the coming years.

1.3 Politecnico di Milano

Politecnico di Milano is carrying activities related to In Situ Resources Utilization ISRU plant design and prototyping to extract water from Moon regolith. In particular, activities are focused on the Carbothermal Reduction (CRB) process, solid-gas based, using methane containing the endothermic reaction temperatures in the range of 950-1000°C. Former in house experimental activities, demonstrated the mentioned process is cost effective: almost no beneficiation is needed to obtain by far conversion efficiency higher than with other processes such as with hydrogen reduction. The reason why stays in the soil composition the most, being the CRB capable to attack the feedstock silicon oxide, representative of almost 50% of the lunar soil. A technique to reduce the coke formation has been also indentified and is going to be experimentally verified within the current year. The current activities are twofold: design at a good level of detail a scaled plant to potentially fly in few years, design, assembly and test a terrestrial prototype plant to experimentally characterize the chemical process in terms of efficiency, to be compared with the already developed numerical model and clarify potential functional criticalities in the plant. Activities are carried on in synergy with ESA, ASI, and OHB company.

A different set of activities is related to Lunar South Pole soil simulant characterization in thermal vacuum conditions. In fact, reproducing a planetary soil simulant bed is a tough challenge starting from the need of repeatable procedures to prepare the soil with desired physical properties, to the need to ensure its preservation during thermal-vacuum operations. Indeed several problems arise when the soil is brought under those



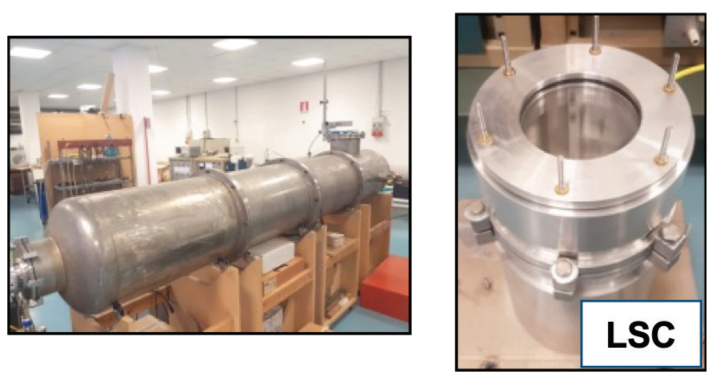
Carbothermal reduction process and schematic of the plant

conditions, i.e. soil disruptions phenomena. Politecnico di Milano is developing a small-scale prototype, starting with the characterization of a lunar simulant bed, with the goal of reproducing lunar poles conditions. The NU-LHT-2M simulant is employed as dry and wet soil bed, compacted by layered vibrations to reduce the trapped air amount; different vibration profiles effects on the final bulk density have been investigated. The profile which got the maximum bulk density allowed obtaining Lunar representative bulk densities. Lunar simulant soil bed underwent medium vacuum conditions at different pressure decay rates with different water saturation level to investigate the bulk density preservation and the soil disruptions. The soil is equipped with thermal sensors to monitor the internal thermal status. Tests showed the soil disruptions events correlation with the T-P profile adopted to get to lunar environmental conditions.

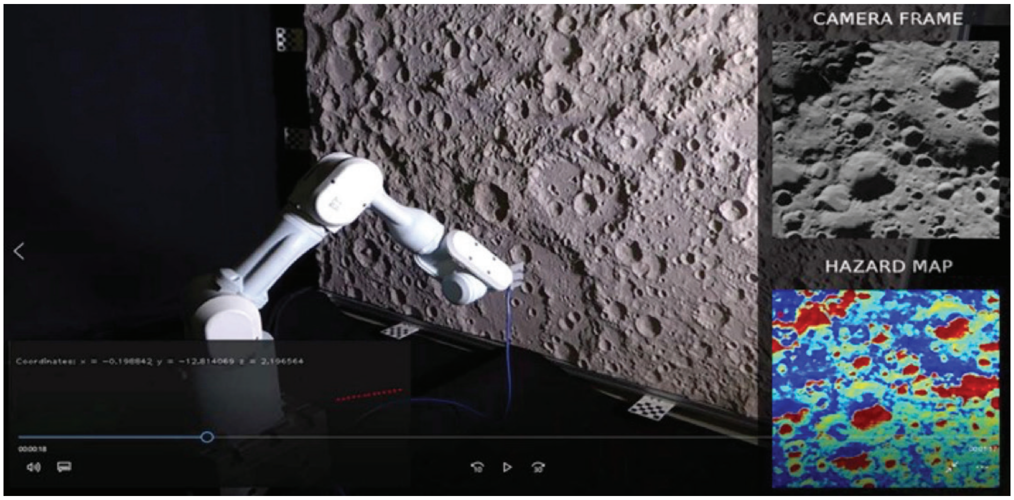
Politecnico di Milano, ASTRA Team, is also working on **Vision based navigation and Hazard avoidance for Autonomous landing**, in particular through the development of a single camera relative Vision-Based Navigation algorithm for planetary landing. The proposed Vision-Based Navigation is based on features extraction and tracking from on board acquired images, supported by filtering to further reduce the state vector error. Within

Experimental results: in vacuum regolith boiling

the curren year a strong campaign with HIL occurred on the in-house GNC facility, specifically implemented for landing and relative Nav testing. The facility, equipped with a Mitsubishi PA-10 robotic arm to reproduce the 6 DoF lander dynamics, a camera, a calibrated 2.4x2m Lunar surface diorama and a dimmable 5600 K LED lighting system to provide fully controllable illumination environment; the facility is available for Vision-Based systems verification and validation up to TRL5. Currently



Part of the experimental set up – small and large vacuum chamber



Landing Facility at ASTRA-PoliMi and NAV and Hazard maps outputs.

the loop I still open, to focus on Hazard detection algorithms, based on ANN, and on mono-camera visual navigation. The work on going focuses on closing the loop on the guidance, to drive the arm accordingly.

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[7] C. Carli, G.Serventi, L. Giacomini, M. Sgavetti 2018. Proclus Crater: Spectral variability within Lunar Highlands. Congresso SGI-SIMP. pg 822. 10.3301/ABSGI.2018.02

3. Public Engagement (including EPO)

In view of the celebrations for the 50th anniversary of the Apollo XI landing on the Moon surface, the Museo Civico di Rovereto arranged a suggestive exhibition, named "La Luna, e poi?", with the sponsorship of the Italian Space Agency and important support from NASA SSERVI. The opening was on December 8th 2018 and it will last until July 2019 and during this long period several special events and conferences are planned. The exhibition allows the visitors to live an immersive experience in the Apollo era and to experience the atmosphere of that inspiring phase of space exploration.

Many original pieces, like tools, books, drawings are exposed together with videos and pictures; virtual reality is also used to make the experience even more exciting. In one of the rooms, a dedicated corner is arranged for SSERVI panels and materials. Moreover, a 1:1 scaled electric powered and functioning model of the lunar rover has been manufactured and exposed.

5. Mission Involvement

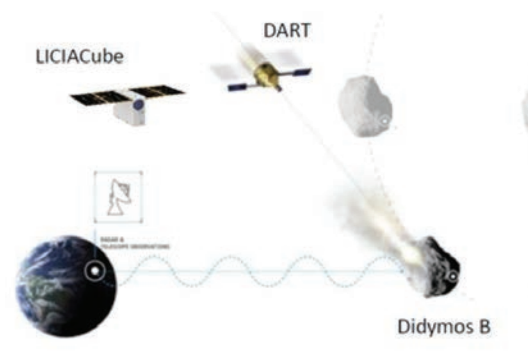
The Italian Space Agency has an important heritage in the development of instruments for Solar System Exploration missions, often in cooperation with international partners. In the past years, ASI also recognized the potentiality of small satellite in the class of nanosatellite/cubesat, in support or as alternative means to implement space missions in a fast, cheap and effective way. Space robotic exploration is one of the areas where cubesats can be used to complement the investigations performed by the traditional sized probes, characterized by larger resources but also complexity and then costs. The nanosat can be devoted to specific tasks, sometimes for a limited part of the entire mission. Hence, nowadays, the new exploration robotic mission concepts often take benefit from the presence of cubesats. Moreover, the limited financial required effort makes missions affordable for a wider group of potential space actors, so allowing the participation of small or emerging countries in big challenges and fostering the international cooperation at different levels.

> The Italian Space Agency is implementing several programs for Space Science cubesats development in international environment.

"**Argomoon**" is a 6U cubesat, being selected in 2016 by NASA HQ Exploration Systems Mission Directorate (ESMD) as a Secondary Payload for the Exploration Mission 1 (currently planned for June 2020) of the Space Launch System (SLS), the heavy-lift launch vehicle designed to allow space exploration beyond Low-Earth Orbit. The first part of the ArgoMoon mission will aim to take significant photographs of the launcher, while in the following six months, the satellite will orbit

around the Earth with an apogee close to lunar orbit, to collect pictures of the lunar surfaces with scientific and outreach purposes. An additional goal of the mission is the validation of new technologies for nanosatellites in the deep space environment. The ProtoFlight Model has been almost completed during 2018 and it will undergo the qualification/acceptance test campaign, before the shipment to USA for final testing and integration onto launcher.

NASA again selected a similar platform, named "**LICIACube - Light Italian Cubesat for Imaging of Asteroids**", to witness the impact effects of the NASA probe "Double Asteroid Redirection Test – DART", on the secondary asteroid of the binary system Didymos, in order to test orbit deflection methods for Planetary Defense purposes. LICIACube will be launched as piggyback of DART spacecraft, then will be separated in proximity of the target and will perform an autonomous fly-by of the binary Didymos system during the final part of the DART mission, collecting pictures of the asteroid surface and of the generated ejecta plume. The LICIACube design, manufacturing, testing and operation will be implemented by Italian company Argotec, based on the heritage gained in the development of the ArgoMoon CubeSat. An important contribution is provided by the scientific community, in particular by the INAF team supporting the remote sensing performance achievement and the data analysis, by the Politecnico di Milano group performing the mission analysis and guidance design and by the University of Bologna, setting up the orbit determination process and radio science measurements. The Phase B in progress activities, carried out in strong coordination with the DART team of JHU Applied Physics Laboratory (APL), are mainly focused on the mission and trajectories analysis, in order to optimize the observation conditions with respect to the on board resources and mission objectives. The operational scenario is discussed and agreed with the APL team, together with the interfaces between the DART spacecraft and LICIACube. Moreover, the payload and platform design is under consolidation and the subsystem expected performances identified and translated into design requirements. Ground support to the mission will be provided by DSN, but ASI will also



maximize the involvement of its own radio tracking facility, the Sardinia Deep Space Antenna, currently being upgraded to enhance its TT&C capabilities.

Both missions will allow Italian community to setup and validate complete end-to-end space systems operating in deep space environment, so paving the way for future opportunities for cooperation and national initiatives.

Among the new initiatives at European level, the Italian proposed mission "**Lunar Meteoroid Impact Observer LUMIO**" has been awarded winner of ESA's Lunar CubeSats for Exploration challenge, and as such it is being considered for future implementation. Politecnico of Milan is Principal Investigator of the mission, proposed with the aim to observe, quantify, and characterize the meteoroid impacts by detecting the impact flashes on the lunar farside. The mission utilizes a CubeSat that carries the LUMIO-Cam, an optical instrument capable of detecting light flashes in the visible spectrum. On-board data processing is implemented to minimize data downlink, while still retaining relevant scientific data. The mission implements a sophisticated orbit design: LUMIO is placed on a halo orbit about Earth–Moon L2 where permanent full-disk observation of the lunar farside is made. This allows obtaining high-quality scientific products. Innovative full-disk optical autonomous navigation has been proposed and assessed. The spacecraft is a 12U form-factor CubeSat featuring novel on-board micro-propulsion, two solar wings equipped with drive mechanisms, and state-of-the-art attitude control system.

1. Netherlands Project Report

1.1 Exploration

The Netherlands are at the Moon. The Netherlands-China Low-Frequency Explorer (NCLE), a low-frequency radio experiment on the Queqiao communications relay satellite, was launched in May 2018. Quequiao reached a Lissajous orbit around the Earth-Moon L2 point, supporting the Chinese Chang'e 4 mission to the lunar far side. This pathfinder instrument is the first step towards a future low-frequency space-based or moon-based radio interferometer which would aim to detect the 21-cm hydrogen line emission from the Dark Ages period of our early Universe.

1.2 Science

In 2018, lunar science in the Dutch SSERVI team was focused primarily on the volatile element budget of the Moon, and on the architecture of the lunar crust. Studies relied on remote sensing data of the mineralogy of the central peaks of lunar impact craters and on high-pressure experiments mimicking the conditions inside the Moon.

High-pressure experiments were performed to quantify the maximum amount of the volatile element sulfur that can be dissolved in lunar magmas (Steenstra et al., 2018). These measurements were needed to assess whether the interior of the Moon was ever saturated in sulfide melt. If sulfide melt formed in the lunar interior, it could have sequestered many chalcophile (sulfur-loving) elements into the deep lunar interior, affecting estimates of the bulk composition of the Moon. Figure 1 summarizes the conclusions of this work. The measured abundances of sulfur in lunar volcanic samples (open symbols in Figure 1) are significantly lower than the sulfur solubility in these samples as determined from the new high-pressure experiments (coloured symbols in Figure 1). The only lunar samples that could have experienced sulfide melt saturation are some of the more evolved Apollo 17 high-Ti basalts, if the sulfides are nickel and/or copper rich. This suggests that sulfide melts likely did not play a prominent role in lunar evolution and simplifies compositional models for the Moon.

Remote sensing studies, done in collaboration with

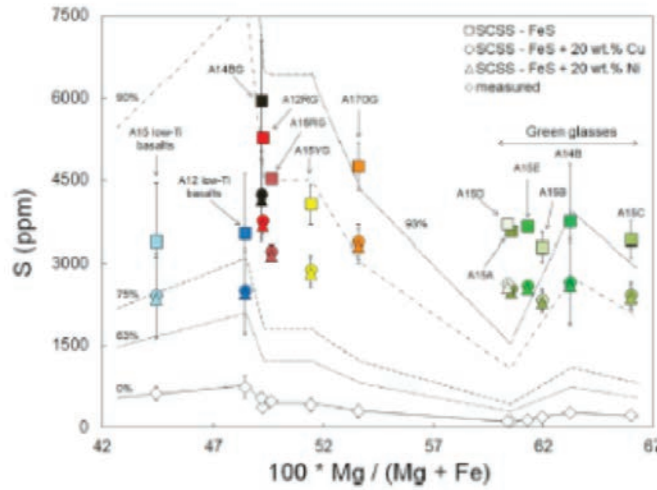


Fig. 1. Comparison between measured sulfur concentrations (in parts per million, ppm) in primitive lunar melt samples (open symbols) and calculated solubilities of sulfur (SCSS) in those same samples based on new experimental data. The horizontal axis is a measure of the major element composition of the samples in terms of their magnesium (Mg) and iron (Fe) content (from Steenstra et al. 2018).

French SSERVI members Flahaut and Quantin, used Moon Mineralogy Mapper (M3) reflectance data taken over the central peaks of >35 craters located in the feldspathic highlands to sample the mineralogy of the lower crust and the crust-mantle interface. Results (Martinot et al., 2018) indicate that plagioclase is widely detected, including in craters thought to sample lower crustal to mantle material, except in central peaks where Low-Calcium Pyroxene was detected. Olivine detections are rare, and identified in rocks thought to be derived from both above and below the crust-mantle interface. Mineralogical detections in central peaks suggest an evolution of the pyroxene composition with depth, that may correspond to the transition from the crust to the mantle. The correlation between High-Calcium Pyroxene and some pyroxene-dominated mixture spectra with the location of maria and cryptomaria suggest lateral heterogeneities exist throughout the lunar crustal sequence.

2. Inter-team/International Collaborations

The Netherlands team have consolidated collaborations with the University of Muenster (Klemme, Bernd) in the area of experimental lunar science, and UK colleagues at Open University (Anand, Franchi). Lunar remote sensing studies were undertaken in collaboration with members of the French SSERVI team (Flahaut at Nancy, Quantin

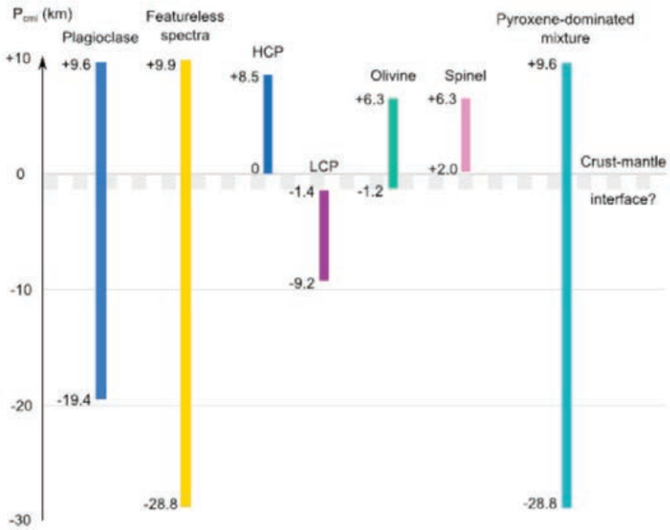


Fig. 2. Schematic view of the mineralogy of the region above and below the lunar crust-mantle interface based on remote sensing data (Martinot et al., 2018). Mineral detections are shown as a function of depth in the Moon. Pcmi=0 (the grey dotted line) denotes the crust-mantle interface derived from Gravity Recovery and Interior Laboratory (GRAIL) crustal thickness model 1. HCP = High-Calcium Pyroxene; LCP = Low-Calcium Pyroxene.

at the University of Lyon). Scientific ties with China have been strengthened by collaborations with Nanjing University (Hui) and collaborations stemming from the development of the Netherlands-China Low-Frequency Explorer (NCLE).

3. Public Engagement (including EPO) Report

Lunar and planetary science education in the Netherlands included planetary sciences courses at BSc student level in Amsterdam, and at MSc level in Amsterdam and Utrecht. SSERVI team members were involved in teaching part of the 2018 Space Science Programme of the International Space University, organized by Delft University of Technology. As was the case last year, Amsterdam undergraduate students submitted some of their work on the design of future lunar and planetary missions to LPSC.

4. Student / Early Career Participation

Undergraduate Students

1. Mr. Bram de Winter, BSc student, Vrije Universiteit Amsterdam, Lunar core formation.

2. Ms. Viktoria Trautner, BSc student, Vrije Universiteit Amsterdam, Lunar core formation. Winner of the 2019 Jelgersma Prize for best BSc thesis in Earth Sciences in the Netherlands.

3. Ms. Eva Kelderman, MSc student, Vrije Universiteit Amsterdam, Lunar core formation.

4. Ms. Elena Giovanco, MSc student, ENS Lyon, Lunar magma ocean.

5. A group of Dutch BSc and MSc students forming one of the project teams for IgLuna, the first ESA_Lab@ in which student teams across Europe develop modular demonstrators that combined will set the foundation for a living in space demonstrator laboratory.

Postdoctoral Fellows

6. Dr. Joshua Snape, Vrije Universiteit Amsterdam, Lunar chronology (Marie Curie Fellow).

5. Mission Involvement

1. Chang'e 4 mission, Prof. Heino Falcke (Radboud University, Netherlands), Netherlands-China Low-Frequency Explorer (NCLE), PI and lead in hardware development at Radboud Radio Lab, Nijmegen

2. Chang'e 4 mission, Melissa Martinot (PhD student Vrije Universiteit Amsterdam, Netherlands), landing site characterization

3. Chang'e 5 mission, Melissa Martinot (PhD student Vrije Universiteit Amsterdam, Netherlands), landing site characterization

4. HERACLES mission concept, Prof.

SSERVI Team Publications in 2018

The following list of 133 publications was compiled from all SSERVI teams, bringing the total for years 1-5 to 877.

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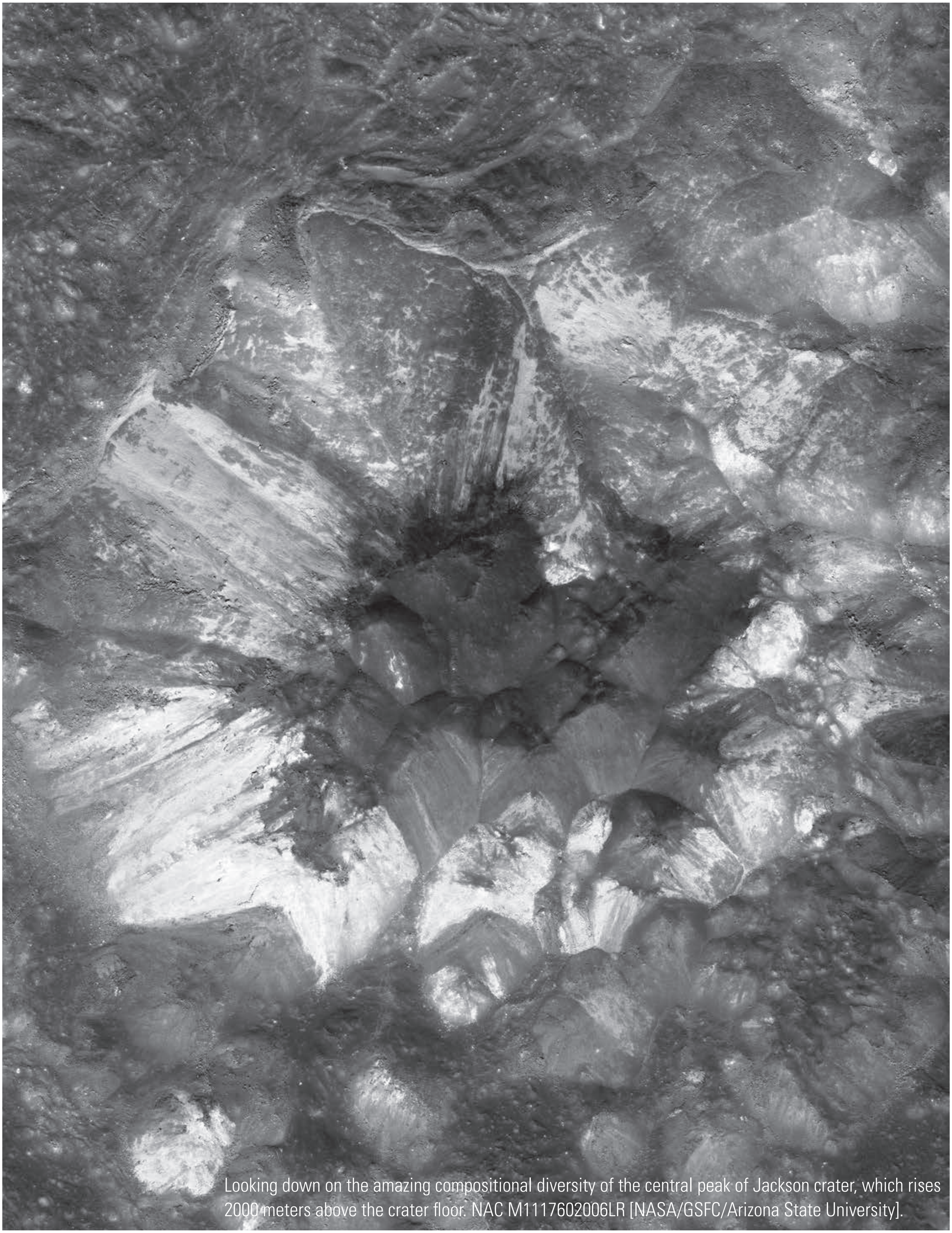

Looking down on the amazing compositional diversity of the central peak of Jackson crater, which rises 2000 meters above the crater floor. NAC M1117602006LR [NASA/GSFC/Arizona State University].