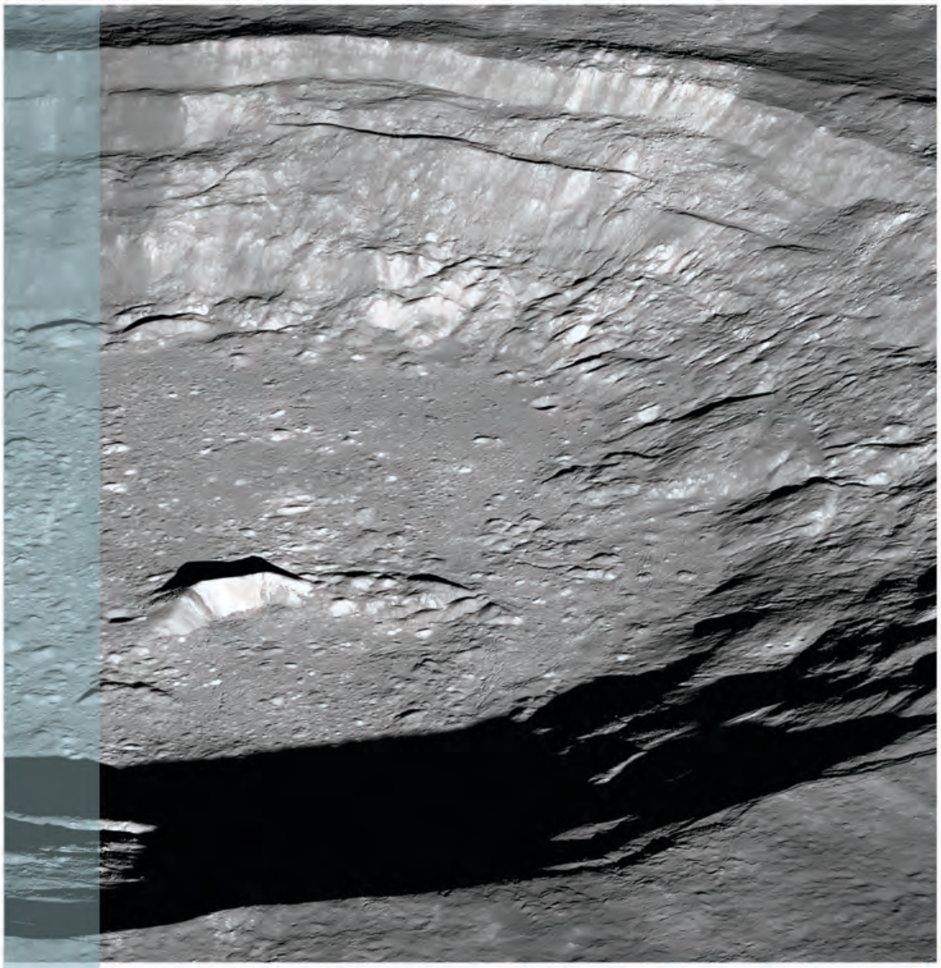
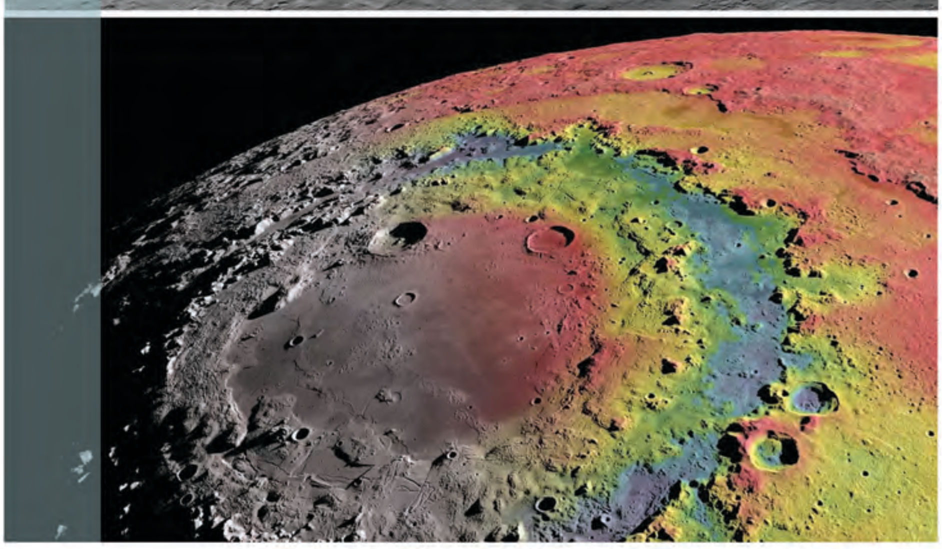
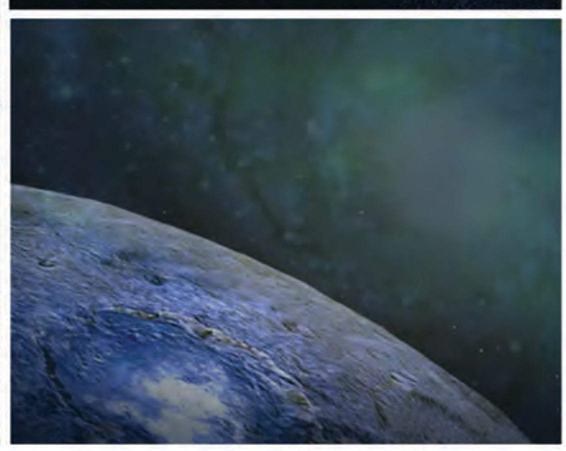
SSERVI ANNUAL REPORT

2017







YEAR FOUR *ANNUAL REPORT*

2017

SOLAR SYSTEM EXPLORATION RESEARCH

VIRTUAL INSTITUTE

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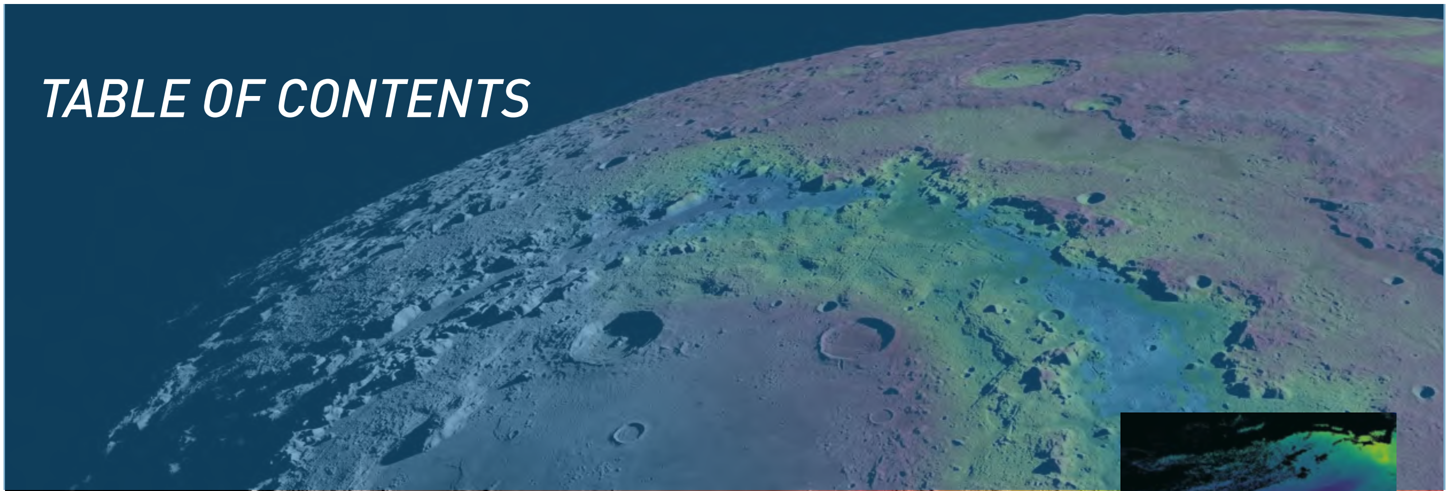
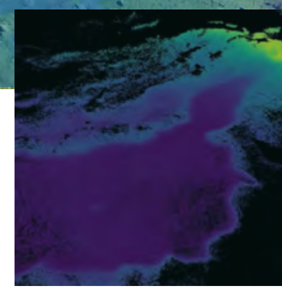
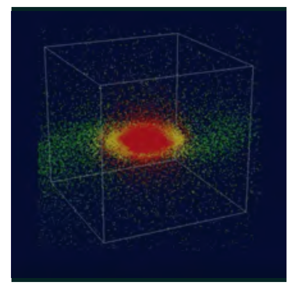
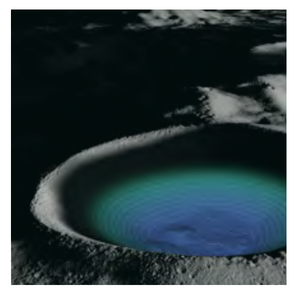
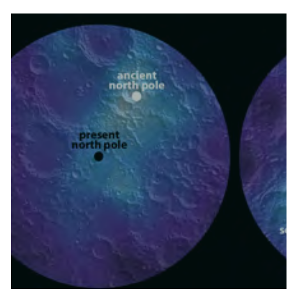










FROM THE BRIDGE

NASA's Solar System Exploration Research Virtual Institute (SSERVI) is pleased to present the 2017 Annual Report. Each year brings new scientific discoveries, technological breakthroughs, and collaborations. The integration of basic research and development, industry and academic partnerships, plus the leveraging of existing technologies, has further 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. 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.

In 2017 SSERVI added four new U.S. teams, bringing the institute total to 13 U.S. teams, and 10 international partnerships. International partnerships collaborate with SSERVI domestic teams on a no-exchange of funds basis, but they bring a richness to the institute that is priceless. The international partner teams interact with the domestic teams in a number of ways, including sharing students, scientific insights, and access to facilities.

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 memory and expands the realm of collaborative possibilities. 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.

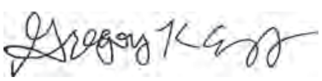
Understanding that human and robotic exploration is most successful as an international endeavor, SSERVI is pleased to have a thriving community of ten international partnerships.

In this report, you will find an overview of the 2017 leadership activities of the SSERVI Central Office, reports prepared by the U.S. teams, and achievements from several of the SSERVI international partners. 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 target destinations. Innovation in the way we access, sample, measure, visualize, and assess our target destinations is needed for further discovery. At the same time, let us celebrate how far we have come, and strongly encourage a new generation that will make the most of future opportunities.

Next year promises to bring its own discoveries and breakthroughs as we mount field expeditions, conduct laboratory experiments and design theoretical models to probe our origins and evolution. Please follow along by visiting our website, sservi.nasa.gov, as well as by subscribing to our Twitter feed and other social media sites.

Yvonne Pendleton

SSERVI Director



Gregory Schmidt

SSERVI Deputy Director
Director of International Partnerships

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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.

The SSERVI 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. We bring multidisciplinary teams together to address fundamental and strategic questions pertinent to future human space exploration, and the results from that research are the primary products of the institute. The team and international partnership reports contain summaries of 2017 research accomplishments. Here we present the 2017 accomplishments by the SSERVI Central Office that focus on: 1) Supporting Our Teams, 2) Community Building, 3) Managing the Solar System Treks Portal (SSTP), and 4) Public Engagement.

Supporting Our Teams

The SSERVI Central Office supports our team research goals not only by ensuring the timely distribution of their funds, but also through the general structure of the institute and the way it operates. Two advantages afforded by the virtual institute model adopted by SSERVI are that we provide long-term, stable environments for projects that require such a platform, and the flexibility to allow course corrections that deviate from the original path if new results merit those changes. As a result, most of the work produced through the institute would not occur in its absence because there are no other NASA programs to which proposers could apply to address questions in this manner.

The SSERVI Central Office is responsible for advocacy of the Institute and ensuring the long-term health and relevance of the Institute. This can take 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-2)

In 2017, SSERVI completed the review of 22 proposals submitted to the CAN-2 proposal call. Through this process, NASA selected and funded four additional teams. Funded by the Science Mission Directorate (not only the Planetary Science Division, but also the Astrophysics Research Division) and the Human Exploration and Operations Mission Directorate (Advanced Exploration Systems Division), the new teams expand and strengthen the research focus of SSERVI. Each team is funded for five years (2017-2022), and will overlap with the CAN-1 teams for approximately two years. The CAN-2 teams and thier Principal Investigators (PIs) are:

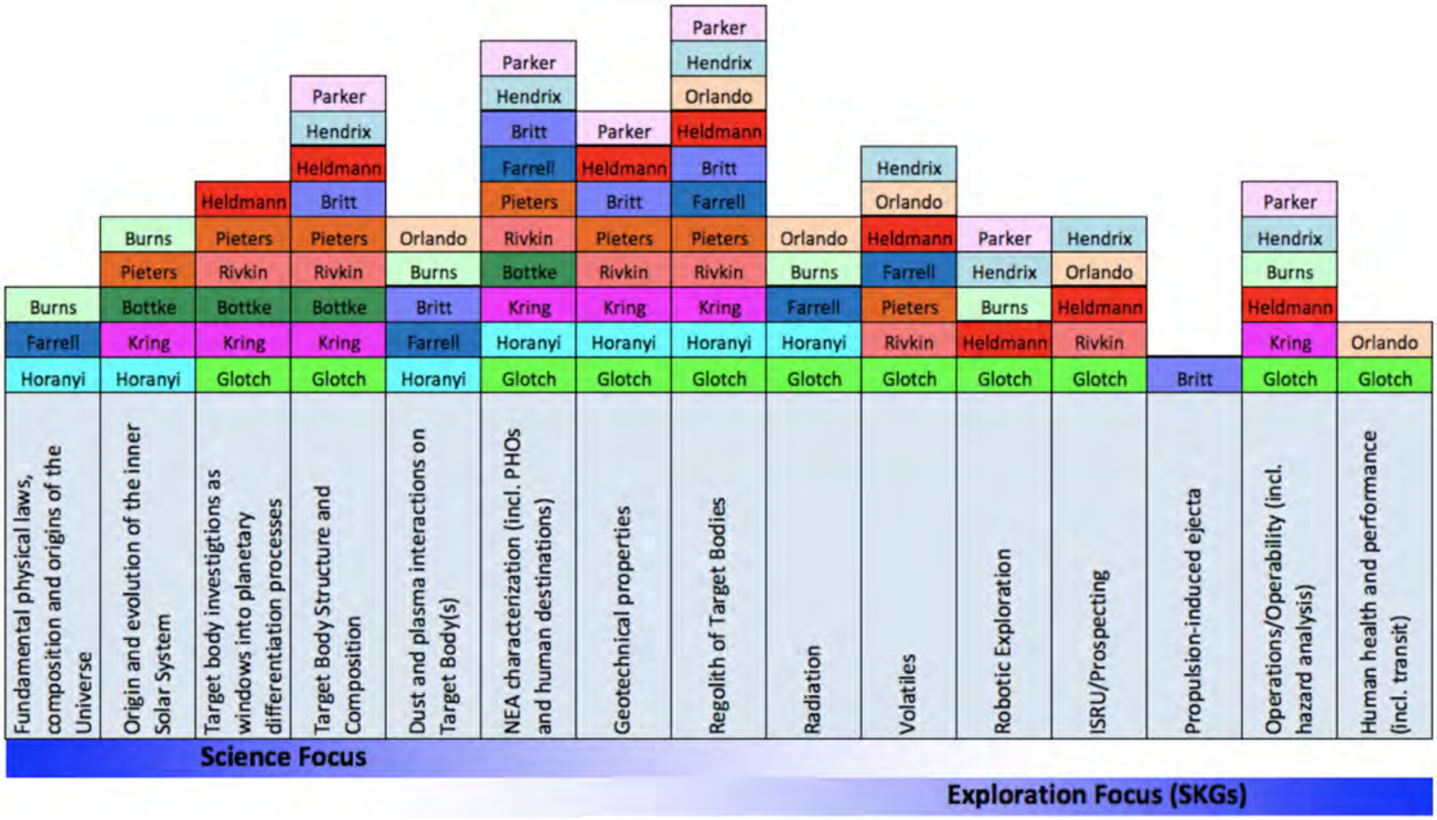
Network for Exploration and Space Science (NESS); PI - Jack Burns, University of Colorado Boulder.

Toolbox for Research and Exploration (TREX); PI - Amanda Hendrix, Planetary Science Institute, Tucson, AZ.

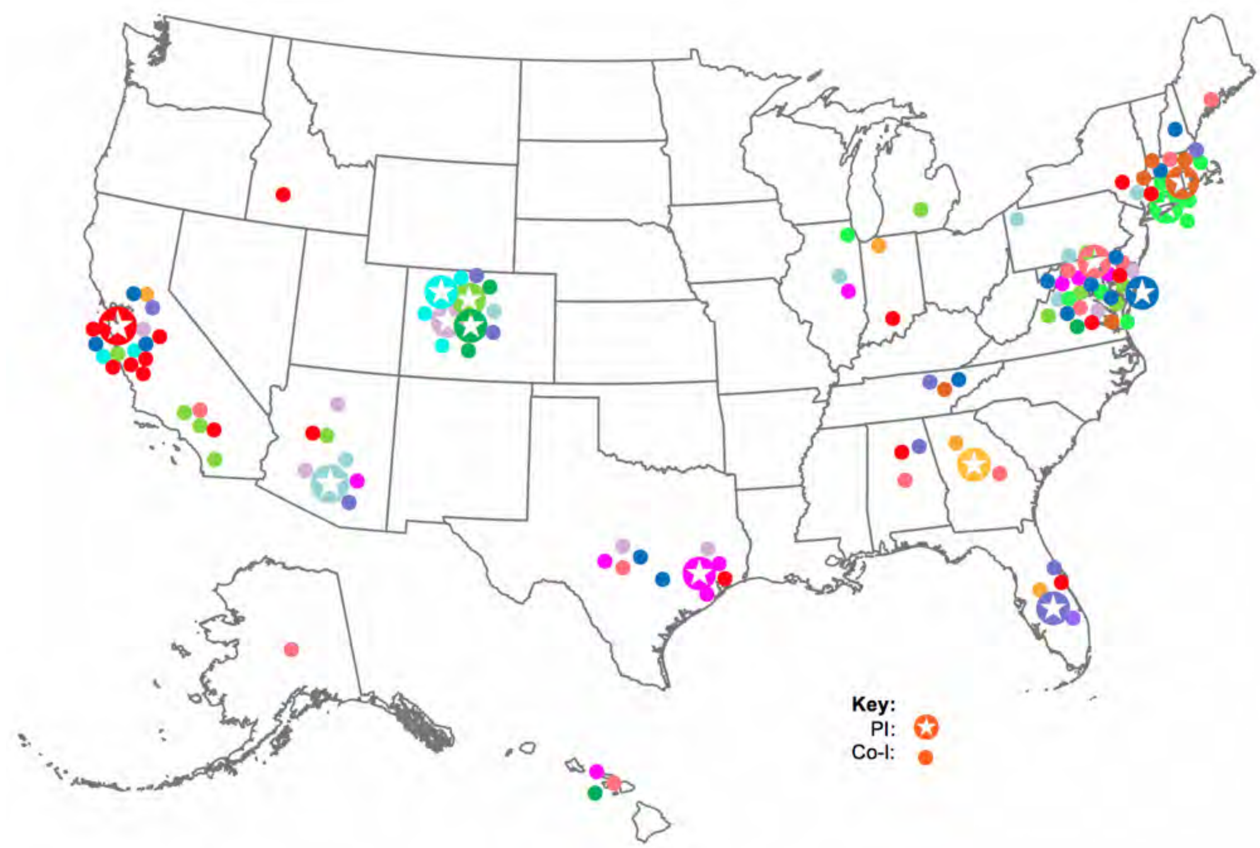
Radiation Effects on Volatiles and Exploration of Asteroids and Lunar Surfaces (REVEALS); PI - Thomas Orlando, Georgia Institute of Technology, Atlanta, GA.

Exploration Science Pathfinder Research for Enhancing Solar System Observations (ESPRESSO); PI - Alex Parker, Southwest Research Institute, Boulder, CO.

Together with the nine teams from CAN-1, SSERVI will address the science and exploration areas:



Science and exploration focus areas of all 13 SSERVI teams.



SSERVI U.S. Team Geography

Reporting

The SSERVI Central Office regularly reports team accomplishments to both the Science Mission Directorate and the Human Exploration and Operations Mission Directorate at NASA Headquarters (HQ), but we also provide visibility of team progress through the SSERVI Headquarters seminar series. Periodically, we select a team Principal Investigator (PI), or representative, to present a seminar at NASA Headquarters based on our strategic assessment of topics most relevant to HQ. In 2017, William Farrell of the DREAM2 team, and Brian Day from the SSERVI Central Office presented headquarters seminars.

Site Visits

Senior leadership from the Central Office conducts team site visits (at least two teams per year) to meet the extended team, including students, and to see their onsite facilities. In 2017, the SSERVI Central Office senior leadership visited the Remote, In Situ and Synchrotron Studies for Science and Exploration (RIS^{4}E) team led by principal investigator Timothy Glotch at Stony Brook University, NY. All SSERVI teams are invited to attend site visits and most site visits attaract several PIs from other teams. In 2017 all of the team PIs were able to attend the Field Investigations to Enable Solar System Science and Exploration (FINESSE) labs site visit, led by Jennifer Heldmann at NASA Ames Research Center, CA (held prior to the NASA Exploration Science Forum at NASA Ames Research Center). Our experience has shown that many cross-team collaborative ideas emanate from these visits.

NASA Postdoctoral Program (NPP)

To further enable cross-team interactions and support the next generation of researchers, the SSERVI Central Office has established a NASA post-doctoral fellowship position to be shared between two or more teams. In 2017, the SSERVI Central Office posted the opportunity and received several applications for appointments in 2018. 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. Katherine Kretke was funded for her second year in 2017 by the SSERVI Central NPP program for her excellent support of the ISET and CLSE teams. The team reports contain information about additional post-doctoral fellows who are supported by and contribute to the research of individual SSERVI teams.

2017 Institute Leadership and Team Member Awards

Our competitively selected teams are leaders in their fields. This is evidenced not only by their publications in well-respected journals and invitations to speak at conferences around the world, but also in the recognition by their peers when they win prestigious awards. Knowing that the following list of awards is likely incomplete, we nonetheless include the following awards received by SSERVI Leadership, Principal Investigators (PIs) and team members in 2017:

SSERVI Central Office:

- Dr. Yvonne Pendleton, Director of the Solar System Exploration Research Virtual Institute at NASA Ames Research Center received the Presidential Rank Award for Meritorious Executive, one of the highest honors available to U.S. government employees.

- The Lunar Orbiter Image Recovery Project (LOIRP) project received the NASA Ames Group/Team award.

SSERVI Teams:

- Dr. William Bottke was honored as a Kavli Foundation Lecturer, 229th American Astronomical Society Meeting, Grapevine, TX.

- Dr. Barrett Caldwell was named a prestigious Jefferson Science Fellow, an initiative of the Office of the Science and Technology Adviser to the U.S. Secretary of State.

- Dr. Robin Canup was elected to the American Academy of Arts and Sciences; she was also appointed to NASA's Planetary Science Advisory Committee.

- Dr. Zena Cardman was selected for the 2017 NASA Astronaut Class.

- Dr. James W. Head III was elected Foreign Member of the Russian Academy of Sciences.

- Dr. Jennifer Heldmann was inducted into the Space

Camp Hall of Fame, U.S. Space & Rocket Center.

• Dana Hurley was appointed to the NASA Planetary Science Advisory Committee.

• Erica Jawin was elected to the Board of Association for Women Geoscientists for a three-year term. She was also awarded the Lunar Exploration Analysis Group's (LEAG) Bernard Ray Hawke Next Lunar Generation Career Development Award.

• Dr. Andrea Jones received a NASA Group Honor Award for MSL Extended Mission-1 Science and Operations Team.

• Dr. Rosemary Killen won the NASA Goddard Space Flight Center Robert H. Goddard award for exceptional achievement in science.

• Dr. Linda Kobayashi received the NASA Exceptional Service Award.

• Dr. Simone Marchi was awarded the 2017 Paolo Farinella prize.

• Dr. Francis McCubbin was given the Nier Prize at the Meteoritical Society meeting.

• Dr. Catherine Neish received the Early Researchers Award from the Ontario Ministry of Research, Innovation, and Science.

• Dr. Dava Newman was awarded the Women In Aerospace Leadership Award, the NASA Distinguished Service Medal, and the Aerospace Medical Association's Henry L. Taylor Award.

• Dr. Gordon Osinski was awarded the Western University Science Outreach Award and was nominated to the Canadian Space Advisory Board.

• Dr. Tom Prettyman was presented with the NASA Exceptional Scientific Achievement Medal.

• Dr. David Saint-Jacques of the Canadian Space Agency, was selected for spaceflight and will launch to the ISS in 2018.

• Dr. Dan Scheeres was elected to the National Academy of Engineering.

• Emily Worsham was awarded the Nininger Prize from Arizona State University.

• Andrew Abercromby, Kara Beaton, and Steve Chappell received a NASA Ames Research Center Special Appreciation Honor Award for collaboration with ARC analog campaigns.

• S. Quintana Bouchey received the LPI 2017 Career Development Award.

• Michael Gerard graduated Summa Cum Laude. He was also awarded the Stephen Halley White prize at the University of Colorado.

• SEEED team Graduate students were winners of the prestigious 2017 Dwornik awards for research presented at LPSC: Terik Daly (Best oral presentation); Kevin Cannon (Honorable Mention Oral presentation); Tess Caswell (Best Poster presentation); Hannah Kaplan (Honorable Mention poster presentation).

• The FINESSE team was presented with a NASA Ames Research Center Group/Team Honor Award.

• Dr. David Kring's "Guidebook to the Geology of Barringer Meteorite Crater, Arizona," 2nd ed. received the Best Guidebook Award of 2017 by the Geoscience Information Society at the recent Geological Society of America meeting.

Community Building

The SSERVI Central Office has the responsibility to grow and maintain a community of researchers beyond those directly associated with the institute as team members. 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 sponsoring the annual NASA Exploration Science Forum and smaller workshops, hosting community-wide virtual events, devloping 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 2017 NESF, which coincided with the 48th anniversary of Apollo 11's return flight to Earth, featured 90 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, along with public engagement discussions, were interwoven among science topics. Other activities included a showcasing of the Trek suite and Tech demo of augmented reality (AR) and virtual reality (VR).

Special guest astronaut Harrison Schmitt, who walked on the Moon during the Apollo 17 mission, led a panel discussion to honor both Eugene Cernan and the Apollo missions.

SSERVI researchers teamed with GSFC's virtual science data team to produce landscapes for AR and VR. Here Alan Stern, principal investigator of the New Horizons mission, uses VR goggles to explore a lunar analog environment in hi-def.

As a tribute to the late Apollo 13 astronauts Gene Cernan and Ron Evans, a special panel focusing on the importance of the Apollo missions was held on July 18.

On July 19, a panel discussion focused on the detection and formation pathways of water on the moon. Alan Stern, principal investigator of the New Horizons mission, gave a keynote address on July 20, about NASA's historic mission to the Pluto system and the Kuiper Belt. Dr. Stern enabled the creation of the NASA Lunar Science Institute in 2008, paving the way for the development of SSERVI in 2013.

The SSERVI Central Office technology team seamlessly integrates virtual presenters and online attendees. The 2017 NESF was attended by 250 people (in-person) and had strong virtual participation (1,104 unique live-stream/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: nesf2017.arc.nasa.gov/program .

The fourth annual NASA Exploration Science Forum (NESF), held July 18-20, 2017 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.

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. In addition, in 2017 SSERVI established 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.

SSERVI Director Yvonne Pendleton presents Maria Zuber with the Eugene Shoemaker Distinguished Scientist Medal at the 2017 NESF.

Eugene Shoemaker Medal

SSERVI's 2017 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. Maria Zuber (Massachusetts Institute of Technology) for her significant scientific contributions throughout the course of her career. The award included a certificate and medal with the quote from Shakespeare, "And he will make the face of heaven so fine, that all the world will be in love with night."

Maria Zuber's research focuses on the structure and tectonics of solid Solar System objects. She specializes in using gravity and laser altimetry measurements to determine interior structure and evolution and has been involved in more than half a dozen NASA planetary missions aimed at mapping the Moon, Mars, Mercury, as well as several asteroids. She was the principal investigator for the Gravity Recovery and Interior Laboratory (GRAIL) mission, and as such became the first woman to lead a NASA spacecraft mission.

Michael J. Wargo Award

The Michael J. Wargo Exploration Science Award is an annual SSERVI award given to a scientist or engineer 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 2017 Michael J. Wargo Exploration Science Award was given to Dr. Lawrence

(Larry) Taylor of the Planetary Geosciences Institute (University of Tennessee, Knoxville).

Lawrence Taylor studied lunar rocks and soils since Apollo 11, and participated in advising the Apollo Astronauts during their EVAs on the Moon. His studies of the chemical, physical, & geotechnical properties of lunar regolith led to several significant geotechnical discoveries related to In-Situ Resource Utilization (ISRU) of lunar materials for establishing a lunar settlement. His efforts expanded into meteorites when many lunar and martian meteorites found in the Antarctic and equatorial hot deserts provided renewed interest and excitement for these heavenly bodies. His zeal for a human-return to the Moon was unabated, and his unexpected passing shortly after the NESF was a significant loss to the community.

Angioletta Coradini Mid-Career Award

The SSERVI Angioletta Coradini Mid-Career Award will be given annually to a mid-career scientist for broad, lasting accomplishments related to SSERVI fields of interest. Named in honor of planetary scientist Dr. Angioletta Coradini, the 2017 award was given to Angioletta posthumously, with her brother, Dr. Marcello Coradini accepting it on her behalf at the NESF. Angioletta Coradini (1946-2011) was an Italian planetary scientist who inspired astronomers around the world. She was a co-investigator for NASA lunar and planetary research (1970–74); a member of the Cassini-Huygens mission Science Team for the CIRS and VIMS instruments, and PI of the VIMS visible channel (1991–2011), and coordinator of the Moon Orbiting Observatory (MORO) proposal and member of the MORO science team (1993–96); and PI of the Jiram Instrument for the NASA New Frontiers Juno mission (2005–11).

Susan Mahan Niebur Early Career Award

The Susan Mahan Niebur Early Career Award is an annual SSERVI 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 have received their PhD within the last ten years, have demonstrated excellence in their field, and have made meaningful contributions to the science or exploration communities. Susan Mahan Niebur (1978-2012) was a Discovery Program Scientist at NASA Headquarters who initiated the Early Career Fellowship and the annual Early Career Workshop to help new planetary scientists break into the field. This year the prize was presented to two outstanding scientists, Dr. Adrienne Dove (University of Central Florida), and Dr. Samuel Lawrence (Astromaterials Research and Exploration Science Division at NASA's Johnson Space Center).

Dr. Dove's research focuses on planetary sciences and dusty plasmas in the Solar System. Her laboratory research on microgravity and dusty plasmas, collisions, and planet formation is helping resolve fundamental mechanisms of dust charging and transport, which have been puzzling scientists for decades.

Dr. Lawrence is an expert in exploration science and extraterrestrial materials, a Co-Investigator on the Lunar Reconnaissance Orbiter Camera science team, and an active member of the Executive Committee of the Lunar Exploration Analysis Group, working to enable human exploration of the Moon and other destinations.

Focus Groups

SSERVI established focus groups to facilitate collaboration between SSERVI Teams and the extended research community. The focus groups meet in person during the NESF each year and virtually in between. Over the past ten years, eight focus groups have been convened on the subjects of Apollo Lunar Surface Experiments Package Data Recovery; Dust, Atmosphere and Plasma; South Pole-Aiken Basin; Bombardment History of the Solar System; Space Commerce; Volatiles; Payloads and Instrumentation, and Field Analogs.

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

> 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.

clarity of the presentation (including accessibility to the non-expert), and impact to science and exploration.

The 2017 NASA Exploration Science Forum Student Poster Competition winners were:

*First Place awarded to Erica Jawin for the poster "The Prinz-Harbinger Medium-Scale Shield Volcano: a Transition in Lunar Volcanic Eruption Style."

*Second Place awarded to Zachary Morse for the poster "Mapping and Analysis of Ejecta Deposits from Orientale Basin on the Moon."

*Third Place awarded to Zach Ulibarri for the poster "Laboratory Study of Hypervelocity Impact-Driven Chemical Reactions and Surface Evolution of Icy Targets."

*Honorable Mention awarded to Karen Abruzzo, Delina Levine, and Pragati Muthukumar for the poster "Mapping Possible Locations for Lunar Ice Mining Based on Topographic, Economic, and Elemental Data."

Lunar Grad Conference

Lunar Grad Con 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 non-threatening environment. More information can be found at: lunarscience.arc.nasa.gov/articles/lungradcon .

Virtual Events

The SSERVI Central Office technology team has a wide array of communication and collaboration tools that have helped build and continue to strengthen our teams and our communities. 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 have been seamlessly integrated to produce virtual seminars and workshops. SSERVI is pleased to facilitate effective communication and to enable collaborative research and data sharing. 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. Furthermore, our tech team also supports a limited number of activities that indirectly support the broader community.

Website Development

The SSERVI Central Office develops websites and web applications to support our communities. Several of these websites are listed below. Nearly every conference, workshop and meeting that SSERVI hosts has a virtual component that becomes an archived resource available through the SSERVI website, sservi.nasa.gov, which is regularly updated with the latest science highlights and results from SSERVI teams. In 2017 the technical staff at the SSERVI Central Office made advancements in web infrastructure security and interface design, providing a modern and reliable user experience across all platforms.

SSERVI has developed and integrated a suite of communication and collaboration tools to strengthen our communities. The SSERVI Central Office technology team regularly evaluates new technologies to improve

The SSERVI Central Office sponsored and supported 78 events in 2017:

- The annual NASA Exploration Science Forum
- 2 SSERVI Director's Seminars at NASA Headquarters
- 7 SSERVI Executive Council Meetings
- 1 SSERVI CAN-2 PI Orientation Meeting
- 1 RIS4E Site Visit
- 1 SSERVI/JAXA Video Teleconference
- 1 CLASS Seminar featuring Carballo-Rubio
- 23 CLASS "Tech and Future of ISRU" Seminar events
- 12 NASA Earth Science and Space Science Fellowships panel reviews
- 5 seminars for the NASA Astrobiology Institute
- 2 multi-day Small Bodies Assessment Group meetings
- 4 Asteroid Threat Assessment Project seminars
- 2 Days of the Global Exploration Roadmap workshop
- 2 NASA Human Research Program (HRP) Pre-Proposal Conferences
- 11 Far Infrared Surveyor Interest Group Webinars
- 1 IMPACT workshop on Dust, Atmosphere and Plasma environment of the Moon and Small Bodies (DAP-2017)
- 1 Autonomy on Future SMD Missions Workshop
- 1 National Autonomous University of Mexico (UNAM) Presentation

Website	Description	URL
SSERVI	Defines the Institute while highlighting SSERVI research, related science, events/activities, and resources to the community. Recorded presentations from previous NESF conferences and seminars can be accessed from this site.	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.	nesf2017.arc.nasa.gov nesf2018.arc.nasa.gov
SSERVI Awards	The SSERVI Awards website highlights past winners of the distinguished Shoemaker Medal, Coradini, Niebur, and Wargo 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, which include "Getting a Feel for Lunar Craters" and "Getting a Feel for Eclipses" books for the blind.	sservi.nasa.gov/books
European Lunar Symposium	The European Lunar Symposium (ELS) website provides users with logistics, registration, and abstract information related to the annual event.	els2018.arc.nasa.gov
Lunar Orbiter Image Recovery Project	The Lunar Orbiter Image Recovery Project (LOIRP) has successfully digitized numerous images from the Lunar Orbiter spacecraft which have been made available on the LOIRP website.	loirp.arc.nasa.gov
Strategic Knowledge Gaps	Strategic Knowledge Gaps (SKGs) represent gaps in knowledge or information required to reduce risk, increase effectiveness, and improve the design of robotic and human space exploration missions. NASA uses SKGs to help inform research and investment strategies, and prioritize technology development for human and robotic exploration. SSERVI has developed a website where users can search and sort through the various SKGs.	In review by NASA HQ prior to release.
Lunar Science for Landed Missions Workshop	The website, developed in 2017 for the "Lunar Science for Landed Missions Workshop" (held in Jan of 2018), hosts all the logistics, registration, abstract submissions, and presentations related to the meeting.	lunar-landing.arc.nasa.gov
Carbon in the Solar System Workshop	The website, developed in 2017 for the "Carbon in the Solar System Workshop" (April 2018) will host all the logistics, registration, abstract submissions, and presentations for this meeting.	carbon-workshop.arc.nasa.gov
Ames Collaboration Team	SSERVI has provided the Ames Collaboration Team with an application that schedules events which are recorded to a database and 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

our multimedia production capabilities and enhance the live and on-demand playback experiences for in-person, virtual, and hybrid events. The 2017 NASA Exploration Science Forum live-stream production integrated the YouTube streaming platform which delivers an engaging experience while accommodating any size audience and reduces technology barriers between content and viewers. This tailored platform integrated with an array of specialized hardware and expertise, significantly improved the live-stream and recording components. Furthermore, using these elements enabled the delivery of full high-definition video and high fidelity audio, live and on-demand closed captioning, and the ability to share, embed, and publish presentation recordings in real-time. Located in the heart of Silicon Valley, the SSERVI Central Office technology team continuously evaluates innovative technologies to identify new capabilities.

Strategic Knowledge Gaps

NASA's Strategic Knowledge Gaps (SKGs) identify missing information needed to send humans beyond low-Earth orbit. The NASA Human Exploration and Operations Mission Directorate (then the Exploration Systems Mission Directorate) initiated the effort as a way to prioritize near- term Agency investments, and inform the planning and design of missions and systems that would enable human missions to the Moon, near-Earth asteroids (NEAs), Mars, and the Martian moons Phobos and Deimos. The SKGs are classified in three categories: 1) required for a successful mission, 2) reduce risk to the mission or crew, or 3) enhance the effectiveness of the mission or crew. These datasets may be obtained on Earth or in space, and by modeling, analog environments, experimentation, or direct measurements.

In 2017, SSERVI contributed to the generation and evaluation of new Phobos/Deimos SKGs and the development of a new SKG website and database. The new website enables members of the community to add publications and data to help close (or partially close) a specific SKG, whereupon a team of experts review the new data and determine the resultant status of the SKG. This website and database will allow decision-makers at HQ to quickly identify needs for gap closure with current or upcoming mission/payload opportunities.

Facilities Open to the Community

The following SSERVI-sponsored facilities can be made available to the broader scientific community. Interested parties should engage the facility POC to discuss scheduling time at the facility, along with any potential associated costs. Research activities that took place using team-supported facilities can be found in the individual team reports; here we briefly describe 2017 activities in the SSERVI Central Office-supported Regolith Testbed.

SSERVI Team Facilities

Dust Accelerator Laboratory (DAL) (U. of Colorado

A 3 MV linear electrostatic dust accelerator 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

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

Dedicated chambers that can be 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)

Spectroscopic data can be obtained for 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)

Spectroscopic tools allow 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)

The density lab includes: (1) A Quantachrome Ultrapycnometer 1200. (2) A new 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%. (3) ZH Instruments SM-30 magnetic susceptibility meter. (4) A fieldspec reflectance spectrometer with a wavelength range of 0.4-2.5 microns. Contact: britt@physics.ucf.edu

GSFC Radiation Facility (NASA GSFC)

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 drop tower provides a zero g experience (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 testbed at NASA Ames is filled with 8 tons of JSC-1A regolith simulant. Excellent for investigations in resource prospecting and regolith. Contact: joseph.minafra@nasa.gov

Regolith Testbed Managed by SSERVI Central Office

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 2017, SSERVI provided the facilities and operational support for innovative lighting research funded by the agency's

The "First Man" movie from Univeral Studios used SSERVI's regolith testbed to recreate realistic sounds from the Apollo missions. In order to recreate realistic sounds, the team used authentic Apollo artifacts such as footware and gloves to simulate a recreation of this heroic event.

Advanced Exploration Systems and Game Changing Development programs. Researchers tested special stereo-camera systems to improve stereo viewing capabilities and understand how robotic systems can navigate in the challenging lighting conditions at the lunar poles. The work produced a Polar Optical Lunar Analog Reconstruction (POLAR) dataset, providing standard information for rover designers and programmers to develop algorithms and sensors for safe navigation. The POLAR dataset is applicable not only to our Moon, but to other airless bodies, including Mercury, the asteroids, and regolith-covered moons like Mars' Phobos.

In 2017, SSERVI created a comprehensive database of regolith simulants for the community. The SSERVI Central Office also provided JSC-1A simulant to Made in Space Inc., furthering a novel technological approach to regolith brick-building. In addition, SSERVI participated in the "Regolith Operations, Mobility and Robotics" technical committee of the NASA and American Society of Civil Engineers (ASCE).

Solar System Treks Project

The Solar System Treks Project (SSTP) is managed by the SSERVI Central Office, overseeing the JPL development team. This year witnessed significant changes as the Lunar Mapping and Modeling Project (LMMP) evolved into the Solar System Treks Project (SSTP) with a significantly expanded scope covering development of new portals for new target bodies, and involving an expanded user base. The original LMMP portal was retired and replaced by the new Moon Trek portal, featuring greatly enhanced data visualization capabilities, improved performance, new data layers, and new analysis tools. In 2017, the development team included the dramatic implementation of virtual reality.

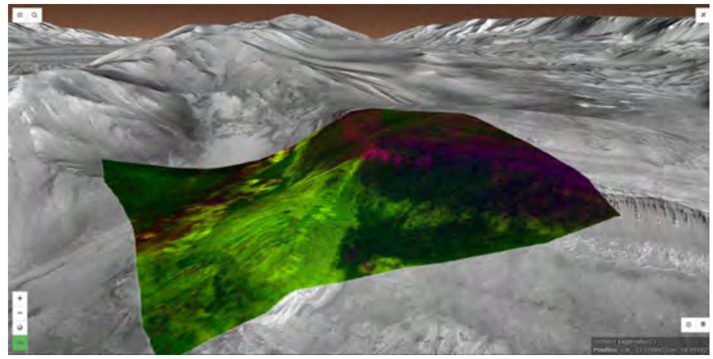
As directed by the Planetary Science Division, SSTP expanded to targets beyond the Moon. Mars Trek 3.0 was released with new tools, the new standardized Trek interface, and new data for Human Exploration Zones. A prototype for Phobos Trek was developed and demonstrated, which integrated data from a number of SSERVI researchers: Tim Glotch (RIS4E)/Phobos thermal modeling; Tim Stubbs (VORTICES)/ solar visibility, flux, incidence angle, and radiation exposure; and Stefaan Van Wal (ISET)/ejection velocity mapping. The Cassini Mission commissioned the project to create a portal for Titan, now under development, along with portals for other moons of Saturn to follow.

Collaborations within NASA this year included sharing code with and ingesting data from Resource Prospector, which included working with the SSERVI DREAM2 team to integrate their surface potential analysis algorithm. SSTP worked with the Astromaterials Curation Office at JSC to integrate their database of lunar samples and MoonDB data, and conducted Moon Trek training for Apollo Lunar Certification staff. Members of the team served on the steering committee for the MarsGIS working group, helped to organize the MarsGIS Workshop, and participated in the Mars 2020 Landing Site Workshop.

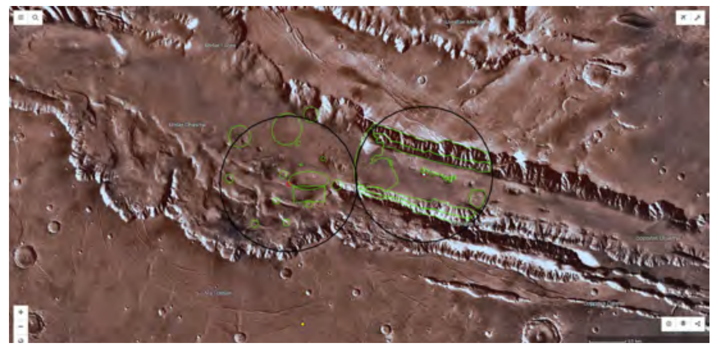
Collaborations with NASA's international partners were especially prominent this year. The Korean Space Agency (KARI) and Geoscience Institute (KIGAM) invited SSTP to Korea to demonstrate Moon Trek. Discussions with KARI considered how Moon Trek could be used for visualization and analysis of data from the Korean Pathfinder Lunar Orbiter. KIGAM explored the ways in which various portals could be integrated into their planetary research and education programs. SSTP gave a remote invited talk about Moon Trek at the Korea-Japan Bilateral Planetary Program's Planetary Geology Workshop. SSTP and JAXA discussed how portals could be used with Japanese missions; portal demonstrations were provided at the Japanese Geoscience Union (JpGU), and the Phobos Portal is being designed specifically to support the JAXA MMX mission. At the invitation of the European Space Agency, SSTP management conducted a workshop on lunar traverse planning with Moon Trek at the ESTEC facility. SSTP also served data from Moon Trek for use in ESA's MoonDesk software. In collaboration with SSERVI's Italian partner, SSTP enhanced Moon Trek with their lunar laser retroreflector and specular reflections studies. The Director General and Deputy Director of the Mexican Space Agency (AEM) discussed using Moon Trek with their upcoming lunar payload, and featured Mars

Trek as an invited keynote talk for their Mars Exploration Congress. Moon Trek and Mars Trek were demonstrated to representatives of Roscosmos attending the GER meeting at Ames.

Outreach to the planetary science community, students, educators, and the general public is a key responsibility for the SSTP project. This year, SSTP was demonstrated at eleven major conferences, and at the SSERVI Director's Seminar at NASA HQ. An SSTP online seminar for librarians assisted with planning events for International Observe the Moon Night (InOMN), and SSTP conducted talks in many schools, libraries, the California State Parks, and at Comic Con. The project serves as key infrastructure for SMD's STEM Activation Initiative. For the third consecutive year, SSTP supported schools and educators in their "Explore Mars!" program in which students use Mars Trek to develop Mars landing site proposals. An especially valuable educational component for the project has been the continuing partnership with California State University, Los Angeles, in which computer science students develop new SSTP components as a senior project.



Sulfates abundance in Melas chasma from CRISM data integrated into MarsTrek.



Exploration zones in Valles Marineris from MarsTrek.

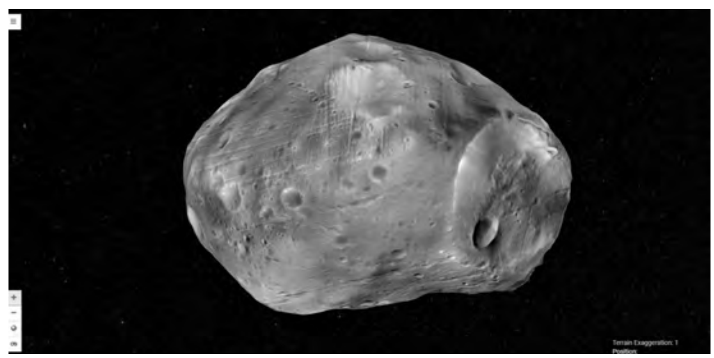
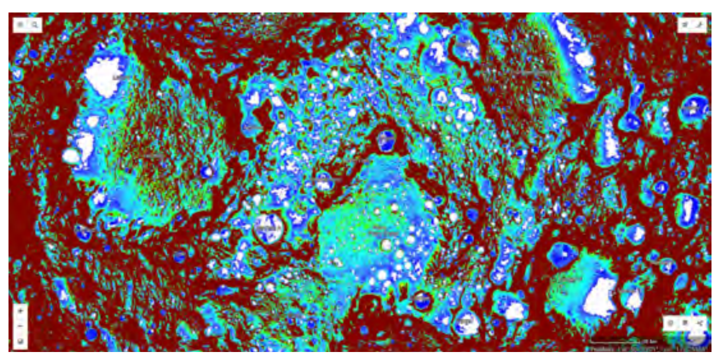


Image capture from PhobosTrek prototype.



Ice stability at depth shown in a MoonTrek map of the lunar north pole.

Public Engagement

The SSERVI Central Office and SSERVI teams conduct extensive public engagement activities throughout the year. The team reports list some of these activities, and the SSERVI Central Office activities for 2017 are discussed here. 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.

Eclipse Events

On Monday, August 21, 2017, North America experienced a total solar eclipse from Oregon to South Carolina. Those with clear skies in the "path of totality" experienced one of nature's most awe-inspiring events—the Moon passing directly between Earth and the Sun to completely cover our star. NASA followed the shadow of the Moon in two retrofitted WB-57F jet planes, provided Livestream coverage of the eclipse with subject matter experts at various locations along the path of totality, and held science briefings. SSERVI participated from start to finish with outreach experts located from Oregon to South Carolina, and distributed approximately 10,000 solar eclipse glasses across the country.

SSERVI Central Office Staff gave an invited talk and watched the eclipse with Vice President Mike Pence at the U.S. Naval Observatory in Washington, DC.

SSERVI Central Staff also assisted SSERVI teams with an eclipse training workshop for 47 South Carolina State Park Rangers and other state park representatives. The

Vice President Mike Pence, watches the solar eclipse, Monday, August 21, 2017, at the U.S. Naval Observatory in Washington, D.C.
Photo credit: NASA/Brad Bailey

training focused on activities to teach the general public about solar eclipses, and how to include and engage sight impaired people with the SSERVI-sponsored "Getting a Feel for Eclipses" book for the blind. In Charleston, SC, SSERVI staff also presented at "Girls Day Out," a science camp for underprivileged students. SSERVI also supported NASA's Solarfest in Madras, Oregon; for more, follow NASA SSERVI's "Road to the Eclipse" chronicled in images on Instagram @nasasservi .

Photo of the Sun's corona during the total eclipse over Madras, OR.
Photo credit: NASA/David Morrison

Braille Books

One of the truly unique products to emanate from a combined effort between the SSERVI Central Office and the SEEED team (Carle Pieters, PI) is a series of books for the sight impaired. In 2017, a book titled "Getting a Feel for Eclipses" joined the unique series of SSERVI braille books, so that one can experience not only the Moon, Mars, and an Asteroid, but also eclipses. The eclipse tactile guide is the latest in a series of space-related braille books, following "Getting a Feel for Lunar Craters" and "Exploring Mars," as part of a larger effort to get students excited about science and math. SSERVI provides design, graphics and print production for these books for the blind. Over 5,000 copies of the eclipse book

were sent to schools and libraries for the blind, science centers and museums, state libraries, NASA centers, and other institutions; the books were also distributed at the National Federation of the Blind Conference in Orlando, FL. For more information see: https://sservi.nasa.gov/books/

Robotics Competitions

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

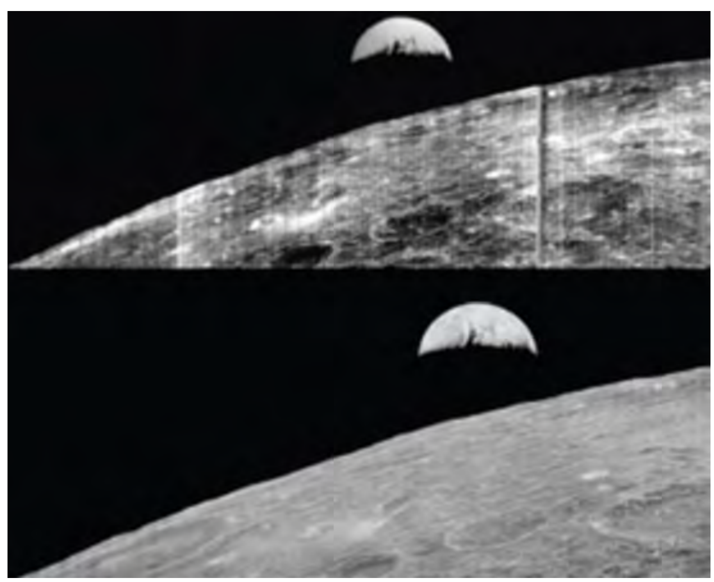
SSERVI Central Office Staff contributed to the 3D-Printed Habitat Challenge, sponsored by NASA's Centennial Challenge, at the CAT proving grounds in Peoria Illinois, August 22-27, 2017. The competition is created to incentivize America's most talented engineers to come up with innovative ways to design and print a habitat that could be used for deep space exploration.

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.

Lunar Orbiter Image Recovery Project (LOIRP)

NASA funded LOIRP to digitally reprocess the original lunar orbiter images that were integral to the safe Moon landing by Apollo astronauts, and the SSERVI Central Office managed the project. In 2017, a comprehensive collection of images from all five Lunar Orbiters was recovered in optimal resolution/dynamic range and delivered to the Planetary Database System. The images have ~4x the dynamic range compared to the original images, with twice the average resolution of archived USGS images. These datasets will be critical to understanding the lunar cratering record over the past 50 years.

The New Museum Los Gatos (NUMU) partnered with the Lunar Orbiter Image Recovery Project (LOIRP) and NASA to honor the 50th anniversary of the lunar orbiter with a spectacular museum exhibit (Sept 22 - May 14), featuring original lunar images from 1966-1967. The "McMoons" exhibit told the little-known story of LOIRP, which began in a Pasadena garage before moving to an abandoned McDonald's restaurant in the NASA Ames Research Park, where archival space history was made.



The reprocessed LOIRP images have ~4x the dynamic range with twice the average resolution of archived USGS images. These datasets will be critical to understanding the lunar cratering record over the past 50 years.

Reaching Underserved Communities

Journey Through the Universe

The SSERVI Central Office participated in the Journey Through the Universe program. During the week of March 13-17, 2017, 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

On Saturday, March 11th, two SSERVI entral Office staff held a certification workshop that enables teachers to borrow lunar and meteorite samples from the historic Apollo missions. 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

Students at Kapiolani Elementary were surprised and excited that NASA had graphic designers like SSERVI Central's Jennifer Baer. Here, Jennifer is showing students how they can edit pictures with illustration software. Credit: Joy Pollard/Gemini.

SSERVI Communications Lead Teague Soderman showed Kaumana students some of the mapping software available online through SSERVI. Credit: Joy Pollard/Gemini.

aboard a great range of spacecrafts.

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. The primary citizen science focus in 2017 was to promote the Fireballs in the Sky program of the Desert Fireball Network (DFN) run by SSERVI's Australian partner. SSERVI presented Fireballs in the Sky to the NASA Citizen Science Forum, the NASA Solar System Ambassadors, the NASA Museum Alliance, the NASA Night Sky Network, and at the American Geophysical Union (AGU) conference, as well as supported Curtin University's presentation at the Citizen Science Association conference in Minnesota. In 2017, the Fireballs in the Sky program was featured at the Astronomical Society of the Pacific (ASP) Summer Teacher Institute, and showcased at the California Academy of Sciences planetarium, which was an exceptional platform on which to display DFN data visualization.

International Observe the Moon Night (InOMN)

SSERVI is a proud sponsor of InOMN, 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

SSERVI's Brian Day (six from the left) and Joseph Minafra (four from the left) led 10 teachers through a workshop that certifies them to borrow lunar and meteorite samples as teaching tools. The samples provided contained lunar rocks harvested from the historic Apollo missions, with advice on how best to use these samples in the classroom. Credit: Joy Pollard/Gemini

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 eighth annual International Observe the Moon Night was held on October 28, 2017. The InOMN 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 (InOMN), which helps to organize hundreds of events around the world. In 2017, SSERVI partnered with the Peninsula Astronomical Society to conduct the Bay

Number of Events	Category	Number of People Engaged
14	Public Events	10,660
17	K-12 Classrooms & Universities	10,691
1	Science Festivals (e.g. Space Festival)	9,000+
6	Professional Conferences	8,182
2	Challenges and Competitions	3,800+
1	National/State parks	135
8	Professional Educators	516
Total: 49		42,984

SSERVI Central Office 2017 Public Engagement Summary

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/

Area InOMN 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.

SSERVI also worked with Mexican colleagues at UNAM University and Universum Science Center to conduct a remote solar eclipse webcast for classrooms across Mexico.

Acknowledgments

The SSERVI Central Office thanks our NASA Headquarters supporters: Jim Green, Sarah Noble and Doris Daou from the NASA Science Mission Directorate; Jason Crusan, Ben Bussey, Victoria Friedensen, and Bette Siegel from the NASA Human Exploration and Operations Mission Directorate. We gratefully acknowledge continued support from NASA Ames Research Center Senior Management, ARC grant specialists, and 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 2017 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 is focused on a synergistic approach to understanding the processes and properties of airless bodies. The team cross-feeds theory, observations and experiments to develop new insights into these exploration targets that can impact the design and operations of both human and robotic exploration. Highlights this year include: (1) Development of asteroid, martian, and Phobos simulants to support exploration research and testing; (2) Support for JAXA Martian Moons eXploration (MMX) with investigations into the physical properties of Phobos surface materials; (3) Observations of asteroids linked with laboratory simulations of space weathering which have developed testable implications for terrains on mission targets Bennu and Ryugu; (4) Development of a 2U CubeSat (SurfSat) to explore the charging of dielectric materials which can directly impact spacecraft design and operations, and a 3U CubeSat (QPACE) to explore planet formation and planetary surface modification; (5) Realization that robots in the annual NASA Robotic Mining Competition have been significantly evolving and improving their overall mobility year-by-year by tracking a combination of metrics developed by CLASS; (6) The team brought together the ISRU community to produce a graduate capstone seminar that captured the current state of ISRU and where it can go from here, and (7) Discovered surprising thermal properties in the critical CM carbonaceous chondrite meteorites that have major implications for sample return and ISRU.

The Center for Lunar Science and Exploration (CLSE) team led by Dr. David Kring at the Lunar and Planetary Institute and NASA Johnson Space Center studies impact history and processes, geochemistry of regoliths, and ages of regolith materials on the Moon and other airless bodies. The team also focuses on near-Earth asteroid identification and characterization. In 2017, a large fraction of the team's work concentrated on the accretion and redistribution of volatile-bearing bodies in the early Solar System, the delivery of that material to the Earth-Moon system, and cycling of those volatiles within planetary interiors before being vented at the surface. In the case of the Moon, volcanically-vented volatiles generated a transient atmosphere, a finding that dramatically and forever changes our view of the Moon. Moreover, that venting may be a major (if not the dominant) source of water ice in the polar regions of the Moon where deposits may be mined for a sustainable exploration effort. The team also investigated strategies for exploring the Moon using crew in orbit and on the surface to support both SMD and HEOMD objectives.

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 fourth program year the team produced over 25 papers on the space environment at airless bodies. In the area of surface interactions, the team presented a new model of the expected solar wind implanted hydrogen trapping in the lunar regolith, performed laboratory experiments in the GSFC Radiation Facility of proton implantation and hydroxyl creation in mineral samples, and modeled the solar wind weathering rate based on new ion measurements from the Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission. In the area of exospheric research, the team presented a generalized model of exosphere creation and simulated lunar exospheric water events from micro-meteoroid impacts with an eye toward Lunar Atmosphere and Duse Environment Explorer (LADEE) applications. In the area of space plasma, team members examined the plasma wave turbulence found overlying lunar magnetic anomalies and examined the possible complex plasma flow around a potentially magnetized asteroid, 16 Psyche. 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 and model the possible deep dielectric discharge that can occur at cold regions on airless bodies. As part of an intra-mural project, the team has published and/or presented a set of models on the space environment at Phobos, including illumination, surface charging, astronaut first contact, and the first preliminary radiation-surface model for this unusual exposed body. To enable this array of 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 and topics have become so intimately connected across these teams that other team investigators at times have operated as an extension of DREAM2, resulting in many cross-team authorships.

The Field Investigations to Enable Solar System Science and Exploration (FINESSE) team led by Dr. Jennifer Heldmann at NASA Ames Research Center is an interdisciplinary team of scientists, technologists, and mission operations specialists focused on conducting field-based research to understand geologic processes on the Moon, asteroids, and Phobos & Deimos while simultaneously preparing for future human and robotic exploration of these destinations. FINESSE includes team members from government, academia, and industry, including both domestic and international partners. The team operates under the philosophy that "science enables exploration and exploration enables science." FINESSE-supported fieldwork has been conducted at Craters of the Moon National Monument and Preserve in Idaho, the West Clearwater Lake Impact Structure in northern Canada, the volcanic fields of Hawaii, and newly erupted volcanic landscapes in Iceland. New laboratory experiments were conducted at the Syracuse Lava Project this year where basalt is melted into lava and solidifies to form volcanic rock under controlled laboratory conditions. In 2017, FINESSE research showed that a new classification scheme for impact rocks is warranted to reflect the formation processes of impact craters throughout the Solar System. The team also demonstrated the power of impact crater age dating and showed that the East and West Clearwater Impact Structures did not form at the same time and instead are the result of two distinct impact events. Exploration of several impact age dating techniques has led to new recommendations regarding sample collection for planetary geochronology missions to accurately date planetary impact structures. The team has also developed multiple new techniques for using remote sensing data (validated through ground truthing) to understand geologic formation histories of volcanic features, which is tremendously useful for lunar studies where in-situ analysis is typically not possible and most science is conducted remotely. FINESSE also conducted high fidelity mission simulations to assess the use and integration of handheld field portable instrumentation for planetary missions. The incorporation of new technologies into future robotic and human missions requires a detailed understanding of scientific objectives and instrument capabilities coupled with strategic and tactical integration into mission planning. FINESSE has outlined optimized use cases for various instrumentation, required data and communications flows for telemetry, and best practices for optimizing scientific output during human and robotic exploration missions.

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. IMPACT provides access to its facilities to the planetary and space physics communities. In 2017, IMPACT expanded the capabilities of its dust accelerator facility to enable dust impact experiments into icy surfaces, studies of high-speed entries of dust particles into the Earth's atmosphere, and the effects of dust impacts on spacecraft instrumentation. New, small-scale experiments were developed to study the interaction of the solar wind with surfaces and magnetic anomalies, the charging and subsequent mobilization of regolith dust. The analysis and interpretation of these experiments were guided by the continued development of a new generation of plasma simulation codes.

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; described here is the progress made in each theme in 2017. In Theme 1, "Formation of the Inner Solar System and the Asteroid Belt," ISET used new models of planet formation via pebble accretion to identify substantial problems with long held views on the formation of planets. The team also showed a substantial fraction of asteroids were implanted into the asteroid belt from the outer Solar System. In Theme 2, "Origin of the Moon and Phobos/Deimos," research showed that Phobos/Deimos could form from a debris disk produced by a Vesta- to Ceres-sized impactor striking Mars. In these models, the moons would mostly be composed of martian debris. In Theme 3, "The History of NEAs and Lunar Bombardment," models of late accretion to Earth were tested and found the amount of material delivered may have been 2-5 times greater than previously thought, with implications for the early history of the Moon. Also found was evidence that the lunar basins Imbrium and Serenitatis are actually similar in age, countering recent geological interpretations. Finally, results indicate that the impact flux on the Earth and Moon increased by at least a factor of 2, approximately 250 Myr ago. This result implies the apparent lack of large terrestrial craters with ages between ~250-650 Myr on stable terrains is a byproduct of a lower impact flux, not preservation bias. In Theme 4, "NEAs: Properties, Populations, New Destinations," ISET examined the evolution of small asteroids via YORP thermal forces that spin asteroids up and down. The team found that if bodies reach a small enough size, the spin rates for disruption ensure that the body components will immediately escape, leading to a convergent series of spin-up events that rapidly disaggregate the rubble pile into its core constituents. ISET also led observations that looked for "minimoons," which may be compelling nearby targets for NASA human and robotic missions.

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, among other activities, (1) developed advanced light scattering models to enable more quantitative analysis of remote sensing data, (2) conducted X-ray and infrared spectral analyses of experimentally space weathered minerals and shown that dust impacts result in drastic changes to infrared spectra that are consistent with observed space weathering trends, (3) conducted field work in a planetary analog volcanic terrain while continuing to refine procedures for the use of portable and handheld instruments for use by astronauts, (4) used X-ray photoelectron spectroscopy and electron paramagnetic resonance (EPR) spectroscopy to study the interaction of mineral surfaces and fluids that result in reactive oxygen species, as might occur in the human lung after inhaling dust particles, (5) demonstrated that lunar regolith simulant results in substantially increased oxidative stress in mouse lung tissue macrophages compared to a non-reactive powder and a control sample, (6) produced an oxygen fugacity (fO_2) calibration curve from vanadium measurements using X-ray absorption spectroscopy, and (7) used scanning transmission electron microscopy (STEM) and electron energy loss spectroscopy (EELS) to map and quantify solar wind helium in lunar ilmenite and chromite grains.

The diverse SSERVI Evolution and Environment of Exploration Destinations (SEEED) team hosted at Brown University and MIT is led by Dr. Carlé M. Pieters and addresses detailed investigations of the chemical and thermal evolution of planetary bodies, the origin and evolution of volatiles, space weathering of regolith in different environments of long-term interest to NASA, and science and engineering synergism. Science milestones during 2017 include: landmark publications on magmatic processes on the Moon; investigations into irregular mare patches that could be either old or extremely young; identification of hydrous lunar pyroclastic deposits from orbit; characterizing the properties of polar ice on Mercury; searching for the origin and distribution of 'featureless plagioclase' that characterizes much of the lunar highland crust; surveying the spectral properties of carbonaceous chondrites, among others. The SEEED team demonstrates dedication to leading, supporting, and participating in a variety of community, international, cross-team, and public engagement activities related to SSERVI goals.

The Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES) team led by Dr. Andy Rivkin at Johns Hopkins University/ Applied Physics Lab focuses on the entire volatile-regolith system occurring on small bodies and on the Moon. The team focuses on the sources, sinks and transport mechanism of volatiles (e.g., H2O, OH); the regolith and its properties and how it acts as a transport medium and storage reservoir; and how volatile and solar resources facilitate planetary exploration. In 2017, the group expanded modeling efforts of the thermal properties of the regolith, penetration of protons into the regolith and thermal fatigue of rocks and regolith generation. A new laboratory facility has been developed to examine how proton bombardment of regolith particles (solar wind bombardment of a surface) influences their ability to store and transport OH. This complements existing facilities that simulate micrometeorite impacts to understand space weathering and the influence of micrometeor impacts on the ability to store and transport volatiles.

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 Exploration Science Pathfinder Research for Enhancing SS Observations (ESPRESSO) team led by Dr. Alex Parker at the Southwest Research Institute in Boulder, CO is developing a toolkit for remotely assessing the mechanical, thermal, and chemical properties of a target body's surface in order to inform strategies for target selection and surface operations. In 2017, the team began establishing and calibrating their laboratory and field instrumentation suites, preparing for full operation in 2018. Project ESPRESSO's Airborne Space Environment Chamber is a facility that will provide community access to a lunar- and asteroid-like gravity and pressure environment for regolith experimentation and hardware testing. The facility is proceeding to detailed design, having passed a fit check onboard the reduced gravity aircraft on which it will fly. Prototypes of both miniaturized instrumented impact probes and a system for measuring the 3D shape and trajectory of high-speed dust grains in free flight were manufactured and are undergoing testing. Core lab instrumentation has been installed and is undergoing optimization and calibration, which will enable ESPRESSO's measurement of critical optical constants for quantitative remote analysis of target body composition.

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 astrophysical measurements of the first luminous objects in the early Universe, radio emission from the Sun, and extrasolar space weather. NESS is developing instrumentation and a data analysis pipeline for studying 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 the 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 Deep Space Gateway in cis-lunar orbit. In 2017, new experiments, using rover + robotic arms and virtual reality simulations, guided 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 fundamental, applied, and operational aspects correlated with radiation processing of natural regolith and man-made composite materials relevant to exploration of near-Earth destinations. In 2017, the team developed a model to describe the diurnal variation of the solar-wind induced optical signature of water on the Moon. It should be generally useful for the prediction of water deposits on the Moon, asteroids and other airless bodies such as Mercury. The model is being tested experimentally using a solar wind proton source and a laser accelerated micrometeorite impactor beam. A solar thermal heater/packed bed flow reactor to produce water from regolith and to measure volatile diffusion transport properties of volatiles was also designed for possible in-situ resource utilization. The team has begun to develop novel polymers and real-time radiation detectors using nanoparticles and 2-D meta-materials. These materials and active dosimetry will be integrated into space-suits and hardware for Extra-vehicular activities (EVA) and surface exploration activities. Overall, the REVEALS effort is addressing a number of SMD and HEOMD objectives to help minimize risks and radiation exposure during human exploration.

The Toolbox for Research and Exploration (TREX) team lead by Dr. Amanda Hendrix at the Planetary Science Institute (PSI) in Tucson, AZ, had a busy year getting started as a new SSERVI team. TREX 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 can also harbor volatiles that can be useful for future In situ resource utilization (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: lab studies, Moon studies, small bodies studies, and field work. In 2017, TREX work focused on getting tasks in each theme area started, with an emphasis on the foundational laboratory spectral work. Initial samples were purchased and prepared, and grain size analyses were performed to assure that the fine size requirement was met. The team began planning for field work that will take place in years 3 and 4. In the field, the team will utilize a rover with instrumentation and software that incorporates the laboratory measurements and results from Moon and small bodies work for automated sample selection in a small body-like environment.

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)

Center for Lunar and Asteroid Surface Science (CLASS)

1 CLASS Team Project Report

• **CLASS Graduate Seminar:** "The Technology and Future of In-Situ Resource Utilization" Talks and course materials are available on-line at the seminar website https://sciences.ucf.edu/class/isru/.

• CLASS joined the NASA All-Sky Fireball Camera Network.

• The Strata-1 experiment finished on the ISS and was returned to Earth for study.

• **Workshops and books:** CLASS Co-I's participated in the International Space Science Institute (ISSI) Workshop "Cosmic Dust from the Lab to the Stars;" a book is in development from this workshop. A book on science from the ARM Formulation Assessment and Support Team is in development. A book based on the ISRU seminar is also in development; a tactile book for the Great American Eclipse was distributed by Cass Runyon and team

HEOMD Support: CLASS is proactive in providing science support for NASA HEOMD exploration needs.

• STRATA 1: CLASS provides most of the science team and the hardware for this JSC ARES-ISS experiment.

• CLASS provides the scientific leadership in partnership with Deep Space Industries to develop a family of asteroid simulants to support NASA exploration goals. New developments include Phobos and Mars surface simulants.

• CLASS supported the Asteroid Threat Assessment Project (ATAP) NASA Ames team with data on physical properties and bolide strength that resulted in a series of model estimates of ground-level overpressure from real bolides

• CLASS PI Dan Britt supported JAXA MMX with investigations of physical properties of Phobos surface materials.

• CLASS worked with Asteroid Rendezvous Mission (ARM) to investigate thermal stress and breakdown on CI/CR like simulant material (Britt, Metzger, Sarid).

• CLASS has taken the lead on research to characterize the potential health effects of Polycyclic Aromatic Hydrocarbons (PAHs) in carbonaceous chondrites.

1.1 CLASS Science Reports

1.1.1 Dan Britt, University of Central Florida

Dan Britt's research group was focused on research into the physical properties of small bodies. He was part of the science team selected for the Lucy Mission, which will fly-by six Jupiter Trojan asteroids. CLASS supported JAXA for their planned MMX mission and hosted Hirdy Miyamoto (JAXA and Tokyo U) and Paul Abell to UCF and DSI to discuss Phobos surface properties and Phobos simulants. Dan Britt and CLASS Co-I Patrick Michel attended a workshop in Tokyo on estimating the physical properties of Phobos and Deimos. In response to JAXA discussions **CLASS developed two Phobos simulants: Phobos Captured Asteroid (PCA-1), and Phobos Giant Impact (PGI-1) to be used for physical properties testing to support the MMX mission.** Graduate student Leos Pohl and undergraduate Cody Schultz have been researching the thermal degradation of serpentines. Schultz made a series of strength and compression tests on CI simulants to determine physical properties. **Post-doc Kevin Cannon and Britt have been working with KSC Swampworks, Florida Tech, and Deep Space Industries to develop a series of martian soil simulants based on the latest rover results.** Deep Space Industries now has simulant available based on CI, C2, CM, and CR carbonaceous chondrites.

1.1.2 Peter Brown, University of Western Ontario

Peter Brown's research group has made extensive progress modelling bolide impacts **to estimate ground damage, in particular the probability that windows are damaged as a function of bolide yield and impact frequency.** This is collaborative work with the ATAP NASA Ames team and has resulted in a series of model estimates of ground-level overpressure from real bolides. Figure 1 shows the ground level overpressure computed via CART3D for the September 4, 2004 fireball off the coast of Antarctica. Results from this work include an estimate of major glass damage in Urban areas once every ~5000 years from bolides and demonstration that impact damage sufficient to cause widespread window damage in urban areas is limited to bolides having yields in excess of 5 kT. This modeling has also led to a refinement of airwave signal measurements for bolides to more accurately estimate yield.

1.1.3 Humberto Campins, University of Central Florida

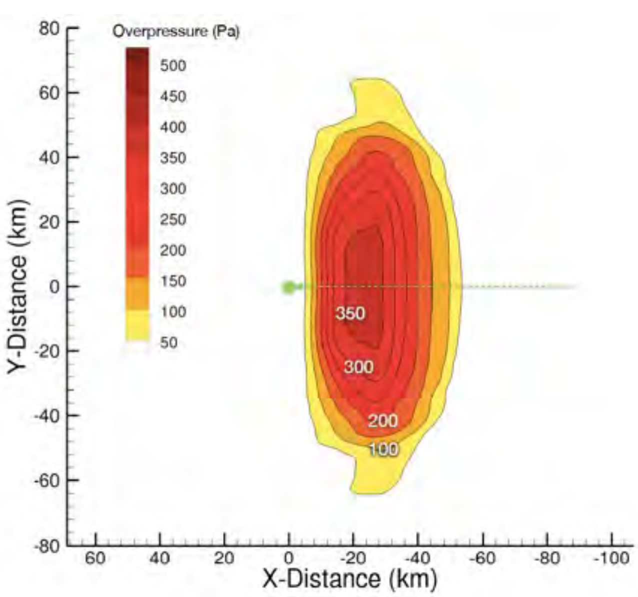


Figure 1. Ground level overpressure (Brown)

Humberto Campins' group has carried out, reduced and analyzed observations that indicate that inner-belt primitive families fall into two spectral groups: Erigone-like (hydrated and spectrally diverse) and Polana-like (no 0.7-µm hydration feature and spectrally homogeneous). These groupings have been confirmed by our latest publications on the Clarissa and Sulamitis families (Morate et al. 2018), and have implications for the surfaces of Bennu and Ryugu. In fact, a combination of dynamical and spectral evidence favors the Polana-Eulalia complex as the most likely origin of Bennu and Ryugu (de León et al. 2018). **Most recently, an agreement between our observations of inner-belt families (Pinilla-Alonso et al. 2017 and Morate et al. 2018) and laboratory simulations of space weathering (Lantz et al. 2015, 2017) has testable implications for Bennu and Ryugu: older terrains would be expected to be bluer than younger surfaces.** The largest group in both families is C-type, with approximately 50% of the observed asteroids; however, the younger Clarissa family has a lower fraction of the bluer "B" spectral class and a higher fraction of the red "X" spectral classes than the older Polana family. These differences are consistent with the space weathering trend suggested by Lantz et al. (2015 and 2017), where the lowest-albedo primitive material gets bluer with space exposure age. This tantalizing agreement between observations and laboratory simulations is preliminary; however, it has testable implications for sample-return target asteroids Bennu and Ryugu.

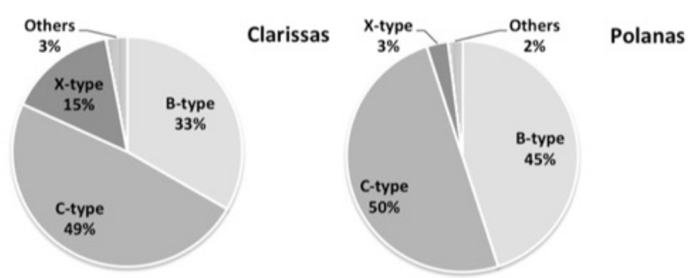


Figure 2. Taxonomical groups in the Clarissa and Polana families

1.1.4 Yanga Fernandez, University of Central Florida

Fernandez supported three graduate students who had CLASS funding. Graduate student Schambeau is working on observations and modeling to study compositional changes in the surface and subsurface layers of active comets so as to understand what structure a small-body needs to have to maintain an icy interior. Graduate student Hinkle has been investigating the surface properties of near-Earth asteroid (NEA) (433) Eros through ground-based, near-IR spectroscopy that simultaneously measures both regolith's scattering and its thermal emission. Jones (graduated Fall 2017) analyzed the surface properties of S-complex NEAs, specifically looking in detail at (1627) Ivar. Fernandez, Hinkle, and Jones are all part of a collaboration with Magri, Ellen Howell (U. Arizona), Sean Marshall (Arecibo Obs.), and Ron Vervack (JHU/APL) that is investigating NEA properties through thermophysical modeling of multi-epoch near-IR spectroscopy of NEAs for which the shapes are already known thanks to delay-Doppler radar imaging. The Figure shows thermal maps of Eros taken over a long campaign of observations that provide the best fit to our extensive near-IR thermal emission measurements. This shows the benefit of repeated observation of NEAs versus simple one-time snapshots. Fernandez also participated in a study of the interstellar asteroid 1I/'Oumuamua 2017 U1, that corroborated the finding that **the rotation period of Oumuamua is on the order of 8 hours and that, importantly, the axial ratio is higher than virtually every other asteroid in our Solar System.**

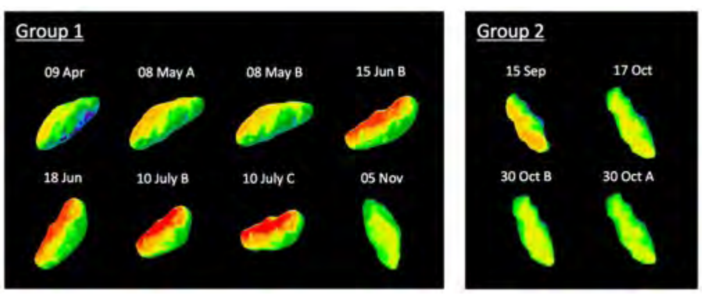


Figure 3. Thermal maps of Eros

1.1.5 Faith Vilas, PSI

Vilas pursued research into the spectral effects of space weathering in the UV/blue spectral region for C-complex asteroids with Amanda Hendrix: Spectra of 6 main-belt C-complex asteroids, covering the 320- to- 640-nm wavelength range, were compared with International Ultraviolet Explorer spectra of 13 C-complex asteroids in the ~210- to- 320-nm wavelength range. This research extended the previous SSERVI result demonstrating that space weathering in the S-complex asteroids is evident in the UV/blue spectral region before it is apparent in the VNIR, due to the presence of iron in olivines. A strong difference between the C-class asteroids and the carbonaceous chondrite meteorites is the strength of the UV absorption. The UV drop-off is quite subdued for CI1 and CM2 types; the CI and CM chondrites have been naturally heated with some metamorphism expected. Vilas and Hendrix continued the analysis of moderate resolution VNIR narrowband spectroscopy of several Jovian irregular satellites. The presence of reddened material, as evidenced in the D-class Trojan asteroids, coupled with absorption features suggesting C-complex asteroids, lends support to the idea that **these objects constitute the end product of the re-accumulation of disrupted material after a violent shuffling event occurred.**

1.1.6 Adrienne Dove, University of Central Florida

Dove's work over the last year has primarily focused on development of the CubeSat SurfSat, in collaboration with members of the NASA Kennedy Space Center (KSC) Launch Services Program (LSP). SurfSat is a 2U CubeSat that will be launched into a polar orbit in the Earth's ionosphere to explore the charging of dielectric materials (such as thermal paints that are commonly used on the exterior of spacecraft) in the context of the ambient plasma environment in order to better characterize the charging mechanisms. This will give scientific context to the charging conditions, but may also inform spacecraft design and launch constraints. Part of this project included the development of a chamber that will be capable of reproducing a wide range of plasma environments (neutral plasma, electron beam, UV photoemission) with broader capabilities that will be used to explore spacecraft charging in other environments, charging of regolith surfaces, and other related effects.

Another major area of effort is the Strata family of experiments, whose aim is to explore regolith segregation and evolution in the long-duration microgravity environment on the ISS. The science team for these projects spans several SSERVI teams and is lead out of JSC. Development this year has included hardware testing and modifications for a suborbital flight test with Blue Origin, and for the follow-up Hermes facility that will be installed on the ISS. We have also been analyzing data from the first Strata mission to correlate regolith behavior with the microgravity and vibrational environment on the ISS. The data suggests that significant vibrational and particle sorting events take place, even in the relatively quiescent environment of the ISS, which leads to varying particle size distributions in the regolith layers.

1.1.7 Dan Durda, Southwest Research Institute

Durda's work has been focused primarily in regular participation in monthly science team telecons/ discussions for the STRATA-1 regolith experiment for the International Space Station (ISS) and its follow-on experiment, Hermes. At least one of the four STRATA-1 experiment tubes will contain (or be dedicated to) an experiment that is focused on some aspect of engineering- or EVA-related operations, in order to keep ISS program office interest, with strong continued support for Hermes. Discussions during our monthly telecons, and in person with Addie Dove, Josh Colwell, and Phil Metzger during CLASS visits at the end of October, 2017, have focused on tests for magnetic grappling/affixing to a chondritic regolith simulant in microgravity.

1.1.8 Chris Herd, University of Alberta

The ongoing, active use of the cold curation facility continues, primarily for the PhD work of Danielle Simkus, who is exploring new types of organic compounds in previously unsampled specimens of the Tagish Lake meteorite, as well as for the development of curation methods for cometary nucleus materials. Six loan requests for Tagish Lake meteorite material from researchers worldwide were filled. The facility and its commissioning are described in Herd et al. (2016).

1.1.9 Cyril Opiel, Boston College

Investigations focused primarily on developing resonant ultrasound spectroscopy (RUS) measurement capability, measuring thermal diffusivity and thermal inertia of a CI Meteorite Simulant provided by UCF and comparing Debye temperatures, Q_D, calculated from specific heat capacity measurements for a variety of iron, ordinary and carbonaceous chondrites. RUS capability allows for bulk moduli and elastic constant measurements of small size, high-Q materials. Data on the CI Simulant used as a pressed powder (1.73 g/cc) confirms previous thermodynamic measurements made on naturally occurring high porosity CM2 meteorites at low-temperatures. A comparison of the specific heat capacity and thermal conductivity for the CI simulants Jbilet Winselwan and Murchison reveals a high correlation for T < 200 K. We now understand the mechanism explaining the **thermal expansion measurements seen in CM meteorites, which shows a second order phase transition and negative thermal expansion as temperature increases 210 < T < 300 K.** Such behavior, not seen in other classes of carbonaceous chondrites or Ni/Fe meteorites, indicates a volumetric contraction due to the particular chemical/material structure of the hydrous phyllosilicates present in the meteorite matrix.

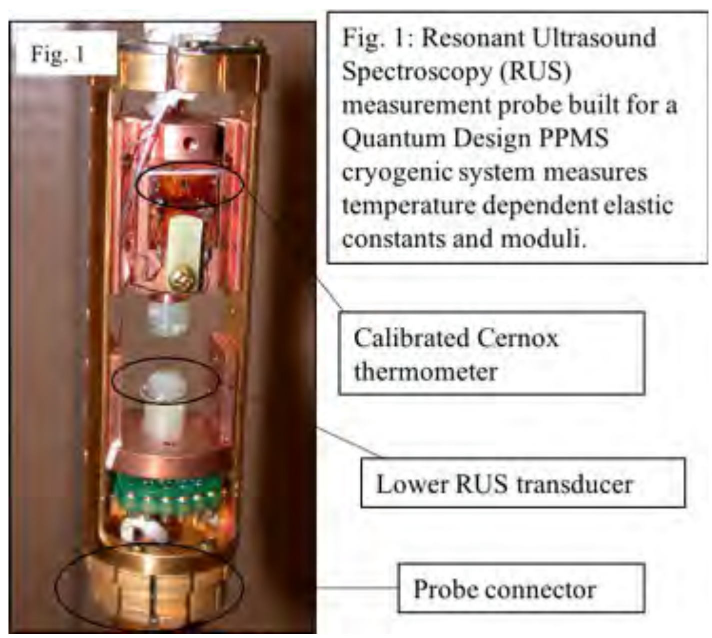
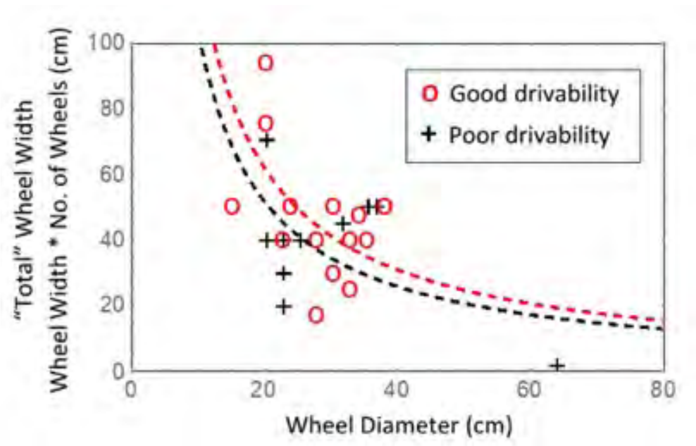


Fig. 1: Resonant Ultrasound Spectroscopy (RUS) measurement probe built for a Quantum Design PPMS cryogenic system measures temperature dependent elastic constants and moduli.



CLASS has discovered a major volumetric contraction in CM carbonaceous chondrites between 210 ← T ← 300 K caused by a mineralogical phase transition. These data have major implications for the evolution of NEA surface material, regoliths, and orbital evolution (1.1.9).

1.1.10 Patrick Schelling, University of Central Florida

Schelling and Dove conducted research on the dissipative and adhesive properties of small mineral grains. We use molecular-dynamics simulations of relevant materials to study the effect of dissociative water adsorption on adhesion of silica mineral grains in head-on collisions. **We established that adsorbed hydroxyl groups (i.e. water) have a significant effect on the likelihood of adhesion.** When hydroxyl groups were not present, we found that grain adhesion occurs at a very wide range of velocities inconsistent with previous theoretical predictions. We have extended this work with a focus towards larger grain sizes, and with different minerals including FeO, so that the results might be developed into a more comprehensive theory that can be scaled to micron-sized grains. We have determined that for particles ≤11nm, strong surface stress occurs during the collision which always results in plastic deformation at all incident velocities. In all cases more than 80% of the incident energy dissipated before the particles can rebound even for collision velocities below 10m/s. We have shown strong disagreement with existing theory.

1.1.11 Philip Metzger, University of Central Florida

Metzger analyzed the performance of robots from the NASA Robotic Mining Competition in 2015 through 2017 and found that the robots' ability to avoid getting stuck in regolith correlates to a nonlinear combination of multiple design parameters, but it does not correlate significantly to any design parameter individually. This was a great surprise, as it was previously believed that wheel diameter would strongly correlate to ability to drive in soft regolith. **The robots have been evolving year-by-year in the competition in the direction of increasing the value of this combination metric, which is also surprising since the teams have not been shown the data and are unaware of the existence of this metric.** From 2016 to 2017, the value of the metric improved by a whopping factor of 30. This finding is being written into a conference paper co-authored by Rob Mueller at NASA KSC. Continued progress mining this large data set will help NASA develop better rovers for planetary surfaces.

NASA Robotic Mining Competition rover mobility metrics show that robots have been evolving toward increasing mobility. This is a complex, non-linear metric and the competing teams are unaware of the full extent of their progress (1.1.11).

1.1.12 Dan Scheeres, University of Colorado

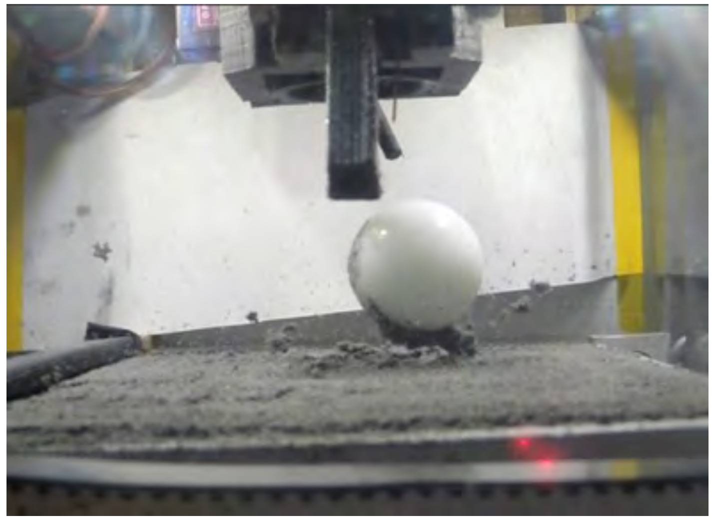
Dan Scheeres (CU) was elected to the National Academy of Engineering. Dan and Paul Sanchez (CU) are collaborating in an ISSI-sponsored (in Berne, Switzerland) research program on asteroid regolith. Dan gave an invited talk on dynamics in the Phobos environment at the ISTS meeting in Japan, in June. Dan gave an invited talk at the Japanese Geophysical Union (JpGU) meeting in a special Regolith Science session. Dan also gave a talk to the 2017 Powders & Grains conference on the nature of rubble pile asteroids. Scheeres is carrying out a study of what the surfaces of rapidly rotating asteroids should be like, in terms of regolith covering.

1.1.13 Larry Taylor, University of Tennessee

Dr. Larry Taylor passed away suddenly this summer. We will miss him. Larry was honored by the award of the Wargo Exploration Science Award by SSERVI. He remained productive and had new results about the integrity of curated lunar soils. Cooper et al. (2015) reported that all lunar soils subjected to air have disintegrated by at least 50%, thus questioning the integrity of lunar sample curation by NASA. Taylor's group made particle size studies on one of the lunar soils (74220 - orange soil) studied by Cooper and demonstrated that there was no deterioration.

1.1.14 Josh Colwell, University of Central Florida

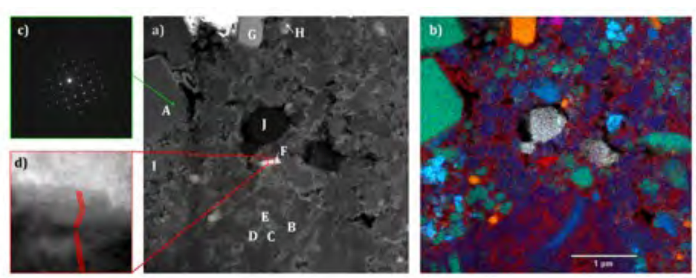
Co-I Colwell and grad student Stephanie Jarmack have developed a new laboratory-based microgravity experiment to study adhesion of regolith to larger objects when they are lifted off the surface as a function of the speed of separation from the surface as well as regolith properties. They have observed mass transfer events with this similar to what has been seen in previous spacecraft-based and airplane-based microgravity impact experiments. Colwell, Julie Brisset, and students have carried out a study of the stress-strain behavior of lunar regolith simulant—with and without water ice grains mixed in—in order to determine the changes in the bulk properties of regolith due to the presence of water ice. They have also carried out a series of 1-g impact experiments into lunar regolith simulant (with and without water ice grains mixed in) at temperatures of ~130K. The impacts are at ~2 m/s and they measure the amount and velocity distribution of ejecta to determine the effect of ice and temp. Experiments led by Dr. Julie Brisset are looking at strength and compressive characteristics of large (cm-sized) particles of Orgueil simulants. These same simulants are being used for low-velocity impact experiments in the CMR Drop Tower. Flight project development includes: Undergrad project to explore landslides in low-gravity (PI Dove) and a recently awarded NASA REDDI grant to explore a new system for anchoring in regolith in low-gravity. In recent microgravity flights we observed minimal ejecta production with the finer simulants due to stronger cohesion between individual grains. Some impactors rebounded and collected a clump of regolith simulant in a "mass transfer" event.



Impact clumping in microgravity showing strong cohesion in fine simulant.

1.1.15 Chris Bennett, University of Central Florida

Chris Bennett has been working on a project with others at UCF to do a multi-instrument study of meteoritic material to understand how amino acids form in them, and if nanoFTIR can tell us anything about correlations between nanoscale and macro-scale observations of aqueous alteration. Bennett has been working with international collaborators at the University of Lille using time-of-flight secondary ion mass spectrometry (ToF-SIMS) and two-step laser mass spectrometry (L2MS) to look for biosignatures



Sample images from a TEM scan of Murchison Meteorite show correlations in the distribution of alteration products.

within CM-type meteorites. We are beginning to map the locations of different organic species (biosignatures, PAHs, etc.) and compare them to the mineralogy. We have seen some preliminary evidence for polypeptides and other expected condensation products that have a lot of significance for astrobiology/exobiology.

2 Inter-team/International Collaborations

2.1 Collaboration with REVEALS team

PI Britt attended the REVEALS kickoff August 14th, 2017 at Georgia Tech in Atlanta. He serves as advisor to the new REVEALS team. Co-I's Bennett, Beltran, and several other UCF faculty are also members of the REVEALS team (Beltran is the REVEALS Deputy PI). Both teams have started collaborations in the early months of the team's funding.

2.2 Collaboration with TREX team

Collaborations between CLASS and one of the new SSERVI teams, TREX – Toolbox for Research and Exploration – occurred during the latter half of the year. TREX PI Amanda Hendrix, TREX Deputy PI and CLASS Co-I Vilas, and CLASS Co-I Campins were awarded Director's Discretionary Time on the Hubble Space Telescope to observe near-Earth asteroid 3200 Phaethon during its close approach to the Earth in November/December, 2017. The observations endeavored to get far UV-visible reflectance spectra of the asteroid, in order to characterize composition and potential weathering affecting the asteroid. Pointing difficulties likely caused by the rapid, non-sidereal movement of the asteroid through the field of view caused the telescope to miss the longer wavelength observations; the telescope did acquire the shorter (FUV) spectra. Data reduction is underway. The analysis of the UV spectral observations of primitive asteroids extends both the CLASS data objectives and the TREX objectives, and is conducted jointly with TREX PI Amanda Hendrix.

2.3 Collaboration with ISET

CLASS and ISET are working together to investigate the surface thermal evolution of asteroid 2008 EV5. Bottke and Britt will be co-advising a graduate student, Leos Pohl of UCF, on detailed orbital and thermal analysis of EV5 and how thermal evolution may affect the object's surface spectra, apparent volatile content, albedo, and strength properties. Co-I Brown also collaborates.

2.4 Collaboration with IMPACT

CLASS PI Britt is working with IMPACT to design experiments addressing the physical properties of icy-regolith surfaces. The goal is to study how the chemical and impact environment on volatile-rich small bodies can produce conditions favorable for the syntheses of the organic precursors of life. Co-I Dove is in discussion for dust impact and charging experiments. Co-I Brown also collaborates on impact and ablation studies.

2.5 Collaboration with SEEED

SEEED and CLASS have collaborated on EPO activities from the beginning of CLASS selection, jointly funding Dr. Runyon as our combined EPO lead. This allows greater synergy in our EPO activities and extends our reach far beyond what each team could do on their own.

2.6 Collaborations with CLASS international partners

During 2017, Cyril Opiel collaborated with Robert Macke and Guy Consolmagno. In particular he supplied heat capacity data on several meteoritic samples to Robert Macke and consulted with him about the analysis of the data in regard to density and porosity. A sample of Orgueil (CI-1) meteorite was obtained from the Specola Vaticana collection for low-temperature specific heat. Humberto Campins collaborated with and advised a number of international graduate students and post-docs. These include graduate students D. Morate from Spain and Mario de Pra from Brazil; postdocs V. Ali-Lagoa from Germany, J. Hanus from France, J. de León from France, and C. Lantz from MIT/France.

2.6.1 Phil Bland – Australia

Peter Brown was involved in collaborations with SSERVI's Australian partner (PI Bland) on the expansion of the Desert fireball network to a global network of fireball cameras. As part of this collaboration our group is field testing several DFN cameras in Canada for eventual deployment across the country to augment the planned global fireball observatory. The 2017 CLASS student exchange program was focused on collaboration with the Australian Desert Fireball Network to help staff expeditions into the Australian outback to recover meteorites previously tracked by the Fireball Network. A UCF undergraduate student, Michael Demasi, participated in recovery activities.

3 CLASS Public Engagement

Our Education and Public Engagement (EPE) team is focusing on using SSERVI content in three areas: 1) infusing arts into traditional science, technology, engineering and mathematics (STEM) lessons; 2) integrating formal, informal and out-of-school experiences to foster content retention; and 3) broadening audience reach to include ALL learners, especially those with disabilities. In 2014, we formed a core team of dynamic science educators, authors, artists and storytellers from around the country to help us develop engaging inquiry-based, hands-on activities using SSERVI data and resources.

We continue to work with an undergraduate student and a recent graduate who are blind. They are helping to develop, review, and test SSERVI-related curricula and activities vetted by the EPE Core Team. With the recent publication of the tactile book, "Getting a Feel for Eclipses," we are attending and presenting at more conferences and workshops. In addition to developing resources for the sight impaired, we are also actively working with a teacher who is deaf and who works with students whose first language is not English. In conjunction with the NASA SSERVI ESF, a team from NASA Ames and the CLASS EPO presented to the CA School for the Blind (Joe Minafra, Cyndi Hall, David Hurd, Maria Royle and Cass Runyon). We conducted a workshop there on the Monday of Forum Week (July 17) and hosted them at NASA Ames Visitor Center on the 18th. We Distributed the 'Getting a Feel for Eclipses' books – just under 5,000 thus far to Schools for the Blind, Museums and Science Centers, Public and Private schools, the National Federation of the Blind, and more. For the Eclipse, Cass and Cindi were at "Eclipse Central" in Charleston. They have also been doing radio, TV and newspaper interviews regarding the book. CLASS Co-I's spread out across the country for the eclipse, and many grateful amateur observers enjoyed the use of the SSERVI-provided glasses!

3.1 Public presentations

3.1.1 Dr. Esther Beltran

Dr. Esther Beltran was invited as the keynote speaker to talk about women's role in technology at the Women in Technology International (WITI)—Tampa Bay's 5th Annual Geek Glam on October, 2017. The title of the talk was: "No limits!" WITI is the premiere global organization empowering women in business and technology to achieve unimagined possibilities. It provides a forum for women to network with each other, forge connections, share resources and discover opportunities in the technology industry. The talk was broadcasted via YouTube across all WITI's International Partners. Attendance on site was over 200 people.

3.1.2 Chris Herd

Chris gave a talk at the Royal Astronomical Society of Canada Edmonton Centre: "Alberta's Role in a New Global Fireball Observatory" on September 11, 2017. Gave a series of interviews commenting on the release of Lapen et al. (2017) Science Advances with JoAnna Wendel, AGU Science Writer for EOS; with Eva Botkin-Kowacki, Christian Science Monitor: http://www.csmonitor.com/Science/Spacebound/2017/0202/What-do-Martian-meteorites-tell- us-about-volcanism-on-the-Red-Planet?cmpid=push013s

3.1.3. Yan Fernandez

Yan gave an invited talk about comets at the 2017 National Astronomy Teaching Summit on August 7. He presented the Science Café talk at UCF College of Sciences on September 28 about the history of eclipse observations. Several CLASS faculty at UCF, including Dr. Fernandez, Dr. Britt and Dr. Bennett, participated in the Physics department Career Day on Oct 21. We had telescopes out for UCF STEM Day on October 27, and several student groups presented, including a student group working in the Center for Microgravity Research on an experiment to understand regolith sloping behavior in low-g. We had a big turnout for International Observe the Moon Night on October 29!

3.2 Robinson Observatory

Co-I Fernandez and graduate student Hinkle ran an extensive outreach program during 2017, making use of Robinson Observatory, UCF's own campus observatory. Fernandez is the director of this facility. We engaged the public in lunar and small-body science at many of these events. We had nine free, public events during the past year to which about 1,100 visitors were able to view the night sky through our telescopes. This count includes both UCF students and members of the general public, including children across all ages. Among these events was our participation on October 29 in "International Observe the Moon Night," which Fernandez and Co-I Dove co-organized. We also held a separate, daytime event on the UCF campus for the August 21 solar eclipse (which was partial in Orlando) to which about 3,000 people attended. We also participated in several events for private groups – elementary school groups and Scouts – both at our observatory itself and at the group's location.

3.3 URF at Boston College

Through the Undergraduate Research Fellowship (URF) program at Boston College, undergraduate researchers learn about meteoritics, perform experiments, and gather data on meteorites for 5-10 hours a week. Christopher Noyes (Spring 2017), Matthew Bonidie, (Spring, Summer, Fall 2017) and Amelia Culp (Spring 2017) participated in meteorite sample preparation, measurement of emissivity, thermodynamic data collection and analysis.

4 Student/Early Career Participation

Undergraduate Students

1. Cody Schultz, UCF, meteorite physical properties (Britt)
2. Makayla Pippen, UCF, meteorite physical properties (Britt)
3. Michael Demasi, UCF, meteorite physical properties (Britt) worked with the SSERVI associate team in Australia (Bland)
4. Brandon Wilson, UCF, Organics in meteorites (Bennett)
5. Brian Ferrari, UCF, Organics in meteorites (Bennett)
6. Christopher Arose, UCF, Organics in meteorites (Bennett)
7. Jonathan Sepulveda, UCF, Organics in meteorites (Bennett)
8. Brett Kochanowski, UCF, Organics in meteorites (Bennett)
9. Ronald Herbert, UCF, helped with design of PARSEC chamber (Bennett)r
10. Jeffrey Jorges, UCF undergraduate, Center for Microgravity Research labs (Colwell)
11. Alexandra Yates UCF undergraduate, Center for Microgravity Research labs (Colwell, Dove)
12. Jacob Kirstein, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)
13. Nadia Mohammed, UCF, Center for Microgravity Research labs, regolith experiments (Colwell)
14. Christopher Cox, UCF, Center for Microgravity Research labs, regolith experiments (Colwell)
15. Elizabeth Warner, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)
16. Sean Shefferman, UCF, Center for Microgravity Research labs, Strata (Colwell, Dove)
17. Addison Brown, UCF, Center for Microgravity Research labs, regolith experiments (Colwell)
18. Anna Metke, UCF, Center for Microgravity Research labs, Strata (Colwell, Dove)
19. Esther Amram, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)
20. Steven Schroeder, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)
21. Theodore Cox, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)
22. Dany Mazboudi, UCF, Center for Microgravity

Research labs, CubeSats (Colwell, Dove)

23. Trisha Joseph, UCF, Center for Microgravity Research labs and Strata (Colwell, Dove)

24. Mariana Mendonca, UCF, Center for Microgravity Research labs, regolith experiments (Colwell)

25. Seamus Anderson, UCF Center for Microgravity Research labs, Strata (Colwell, Dove)

26. Tom Miletich, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)

27. Emily D'Elia, UCF, Center for Microgravity Research labs, flight projects (Colwell, Dove)

28. Ryan Boehmer, UCF, Center for Microgravity Research labs, Strata, flight projects (Colwell, Dove)

29. Alex Heise, UCF, Center for Microgravity Research labs, Strata, flight projects (Colwell, Dove)

30. Michael Fraser, UCF, Center for Microgravity Research labs, Strata (Colwell, Dove)

31. Gillian Gomer, UCF, Center for Microgravity Research labs, Strata (Colwell, Dove)

32. Jacob Hambor, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)

33. Diego Briceño, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)

34. Dylan Rosenberg, UCF, Center for Microgravity Research labs, CubeSats (Colwell, Dove)

35. Sumayya Abukhalil, UCF, Center for Microgravity Research labs, regolith experiments (Colwell, Dove)

36. Chang Yu Sung, University of Western Ontario, VLF radiation from meteors (Brown)

37. Denis Heynen, University of Western Ontario, VLF radiation from meteors (Brown)

38. Sean Huggins, University of Western Ontario, EMCCD matched filter detection for meteors (Brown)

39. Michael Molliconi, University of Western Ontario, Specular radar/optical simultaneous measurements (Brown)

40. R. Sheihk, UCF, asteroid observations (Campins)

41. M. McCarty, UCF, asteroid observations (Campins)

42. Hanna Lyons, UCF/University of Florida, CLASS and REVEALS-relevant internship (Beltran)

43. Christopher Noyes, Boston College, measurement and analysis of carbonaceous chondrite thermodynamic data (Opeil)

Graduate Students - PhD

44. Leos Pohl, UCF, strength of meteorites, thermal processing (Britt)

45. Westly Chambers, UCF, plume interactions, Regolith jetting interactions (Britt, Metzger, Dove)

46. Amy LeBlue-Debartola, UCF, Organics in meteorites (Bennett)

47. Michael Mazur, University of Western Ontario, Origin of low velocity meteoroids at Earth (Brown)

48. Chang Yu Sung, University of Western Ontario, Search for VLF emission from fireballs (Brown)

49. Mark Froncisz, University of Western Ontario, Detecting interstellar meteoroids using radar (Brown)

50. Denis Vida, University of Western Ontario, High precision optical meteor reduction techniques (Brown)

51. Caroline Gi, University of Western Ontario, Using bolide airwaves to estimate meteoroid source characteristics and window damage potential (Brown)

52. Jenny McIntyre, UCF, Thermal and orbital modeling (Sarid, Britt)

53. Anicia Arredondo, UCF, asteroid observations (Campins)

54. Zoe Landsman, UCF, asteroid observations,

compositions (Campins)

55. D. Morate, Spain, asteroid observations (Campins)

56. Mario de Pra, Brazil, asteroids (Campins)

57. Mary Hinkle, UCF, surface properties of Eros through ground-based, NIR spectroscopy (Fernandez)

58. Dr. Jenna Jones, UCF, surface properties of S-complex NEAs (Fernandez) (graduated)

59. Charles Schambeau, UCF, compositional changes in the surface/subsurface of active comets (Fernandez)

60. Dr. Abrar Quadery, UCF, atomic-scale simulation of collisional adhesion and energy dissipation (Schelling, Dove)

61. William Tucker, UCF, catalytic activity of iron nanoparticles on the surfaces of reduced olivine (Schelling)

62. Baochi Doan, UCF, atomic-scale simulation of collisional adhesion and energy dissipation (Schelling)

63. Dr. Danielle Simkus, University of Alberta, organics in Tagish lake meteorite (Herd)

64. Nicholas Castle, University of Alberta, petrology of Martian and eucrite basalts (Herd)

Graduate Students – MS

65. Cosette Gilmour, University of Alberta, ordinary chondrite metal and Tagish lake water – mining perspectives (Herd)

66. Ebberly MacLagan, University of Alberta, impact melt structures (Herd)

Postdoctoral Fellows

67. Kevin Cannon, working with Dan Britt on simulants, ISRU, and asteroid mineralogy

68. V. Ali-Lagoa, Germany, work with Humberto Campins on asteroid classification

69. J. Hanus, France, collaboration with Humberto Campins

70. J. de León, France, collaboration with Humberto Campins

71. C. Lantz, MIT/France, collaboration with Humberto Campins

72. Nicole Spring, University of Alberta, cometary analogs and cold curation (Herd)

5 Mission Involvement

1. New Horizons Kuiper Belt Extending Mission, Dan Britt, Science team member

2. Lucy, Dan Britt, Science team member, working group leader

3. GRASP (Geophysical Reconnaissance Asteroid Surface Probe), Peter Brown and Dan Britt, provide linkage between bolide measurements which provide estimates of physical structure and characteristics of meter-sized near-Earth objects and GRASP measurements of in-situ boulder properties on an NEO surface

4. NEOCam, Yan Fernandez, mission is currently in extended Phase A, science team member

5. OSIRIS-Rex, Yan Fernandez, mission is currently on-route to asteroid Bennu, collaborator

6. CAESAR, Yan Fernandez, mission is currently in New Frontiers Phase A, science team member

7. OSIRIS-Rex, Humberto Campins, mission is currently on-route to asteroid Bennu, science team member

8. LRO, Faith Vilas, LAMPS, Participating scientist

9. Hayabusa-2, Faith Vilas, Joint Science team member, reflectance spectra

David Kring

Lunar and Planetary Institute, Houston, TX

Center for Lunar Science and Exploration (CLSE)

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

1.1 Science

The scientific objectives of the Center for Lunar Science and Exploration are tied together by collisional and impact cratering processes and the evolution of material, especially volatiles, that are delivered by those processes. In our parallel exploration studies, we developed strategies for testing emerging concepts with future lunar surface missions and, in the case of volatiles, prospect for and harvest resources to support a sustainable exploration program.

We have been addressing the earliest phases of accretional collisions using both a theoretical pebble accretion model (led by SSERVI NPP Kretke, submitted) and with isotopic signatures of distinct nucleosynthetic reservoirs in the solar nebula (Bermingham and Walker, 2017; Bermingham et al., submitted). Previous analyses of Apollo samples by our team and its SSERVI international partners (e.g., Barnes et al., 2016) suggested water within the Earth-Moon system was delivered by planetesimals with carbonaceous chondrite affinities. Our work this year suggests those carbonaceous, water-bearing materials may have accreted as planetesimals in the outer Solar System beyond Jupiter and then been transported and mixed into the inner Solar System.

Interestingly, we found evidence in two meteorites that complex prebiotic chemistry occurred in one of those small, water-rich worlds circa 4.5 Ga during the first few million years of Solar System evolution (Chan et al., 2018).

The final stages of collisional accretion that produce larger planets reshaped the nascent Earth and created the Earth-Moon system. Analyses of volatile elements, in this case Bi, Cd, In, and Sn, revealed new details of that process. In our own Earth's mantle, the concentrations of those elements appear to have been set by volatile-depleted precursors and core formation. Analyses of lunar samples suggest, however, that all four of those elements, plus Zn, have mantle concentrations lower than expected and require an additional depletion mechanism such as loss during the giant impact or subsequent magma ocean (Righter et al., 2017a).

Two of the volatiles we measured in lunar glasses (S and C), combined with new metal/silicate partitioning experiments, provided the data needed to derive a lunar core composition (Righter et al. 2017b). We then used phase equilibria to evaluate that composition to determine if the core was initially liquid (yes), when it crystallized (very early), and how long it stayed molten (a few billion years, consistent with measurements of a waning lunar magnetic field). The results of this study were featured on the main NASA website.

Volatiles in the lunar interior can be vented at the surface by volcanic processes. Using analyses of Apollo samples, we calculated the production function of CO, H_2O, H_2, OH, and S vented during the eruption of the Moon's mare basalts, which cover more than 17% of the surface (Needham and Kring, 2017). During peak mare emplacement ~3.5 Ga, gas was being vented faster than it could escape to space, so the Moon developed a transient atmosphere (**Fig. 1**) that persisted for ~70 million years. At its peak, the atmosphere had an atmospheric pressure 1.5 times greater than that at Mars today. The mass of volatiles vented was far greater than the mass

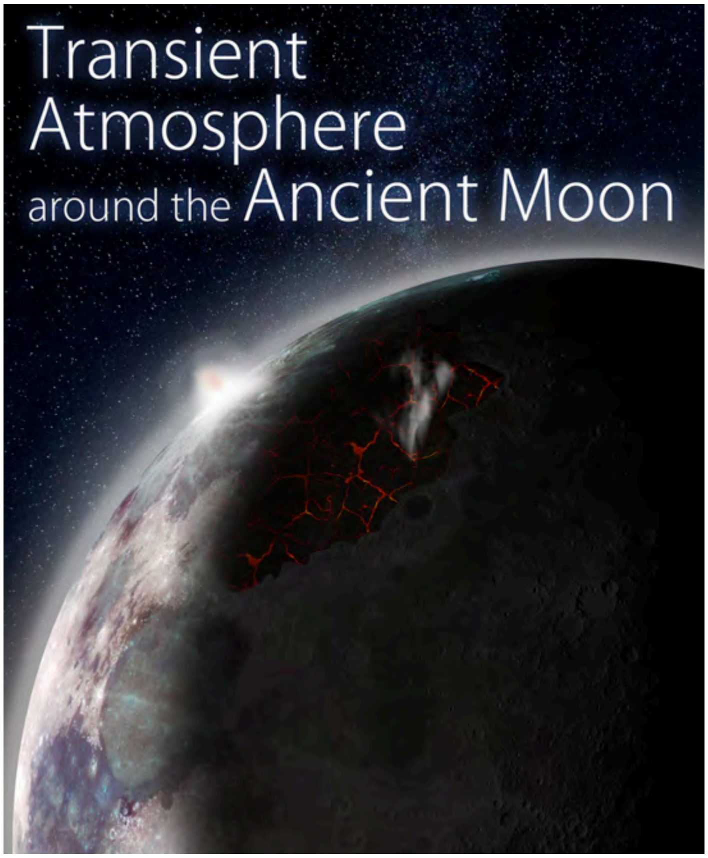


Figure 1. Volcanic eruptions long ago created a transient atmosphere around the Moon that may have been an important source of volatiles suspected to be trapped within polar deposits. Illustration credit: MSFC and LPI.

of water ice estimated to exist in permanently shadowed regions (PSRs) around the lunar poles, so the mare may be an important indigenous source of those icy deposits. Future missions should be designed to make suitable measurements to test that hypothesis. The results of this study were also featured on the main NASA website.

An ongoing study, prompted by a SSERVI-sponsored workshop about lunar water, is examining the proportion of volatiles released via moonquakes that de-gas the lunar crust (Taylor, Kring, and Needham). Preliminary results indicate moonquakes are not a large source of volatiles deposited in the polar regions, but it is an ongoing process, whereas the mare eruptions no longer produce volatiles.

While volatiles have been a good tracer of accretional and other evolutionary processes of the Earth-Moon system, we also utilized highly siderophile elements. In a collaboration with a SSERVI team at the Southwest Research Institute, we modeled the accretion of those elements in large collisions that peppered the Earth-Moon system during the first few hundred million years of Solar System history. The modeling revealed (**Fig. 2**) that siderophile material was, in some cases, incompletely accreted, as it was lost as high-speed ejecta, and heterogeneously accreted to the cores (Marchi, Canup, and Walker, 2017). Thus, the estimated flux of impactors to the Earth and Moon is larger than previously estimated.

To determine the cadence of that bombardment, we continue to probe the Ar-Ar radiometric ages of impactites in the Apollo and lunar meteorite collections and a parallel set of impactites from the asteroid belt (e.g., Swindle and Weirich, submitted; Niihara et al., submitted). We have also been updating techniques for determining the U-Pb ages of impactites with foundational studies of the minerals, like zircon, that provide those measures (Timms et al., 2017). Because the Ar-Ar and U-Pb systems are reset by different impact conditions, the parallel use of those systems will provide a more robust measure of impact ages.

The largest lunar impact events, like the Schrödinger

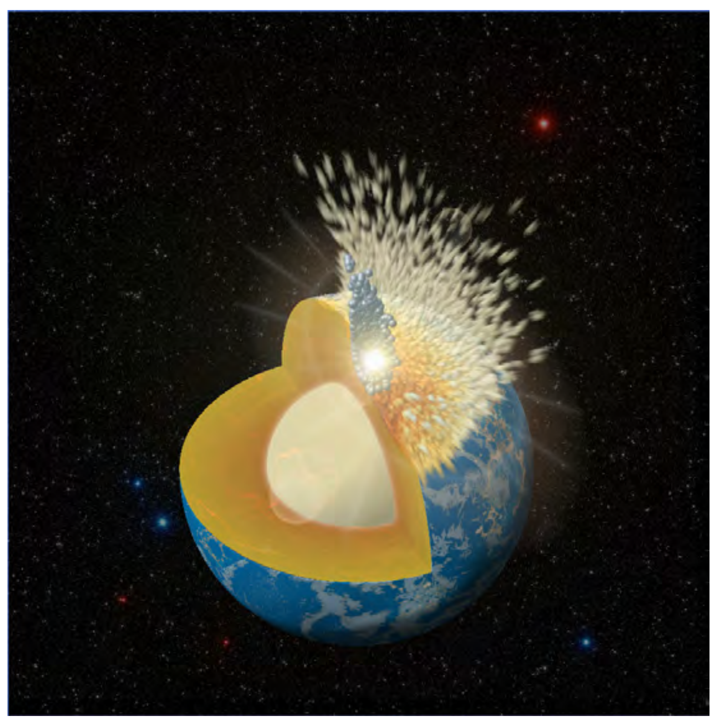


Figure 2. Model calculations of large impacts and the fate of accreting material indicate the flux of impacting objects to the Earth-Moon system was larger than previously suspected during Earth's Hadean epoch. Illustration credit: Marchi\SwRI.

basin-forming event, created impactites and uplifted samples from deep within the lunar interior that can be used to test several major concepts, such as the lunar catalclysm hypothesis, lunar magma ocean hypothesis, and the nearside-farside crustal dichotomy. We have been probing the Schrödinger basin with remote sensing techniques and, this year, by using the Chicxulub impact crater on Earth as an analogue. The Chicxulub peak-ring basin, famous for its link to dinosaur extinction, has many of the same attributes as the Schrödinger basin. We have been able to leverage an investment that the International Ocean Discovery Program and International Continental Scientific Drilling Program made in a borehole into the peak ring of the Chicxulub crater. Our studies of that crater and the lithologies recovered (e.g., Kring et al., 2017) have sharpened our insights of the Schrödinger basin impact, other lunar impacts, and plans for suitable landing sites and traverses to address National Research Council recommendations for lunar science.

> It is impossible for an astronaut to take a single step on the Moon without stepping into or onto an impact crater.

Smaller, simple craters are far more common on the lunar surface and, thus, also disserve some attention. Again, we have been using remote sensing techniques to study those craters, while also using a terrestrial analogue for additional insights. In this case, we have been studying the ejected blocks of material around Meteor Crater, Arizona (Durda and Kring, in preparation). That impact site is also the destination of one of our SSERVI-sponsored training and research programs. To support that program, we greatly expanded and updated the geologic guidebook for that crater (Kring, 2017). The volume (**Fig. 3**) received the best guidebook award for 2017 from the Geoscience Information Society at the Geological Society of America meeting. Both the Chicxulub and Meteor Crater efforts assist our interpretations of Apollo and lunar meteorite samples.

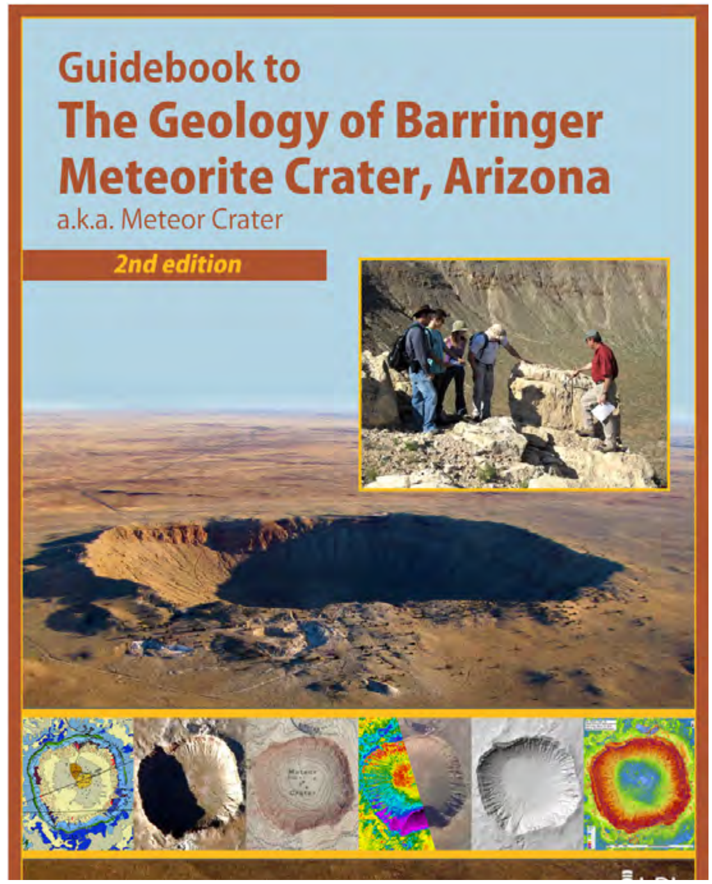


Figure 3. Cover of an updated geologic guidebook for Meteor Crater, a lunar analogue site still providing new insights about the most common process shaping airless bodies and, for that reason, also a key training site for the CLSE program.

Several elements of our research were featured in newspapers and magazine articles around the world. Our work was also featured in a new book by award-winning author Elizabeth Rusch. Her book, “Impact! Asteroids and the Science of Saving the World,” was released November 14, 2017. The book is written for children ages 12 to 16, but adults find it engaging too.

1.2 Exploration

Our team investigated a large number of issues related to human exploration of the lunar surface and provided some options for integrating exploration and science activities to maximize the productivity of a future lunar surface program. In a series of briefings, we (i) provided potential exploration mission objectives for crew on Orion; (ii) examined the integration of human and robotic deep space activities; (iii) objectives for human-assisted sample return missions to the Schrödinger basin; (iv) assessed landing sites and crew activities in the five

ISECG design reference missions to the lunar surface; (v) assessed tele-robotic traverses of rovers between the landing sites in the ISECG design reference missions; and (vi) provided multiple briefings on the potential of small pressurized rover operations on the lunar surface, including the enhanced productivity of suitports and the potential of conducting subsurface surveys for water ice deposits. With SSERVI colleagues at the University of Colorado, Ames Research Center, and Lockheed Martin, we investigated tele-robotics that might be used between an orbiting vehicle (e.g., the Deep Space Gateway) and the lunar surface. Finally, because of the ISRU potential of volatile deposits on the Moon, we investigated sources of those volatiles that may be related to the lunar interior and geologic processing, sources that are more than sufficient to produce most of the ice deposits thought to exist in permanently shadowed regions.

> Twenty-seven missions have reached the lunar nearside surface. None have reached the farside surface. If we are going to explore the unexplored, let's land on the farside.

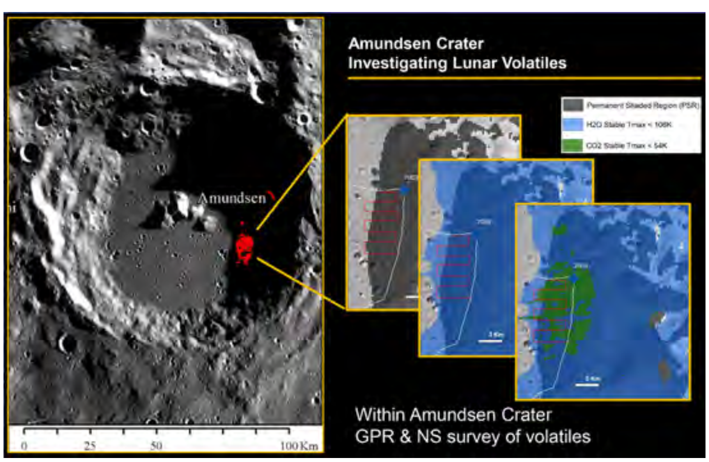


Figure 4. Studies revealed that tele-operation of a small pressurized rover between crew landing sites can survey permanently shadowed regions for recoverable deposits of water ice and other volatiles.

Figure 5. A review of the operational capabilities of the Lunar Electric Rover in field tests, coupled with an analysis of reasonable lunar surface traverses, confirmed that a pressured rover with suitports provides a mobility solution that is easier on crew and enhances their productivity.

Major findings include: (i) In situ robotic measurements of potential ice deposits should have a mass spectrometer for determining whether the ice has an indigenous source or a meteoritic source. Those measurements will help determine the transport and depositional mechanisms for volatiles and, thus, provide a model for estimating resource potential at other lunar locations; (ii) Tele-operation of small pressurized rovers (SPRs or LERs) between human landing sites can produce major surveys of permanently shadowed regions (PSRs) for water ice (**Fig. 4**) needed for a sustainable exploration program; (iii) Astronaut EVA in a SPR or LER (**Fig. 5**) will be more efficient, productive, and easier on crew if it is a relatively low pressure vehicle (e.g., 8 psi) with suitports rather than a relatively high pressure vehicle (i.e., 14.7 psi) with an airlock; (iv) The Deep Space Gateway (DSG) could provide a platform for monitoring the impact flux to the lunar farside and, depending on the DSG orbit, nearside locations not observable from current Earth-based monitoring stations; (v) Human-assisted lunar sample return using tele-robotically driven rovers can address multiple science and exploration objectives and produce 15 to 20 kg of samples per mission; (vi) Data rates >1 Mbps are needed for ops in the vicinity of the Moon. A potential component of a communications network may be NSTP-Sat, which is available to NASA.

Because we use Apollo samples and the experience of

Apollo to guide so much of our work, our team is always anxious to discuss samples, exploration strategies, and operational realities with our Apollo-era colleagues. This year, on the occasion of the 45th anniversary of the Apollo 17 mission, we co-hosted a visit by astronaut Harrison "Jack" Schmitt to the LPI, where he met with our team to discuss lunar science and exploration activities. Indeed, the concept of a future consortium study of Apollo 17 Station 2 Boulder 1 emerged from those discussions. Dr. Schmitt then graciously let us open the doors to the public where he informally met with them in our Regional Planetary Image Facility and later spoke to them in a lecture presented in our auditorium (**Fig. 6**, **top**). That event preceded, by just a few days, Dr. Schmitt's visit to the White House (**Fig. 6**, **bottom**) where the national space policy was redirected to return astronauts to the lunar surface for "long-term exploration and utilization."

Figure 6. The CLSE team helped the LPI host Apollo astronaut Harrison "Jack" Schmitt for a public event and lecture on the occasion of the 45th anniversary of the Apollo 17 mission (top). While we were looking at the past for inspiration, our team is also looking forward to implementing a new national space policy that directs astronauts to return to the lunar surface for "long-term exploration and utilization," as signed (bottom) December 11, 2017, in Dr. Schmitt's presence, a few days after he spoke at the LPI. Illustration credit (bottom): Official White House Photograph by Joyce N. Boghosian.

1.3 Training

A very important part of the CLSE team's activities are programs designed to train young investigators in the field of Solar System science and exploration.

This year we collaborated with SSERVI international partners in Canada to host the third edition of our Short Course and Field School at the Sudbury Impact Structure, which utilizes the facilities at Laurentian University in Sudbury, Ontario and field stations throughout the >60 km wide Sudbury impact basin. Students are provided introductory lectures, an opportunity to study a world class set of samples, and, most importantly, study the intricacies of an impact basin similar to those that might be explored on the Moon and Mars. Exposing students to the scale of such an immense structure, and discussing methods for exploring it, and learning how to identify the best set of samples for analyses is an illuminating experience that will assist them in their research and potentially in future mission planning if that type of opportunity presents itself.

Next year, we will host the fifth edition of the Field Training and Research Program at Meteor Crater. In preparation of that activity, we revised the geologic guidebook for the crater and posted it online for students, faculty, and the entire planetary community to use. The electronic edition of the guidebook can be found at https://www.lpi.usra.edu/publications/books/barringer_crater_guidebook/.

Our field training and research programs at Meteor Crater, the Sudbury impact structure, and in volcanic terranes have provided exceptional opportunities at some of the world's best planetary analogues sites for over 165 graduate students thus far.

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.

We have been examining the pebble accretion model for volatile-rich and volatile-poor planetesimals from the nebular disk. That work is catalyzed by Dr. Katherine Kretke, who was selected to represent SSERVI through the NASA Postdoctoral Program. Kretke is working with Bill Bottke and Hal Levison, both of whom are senior members of a Southwest Research Institute (SwRI) SSERVI team, and our own team's David Kring.

In a second collaborative effort with that SwRI SSERVI team, our team's Rich Walker has been working with SwRI's Simone Marchi and Robin Canup. They produced an exciting finding regarding the accretion of material to the early Earth-Moon system, as described in greater detail in Section 1.

We continued working with SSERVI PI Dan Britt at the University of Central Florida and one of his students. Both Tim Swindle and David Kring of our team have been coordinating fall statistics of meteorites to better assess the strengths of boulders on asteroids that could be visited robotically or with crew in the future.

Prompted by the success of our study of lunar volatiles and the thin atmosphere it may have generated around the Moon, we initiated a study with Alejandro Soto, of SwRI, who is a member of the SSERVI team led by Thomas Orlando at Georgia Tech University. 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.

Likewise, one of our team's Co-investigators, Jake Bleacher, at NASA Goddard Space Flight Center, and also a member of the SSERVI teams led by Jen Heldmann (NASA ARC) and Tim Glotch (Stony Brook University), has been working with PI Kring and Jim Head on the Brown SSERVI team and others on additional operational concepts that will be summarized in chapters for a new edition of the book New Views of the Moon.

These and other opportunities to work with colleagues across SSERVI have proven to be an exciting and rewarding part of our program.

3 Public Engagement

3.1 Exploration of the Moon and Asteroids by Secondary Students

At the 2017 NESF, the 2016-2017 team from Commack High School (NY) presented their poster.

80 students from 9 schools across the country are participating in the current 2017-2018 program (**Fig. 7**)

Student research includes (a) an investigation of CME events and their potential to increase the production rate of water on the lunar surface and (b) assessing crater depth-to-diameter ratios and rock abundances with crater age.

Teams will submit research results in poster format to CLSE in April; the top four posters will be selected soon thereafter and one team will then attend the 2018 NESF.

3.2 Traveling Library Exhibits

10 unique locations displayed our exhibits, reaching an estimated 15,000 people.

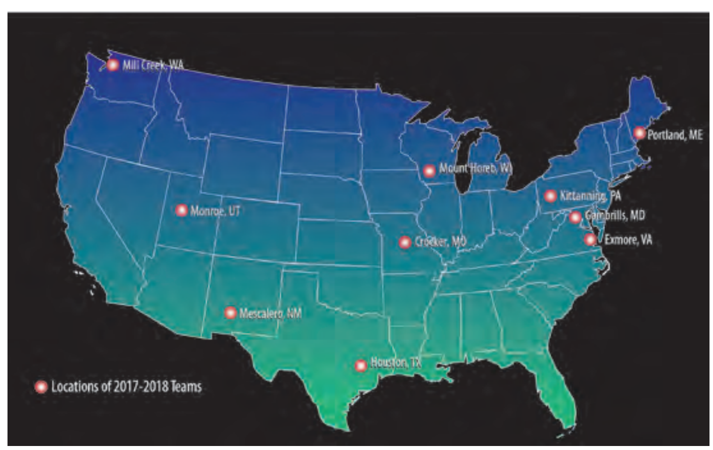


Figure 7. Map with the locations of high school research teams participating in the 2017-2018 ExMASS program.

3.3 CosmoQuest YouTube Live Events

Reached ~200 real-time viewers, followed by ~900 views of the recordings and an estimated 25,000 podcast downloads.

3.4 Public Engagement Forums

Hosted two August solar eclipse events.

Hosted an International Observe the Moon Night event.

PI Kring gave two public presentations at the Houston Museum of Natural Science – one covering lunar exploration and the other discussing near-Earth asteroid hazards.

We participated in an Earth Day event; we created and displayed a new exhibit explaining the connection between lunar exploration and our understanding of the Earth. Exhibit art was distributed to other SSERVI teams via SSERVI Central for broader use.

3.5 Synergies

Shaner continues to serve on the International Observe the Moon Night coordinating committee.

Guests for YouTube Live events included members from the VORTICES and FINESSE SSERVI teams.

Scientists with CLSE and VORTICES are student team advisors for the ExMASS program.

4 Student/Early Career Participation

Postdoctoral Researchers

1. Dr. Jeremy Bellucci (Swedish Museum of Natural History)

2. Dr. Katherine Bermingham (University of Maryland)

3. Dr. Katherine Kretke (SSERVI NPP: Southwest Research Institute & USRA-LPI)

4. Dr. Claire McLeod (University of Houston)

5. Dr. Katharine Robinson (USRA-LPI)

6. Dr. Martin Schmieder (USRA-LPI)

7. Dr. Barry Shaulis (USRA-LPI)

8. Dr. Joshua Snape (Swedish Museum of Natural History)

9. Dr. Timmons Erickson (USRA-LPI)

Graduate Student Researchers

10. Sky Beard (University of Arizona)

11. David Burney (University of Notre Dame)

12. Justine Grabiec (University of North Carolina)

13. Connor Hilton (University of Maryland)

14. Trey Lobpries (University of Houston)

Undergraduate Student Researchers

15. Emma Hon (University of Hawaii at Manoa)

16. Laura Seifert (University of Arizona)

Short Course and Field School at the Sudbury Impact Structure

17. Michael Bouchard (Washington University in St. Louis)

18. Sietze Jan de Graaff (Vrije Universiteit Brussel)

19. Leticia De Marchi (Auburn University)

20. Scott Eckley (The University of Texas at Austin)

21. Sierra Ferguson (Arizona State University)

22. John Gemperline (University of Colorado, Boulder)

23. Madison Hughes (Washington University in St. Louis)

24. Carol Hundal (Wellesley College)

25. Pim Kaskes (Vrije Universiteit Brussel)

26. Ari Hirsh Dickman Koeppel (The City College of New York)

27. Katrina Korman (Temple University)

28. Margaret Landis (University of Arizona)

29. Ebberly MacLagan (University of Alberta)

30. Xiaochen Mao (Washington University in St. Louis)

31. Dr. Martin Schmieder (USRA-LPI)

32. Kaitlyn Stacey (University of Texas at Dallas)

33. Jesse Tarnas (Brown University)

Cross -Team Graduate Student Researchers

34. Michael Demasi (University of Central Florida)

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

William Farrell

NASA Goddard Space Flight Center, Greenbelt, MD

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

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). We also have 2 derived themes: one being team intermural studies, like that recently performed on the space environment at Phobos (1.5) and the other being DREAM2's footprint into mission activities (5.0).

1.1 Plasma Environment

The DREAM2 plasma team continued its successful campaign to understand the interaction between airless body surfaces and exospheres of all scales with the space environment. Airless bodies represent arguably the most common object in our Solar System and beyond, and they interact directly with the space environment, which consists in large part of plasma. Indeed, by most estimates, more than 99% of the visible matter in the universe is ionized and therefore classified as plasma. The plasma-surface and plasma-exosphere interactions that the DREAM2 plasma team studies are therefore of fundamental importance in our universe, with implications for airless bodies of all sizes both within and outside of our Solar System.

The DREAM2 plasma team conducted fundamental data analysis and theoretical investigations focused on Phobos, the Earth's Moon, and small bodies. Several studies highlighted the space environment of and potential future mission concepts for the exploration of Phobos [Farrell et al., 2017; Collier et al., 2017]. Other highlights include fundamental investigations of the physics of the interaction of the solar wind with small-scale magnetic fields at the Moon [Halekas et al., 2017] and the characteristics of the resulting low-frequency electromagnetic turbulence in the space surrounding the Moon [Howard et al., 2017]. DREAM2 plasma team members also studied solar wind and photon interactions with the lunar regolith, revealing the response of the regolith and the nearby electrostatic environment to solar ultraviolet photon flux [Harada et al., 2017], and determining the surface weathering rate of small regolith grains under solar wind bombardment [Poppe et al., 2017].

A highlight of the DREAM2 plasma team's 2017 research was the first plasma simulation of the solar wind interaction with 16 Psyche (**Figure 1.1.1**) [Poppe and Fatemi, 2017], in anticipation of measurements from the upcoming Psyche mission now in development. These sophisticated simulation results will be critical for interpreting Psyche magnetometer measurements and inferring not only the physics of the plasma interaction but also the internal structure and magnetization of Psyche, by differentiating the magnetic field signatures expected for the interaction between magnetized and unmagnetized obstacles.

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

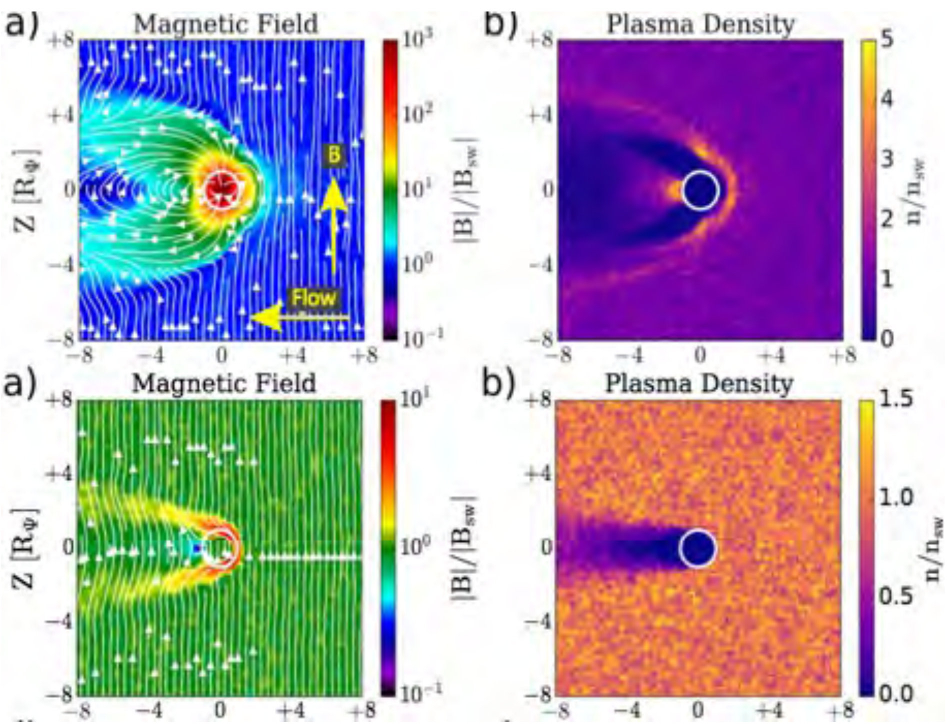


Figure 1.1.1 Predicted magnetic field and plasma density at 16 Psyche for magnetized (top) and unmagnetized (bottom) cases.

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

Killen et al [2017] published a generalized exosphere model determining the species mass that could be captured as a function of surface energization process and planetary body mass. **Figure 1.2.1** shows the water (AMU=18) escape fraction as a function of airless body radius. Note that for source energy (or temperature) for thermal and impact processes at the Moon, water can mostly be retained. However, for the energetic plasma sputtering process, the release of water is energetic with a substantial portion escaping the Moon. At low-gravity Phobos, surface water will not be gravitationally bound even for weak thermal release processes.

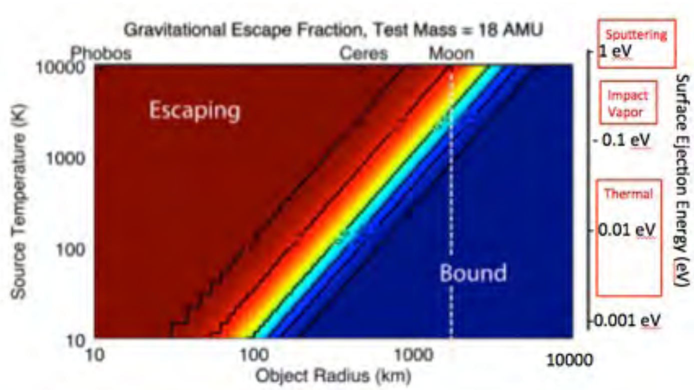


Figure 1.2.1 – Gravitational escape fraction for water as a function of airless body size [Killen et al., 2017]

Hurley et al. [2017] published studies of the contribution of micrometeoroids to the inventory of surface water in the Moon's exosphere and on the surface to compare with LADEE results.

Killen et al. continues to observe the lunar sodium exosphere remotely using their coronagraph situated at the Winer Observatory in Sonoita, Arizona. They reported results at the NASA Exploration Science forum, the annual Division of Planetary Sciences (DPS) meeting and at the American Geophysical Union (AGU), and featured the new observation of possible north/south asymmetries in the lunar sodium exosphere.

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. Within their specialized chamber, a layer of molecules can be laid out onto a regolith bed (including small 'smokes' and Apollo soil samples). The temperature is allowed to rise via a laser heating system. The desorption of carbon dioxide, methane and argon to Apollo soil samples has been examined.

Killen and David Williams are continuing a study of the lunar exosphere using the recently archived LACE data from Apollo 17. In addition, Killen is collaborating with Prabal Saxena, Avi Mandell and Noah Petro on examining moderate volatile loss through lunar history. Collier has phase A funding for PRISM, a Phobos Regolith Ion Sample Mission with Killen, Stubbs and Farrell supporting the effort.

1.3 Radiation Environment and Humans

The DREAM2 radiation team continued to explore how energetic charged particles affect the surface of the Moon and of Phobos. While plasmas interact with the surface 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 down to ~1 m. Not only can they modify regolith at depth, but they also enable us to probe the regolith. We highlight some work below, but other ongoing work ranges from inferring the past heliospheric conditions to how the radiation is modulated throughout the heliosphere [Rahmanifard et al., 2017; Quinn et al., 2017; Schwadron et al., 2017a; Schwadron et al., 2017b; Winslow et al., submitted to Astrophys. J.]

One highlight of this year's work continued previous investigations of how SEPs can cause dielectric breakdown in the top ~1 mm of soil within the Moon's permanently shadowed regions (PSRs) [Jordan et al., 2017]. A sufficiently large SEP event could deposit enough charged particles to increase the subsurface electric field to the point of dielectric breakdown (**top of Fig. 1.3.1**). Because breakdown vaporizes and melts material, it might weather soil in a way similar to meteoroid impacts. By comparing energy budgets, team members predicted that dielectric breakdown weathering is as important in PSRs as meteoroid impacts, affecting 10-25% of the regolith. They also extrapolated this work to Mars's

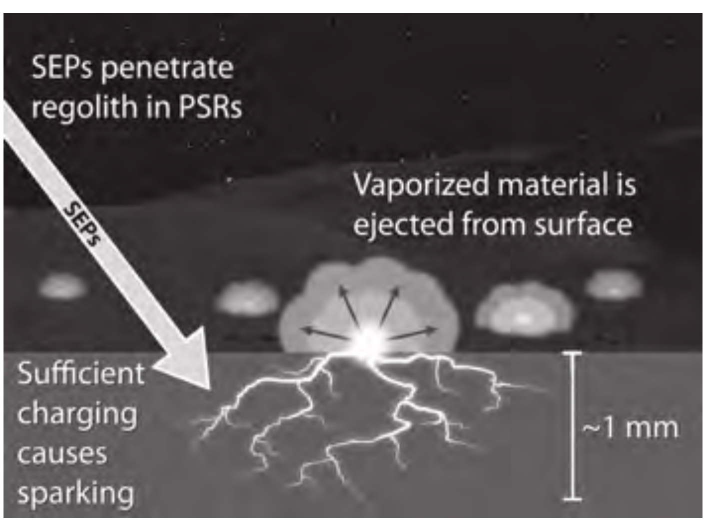


Fig. 1.3.1. (Top) Illustration showing how SEPs can penetrate the soil in lunar PSRs and cause dielectric breakdown.

satellite Phobos [Jordan et al., accepted in Adv. Space Res.]. If the electrical properties of its regolith are similar to the Moon's, then breakdown weathering may also be important there.

Another highlight is that the radiation team has begun to leverage a process generated by GCRs to help determine whether, as suggested by other studies, hydrogen varies diurnally on the lunar surface [Schwadron et al., 2017]. When GCRs collide with nuclei in the regolith, they release neutrons and "albedo protons." Unlike neutrons, which are suppressed when they encounter a layer of hydrogen, albedo protons are enhanced: some of the neutrons collide with the hydrogen (i.e., protons) and eject those protons. Since they originate at a depth of ~1-10 cm, albedo protons are a critical link between the reflectance data (surface) and the neutron data (~50 cm depth). Using the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter (LRO), team members have detected diurnal variation in the albedo protons which may, in part, be due to diurnally varying hydrogenation. The team has developed a new analysis and observational techniques to continue this exploration.

1.4 Surface Interactions

The harsh space environment—including impactors, energetic plasma, and radiation—creates damage within the regolith-rich surfaces at airless bodies. In PY 4, DREAM2 team members further examined the surface response to this environment. We highlight some of the activity below, but do not list all the ongoing work. See the full list of publications in the bibliography at the end of this report that identifies further activity.

Team members Farrell, Hurley, McLain and Zimmerman, along with DREAM2 intern Esposito, published a model of solar wind hydrogen implantation and expected surface hydroxylation (**Fig.1.4.1**). The model predicted the amount of retained hydrogen at the Moon as a function of solar zenith angle—including the effects of H atom diffusion in damaged, irradiated silica surfaces. While a set of remote sensing IR observations have observed this OH in lunar regolith, to date there has not been a comprehensive solar wind-OH model to place these observations in context.

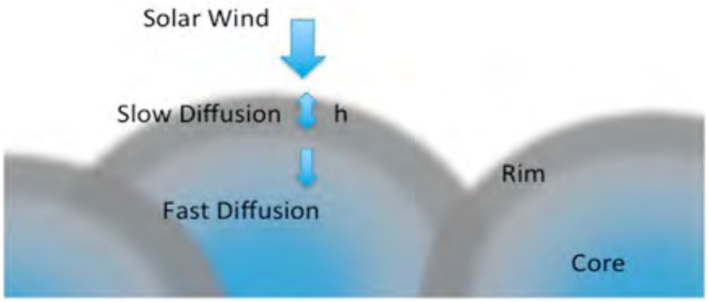


Figure 1.4.1: An illustration of the region of hydrogen 'slow' diffusion given solar wind protons as a source [Farrell et al., 2017]

The model predicts a lunation variation in OH content that was more recently confirmed in the IR observations. The model also predicts a reduction in OH formation in magnetic anomalies due to the reduced energy and flux of the incoming solar wind protons. The reduction in energy makes the implantations occur at a shallow depth—which allows for quick diffusion out of the surface. The lack of OH in magnetic anomalies via remote sensed IR has also been reported.

Poppe et al. merged ARTEMIS time-averaged solar wind proton and He ion energy distributions with ion transport models of lunar-like material. They demonstrated the high energy tail of the solar wind energy distribution could create amorphousization (crystal lattice destruction) at relatively large 100-200 nm depths. Such deep damage had been reported previously from electron transmission studies of Apollo samples. In essence, they linked the plasma observations to the grain damage found in lunar samples.

McLain, Loffeler and Hudson continue their laboratory investigation of proton implantation and associated hydroxylation using the unique Goddard Radiation Facility. In PY4, they completed and tested the DREAM2 beam line and have made preliminary implantation results, finding H becomes trapped in fused silica to form OH when irradiated for ~24 hours in a 1 keV proton beam. In PY5, we will then irradiate and damage the surface using a 1 MeV Argon beam to determine the effect on retention of the lower energy implanted H atoms. This two-beam experiment is a unique contribution to understanding the ability of oxide-rich regolith to act as a sort of catalyzing surface to create more complex chemical products like OH, water, and methane.

DREAM2 team member Marshall has been investigating how particulate materials respond to transport forces, abrasion, tribocharging, and cohesion in airless or near-airless Solar System environments with relevance to understanding fundamental physical processes as well as the response of Solar System body surfaces to contacts with astronauts or mechanical objects. He is currently examining the requirements for grain lifting from airless bodies, including adhesion effects.

Team members Stubbs and Glenar are currently modeling the radiated power at lunar polar regions from sunlight reflected from the Earth (i.e., Earthshine). They have developed a visible and IR model of the Earth reflectance and will consider how this Earth shine will illuminate polar craters using LOLA topo maps along with the Moon's orbital orientation. This work is in support of the Lunar Prospector Mission.

1.5 Progress on the Space Environment at Phobos Study

During PY4 the team continued to extend their work on the space environment at Phobos. In PY4 DREAM2 team members published a set of papers to the 'Science and Exploration of Small Bodies' special issue of the journal 'Advances in Space Research.' Presentations were also made at the Lunar and Planetary Science Conference (LPSC), the NASA Exploration Science Forum (NESF), and the Division of Planetary Science (DPS) meeting (**Figure 1.5.1**). In the summer of 2017, we also issued a press release on the possible surface charging at Phobos (https://www.nasa.gov/press-release/goddard/2017/mars-electric-moons) and shortly thereafter made a presentation at NASA HQ on the space environment at this enigmatic body.

The current list of papers from the DREAM2 Phobos study include:

- Poppe et al 2016: Phobos neutral and ion torus, JGR [published]
- Farrell et al. 2017: Hydroxylation at the Moon and Phobos, JGR [published]
- Killen et al. 2017: General Scaling of Exospheres, ASR/SB [published]

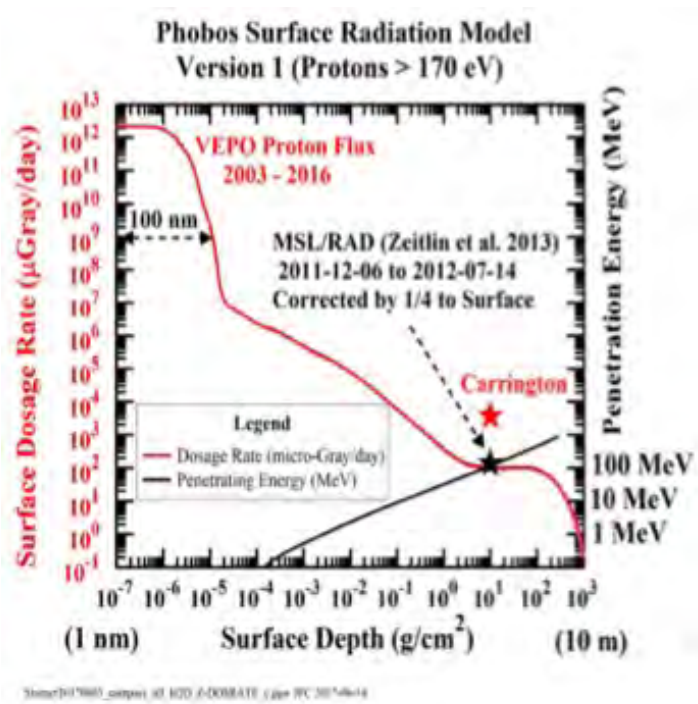


Figure 1.5.1: A model of the Phobos radiation-surface interaction presented by Cooper et al. (2017) at the AAS/DPS meeting this past fall, 2017. Most of the influx of radiation (170 MeV protons) is attenuated in the first few meters of regolith.

- Hartzell et al. 2017: Cohesive regolith on human explorers, ASR/SB [in press]
- Farrell et al. 2017: Electrical environment at Phobos, ASR/SB [in press]
- Jordan et al., 2017: Dielectric breakdown at Phobos, ASR/SB, [in press]
- Collier et al., 2017: Smallsat mission to Phobos, to be submitted in ASR/SB [completed manuscript]

Extended Abstracts

- Hurley et al, Impact Gardening at Phobos, 3rd P/D Workshop
- Stubbs et al., Solar illumination at Phobos, LPSC 2017

1.6 Conclusions and RP

The next topic for a DREAM2 Intramural study is the lunar environment expected to be encountered during the Resource Prospector (RP) mission. We initiated the study in PY4 and will continue the work in PY5. Specifically, we have created models of RP rover wheel charging that would be useful to determine rover speeds in low plasma PSR regions. If the wheel moves over the surface too fast, excess tribo-charging could occur in PSR regions with low plasma influx. Prim and Hurley are also examining the effect the landing craft exhaust plume will have on the local volatile environment. 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 in excess of 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. Stubbs and Glenar are creating a model of Earthshine into regions where RP will examine. 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. RP's NIRVSS system may have the potential to directly observe the discharge event.

There were many 10's of DREAM2 scientific and outreach activities occurring during PY4, and we highlight a few of these herein. We continue 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 that contribute to the complexity of interactions between the environment and surface. As we note in the RP study, RP is sent to prospect for resources, but RP's own effect on the fragile environment

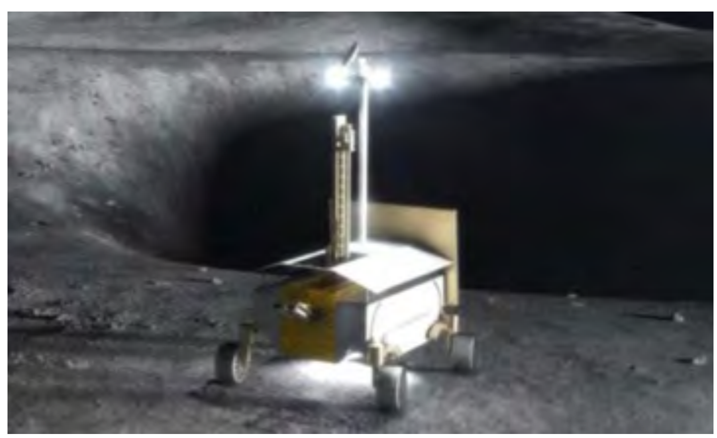


Figure 1.6.1: An illustration of the RP lander.

may impact the prospecting process. DREAM2 is poised to examine and assist the RP team in evaluating these lander-surface-environmental effects.

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 recently proposed to share an NPP position via a SSERVI-Central slot. We are currently working on a Long Duration Exposure Platform (LDEP) to be placed on the Deep Space Gateway to examine the effects of solar wind and impact weathering on a set of 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: Strong collaborating work on solar wind/ airless body interactions, volatile interactions, and Orion/asteroid interactions and lunar pits. Strongest collaborations with individuals Zimmerman, Hurley, Prem, & Hibbitts.

RISE4: Strong collaborating work on lunar pits, with the RISE4 field team providing lidar input to pit environment models shared by DREAM2 and VORTICES. We are working with RISE4 team to pursue opportunities to architect, design and build future exploration-oriented field instrumentation for astronaut use.

IMPACT: 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. DREAM2 modelers are working with IMPACT modelers on magnetic anomaly studies.

FINESSE: We share Co-Is in 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.

International Partners

Japan: DREAM2 team members work closely with Dr. Y. Saito, the Kaguya plasma and mag PI, at the Institute of Space and Astronautical Science, on lunar plasma interactions. Prof. Halekas took a sabbatical from his then-position at UCB in the late 2000's (as part of NLSI) to enhance the relationship—which continues to be very fruitful. The teams are currently working together to integrate the ARTEMIS, Lunar Prospector MAG/ER, and Kaguya plasma data sets. Kaguya Co-I M. Nishino makes regular visits to UC Berkeley to discuss the plasma and exosphere interactions at the Moon. Many DREAM2 and Kaguya plasma team members are working together on a New Views of the Moon 2 chapter on 'Dust, Atmosphere, and Plasma at the Moon.'

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. We continue to team with our Kiruna partners in our cubesat proposals, like the SIMPLEX HALO proposal lead by Collier.

3 Public Engagement

3.1 Undergraduate Internship Program

Summer 2017 marked a fourth successful DREAM2 Undergraduate Internship Program. Team members at GSFC (W. Farrell, R. Killen, M. Sarantos, M. Collier, T.

Stubbs, J. Cooper, L. Bleacher) hosted eight students, including seven from a 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 DREAM2Explore Educator Professional Development Workshop

The DREAM2 Education and Public Engagement Team also led the third annual DREAM2Explore Educator Professional Development Workshop, which took place from June 26-July 1st, 2017. Fifteen science teachers from around the country, grades 6-9, participated. DREAM2Explore was an in-depth week of hands-on activities, discussions, presentations by DREAM2 team members and other GSFC subject matter experts, tours, and networking opportunities. Content focused on SSERVI target bodies–Earth's Moon, near-Earth asteroids, and the moons of Mars–including formation and evolution, the space environment, NASA's current plans to explore these objects, and NASA's "Journey to Mars." Participating DREAM2 team members included B. Farrell, J. Bleacher, A. Jordan, J. Cook, R. Killen, M. Loeffler. FINESSE PI Jen Heldmann participated as well. Tours included GSFC integration and testing facilities, a behind-the-scenes visit to the meteorite collection at the Smithsonian's National Museum of Natural History, and a tour of the National Air and Space Museum.

A survey was issued at the workshop's conclusion to gauge its success. 100% of DREAM2Explore participants strongly agree that: The workshop allowed them to acquire a new understanding of planetary science and exploration that will be valuable in working with their students in the future, and they acquired activities while at the workshop that they will use with their students. Participant quotes included the following: *"It exceeded my expectations. I am far more confident to facilitate the learning experience for my students." "These workshops are very valuable. The knowledge will be passed on. It is hard to tell how many lives will be touched by what we learned this week."*

4 Student / Early Career Participation

Undergraduate Students

DREAM2 co-I Prabhakar Misra at Howard University won a separate 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:

- Skylar Grammas
- Sirak Fessehaye
- Jamil Johnson
- Grace Kenlaw
- John Clark
- Trey Jean-Baptiste

The PI institution, GSFC, is a government laboratory and thus does not have direct access to students. However, DREAM2 E/PO Lead Lora Bleacher has leveraged NASA internship programs to enable early career STEM undergraduates at Howard University and other academic institutions to work at the GSFC facility. This approach has been wildly successful: it allows access and participation of DREAM2 and STEM activities to a great number of students. Our academic partners also have been extending the pipeline with graduate and post-doc personnel. These early-career activities and participants are listed:

- Keenan Hunt-Stone (Howard)
- Iman Ahmed (Howard)
- Edward Williams (UMD)

Graduate Students

- Heidi Fuqua, UCB, Lunar Plasma Interactions
- Colin Joyce, UNH, Radiation studies
- Stephanie Howard, Iowa, Solar wind plasma disturbances at the Moon
- Fatemeh Rahmanifard, UNH, Radiation
- Philip Quinn, UNH, Radiation

Postdoctoral Fellows

- Charles Lue, Iowa, Space Plasma and ARTEMIS
- Jeff Walker, Iowa, Space plasma and dust
- Rika Winslow, UNH, Radiation studies
- Orenthal Tucker, GSFC, Hydrogen Cycle and Exospheres
- Dov Rhodes, GSFC, Charging on human systems (arrives in April)

New Faculty Members

- Menelaos Sarantos, NASA Civil Service, GSFC, Exospheres

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/Resource Prospector/Colaprete/NIRVSS lead
29. AES/Resource Prospector/Elphic/NSS lead
30. AES/Lunar IceCube/Clark/Science PI
31. HSD/ARTEMIS/Halekas/Deputy PI
32. HSD/ARTEMIS/Delory/Co-I
33. HSD/WIND/Collier/Deputy PI
34. HSD/WIND/Farrell/WAVES and MFI Co-I
35. HSD/Parker Solar Probe/Farrell/Co-I
36. HSD/Parker Solar Probe/Schwadron/Co-I
37. HSD/IBEX/Schwadron/Co-I
38. HSD&ESA/Solar Orbiter/Collier/co-I Heavy Ion Sensor (GSFC lead)
39. HSD&ESA/SMILE/Collier/Co-I
40. HSD/CuPID cubesat/Collier/Co-I and instrument lead
41. ESA/BepiColumbo/Killen/Co-I
42. ISRO/Chandrayaan-1/Holmstorm*/Co-I
43. JAXA/Kaguya/Saito*/PI
44. JAXA/MMX/Elphic/MEGANE Co-I
45. KARI/KPLO/Elphic/MEGANE Co-I
46. DoD (Space Test Program)/FASTSAT/Collier/Co-I and instrument lead
47. DoD (Space Test Program)/USAF DSX/Farrell/Co-I and Search coil build lead

Mission-recognized supporting roles includes:

46. PSD/Lunar Reconnaissance Orbiter/Glenar/LAMP data analysis
47. PSD/ Lunar Reconnaissance Orbiter/Prem/Diviner and Mini-RF data analysis
48. PSD/ Lunar Reconnaissance Orbiter/Wilson/CRaTER data analysis
49. PSD/ Lunar Reconnaissance Orbiter/Jordan/ CRaTER data analysis
50. PSD/LADEE/Marshall/UVS instrument calibration
51. PSD/Cassini/Cooper/CAPS team member, data analysis
52. PSD/Cassini/Hurley/Enceladus modeling
53. HSD/ARTEMIS/Poppe/plasma data analysis
54. HSD/ARTEMIS/Fatemi/plasma data analysis & modeling

Jennifer Heldmann

NASA Ames Research Center

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

1 FINESSE Team Project report

Multiple research projects pertaining to the geologic processes of impact cratering and volcanism have been completed this year by the FINESSE project. We seek to understand volcanics and impact cratering 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 Impact Crater Formation

The kinematics of complex crater formation are uncertain, especially within crystalline rocks. Comparing geologic observations of deformed shocked target rocks with numerical simulations of crater formation and collapse can help address this issue. To that end, the West Clearwater Impact Structure (WCIS) is used as a terrestrial analog to understand crater formation. Drill cores and samples were analyzed using petrographic methods to determine shock pressures, and numerical simulations were run to simulate crater formation and the distribution of shock throughout the system. Results suggest that the variability of shock pressures is highest in the upper 200 m, which correlates with the highest degree of deformation. Results also show that the size of coherent rock blocks in complex crater formation gets progressively larger away from the impact location.

> Field studies of a terrestrial impact crater have shown how shock processes deform rocks during impacts, and how our canonical interpretation of rock types at impact sites requires revision to accurately understand how impact craters form in the Solar System.

Another interesting result from the analysis of WCIS samples was the unique properties of the impact rocks which highlight the need for revised rock classification schemes for impact sites. One of the most distinctive impactites at WCIS is a breccia containing variable proportions of red, oxidized impact melt glasses set in a fine-grained matrix. There is a complete continuum from melt-free lithic impact breccias to clast-poor impact melt rocks at WCIS. Contacts are gradual in most instances and in many outcrops, both the melt and clastic component can be considered the groundmass and vice versa. It is, therefore, not possible to classify these rocks according to the current IUGS classification scheme, and a revised scheme for such impactites is suggested. In addition, “melt-rimmed” lithic clasts and “aerodynamically-shaped glass bombs” are common in the impact melt-bearing breccias at WCIS beneath the coherent impact melt sheet. Usually such rocks would be interpreted as airborne, but this is not the case at WCIS since these rocks are below the impact melt sheet. Again, a new interpretation is warranted based on the terrestrial field observations, this time based on properties of rocks which have a different mode of origin than typically assumed.

1.1.2 Geochronology

This past year has seen a major step forward in our understanding of the precise age of the West Clearwater impact structure (WCIS). Efforts have focused on the development of strategies for multichronometric studies of impact rocks through analog work at West Clearwater but will be applied ultimately to future exploration targets. Previous work on WCIS using the 40Ar/39Ar method on bulk melt rock samples, the (U-Th)/He method on single zircon crystals, and the Rb/Sr method on bulk rock resulted in age estimates ranging from 286.2 ± 2.6 Ma to 271 ± 15 Ma (all uncertainties reported at the 2σ level). Of all the chronometers that might be applied to impact melt rocks, the U/Pb zircon method has the potential to provide the most precise constraints. However, many impact melts contain zircons inherited from the target region that have not had their U/Pb systematics reset by the impact event and thus do not accurately record the age of the impact event, so the key to using zircons successfully for impact dating is to isolate neoblastic zircons (or zircon overgrowths) that grew directly from the impact melt. As part of the FINESSE project, we have surveyed the zircon populations of several samples using reconnaissance laser ablation plasma-source quadrupole mass spectrometry and identified one clast-poor impact melt breccia from West Clearwater that contains an abundance of young zircons ranging in age from ca. 293 Ma to ca. 289Ma, which are interpreted to be neoblastic. We have established high-precision U/Pb dates for five of these zircons. They yielded concordant data with an inverse variance-weighted mean for ID-TIMS 206Pb/238U date of 286.71 ± 0.33 Ma, which presently stands as the most precise and likely most accurate age for the WCIS. The weighted mean ID-TIMS 206Pb/238U age of the concordant zircons is 286.71 ± 0.33 Ma (MSWD=0.87, N=5, 2σ error includes the error on the decay constant). This is interpreted as the new best estimate of the West Clearwater impact age, and this measurement has increased the precision on the timing of the impact by a factor of ~8 relative to the previous best measurement of 286.2 ± 2.6 Ma.

Studies of additional samples are underway, and preliminary results indicate that different samples from the same impact structure, even when lithologically similar, are not similarly useful for precisely constraining the impact age. (In fact, we have found no other samples as yet with neoblastic zircons.) This finding has important implications for future mission planning, because it means that determining precise ages for impact events on other planetary bodies will likely necessitate a large number of returned samples collected from a broad area within an impact site, not a single sample as might be collected by a stationary robotic lander.

> Age-dating of impact craters in future planetary geochronology missions will require a large number of returned samples collected from a broad area within the impact site.

1.2 Volcanism

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

The rheological evolution of lunar lava, in this case a two-phase suspension of melt and crystals, during cooling and crystallization is yet poorly understood. Terrestrial lavas undergo a change in flow laws, whereby the viscosity strongly increases upon crystallization and becomes strain rate dependent. This change in rheological behavior relates to the thermo-mechanical erosion potential of lunar lavas, a mechanism proposed to form sinuous rilles on the lunar surface. So far, studies have explored the erosive potential for crystal-free lavas only.

We studied the rheology of two lunar analog lavas, a KREEP and Ti-rich lunar mare basalt, during cooling and crystallization via a series of laboratory experiments. The relationship between temperature, crystallinity, and rheology is fully described for both analog lavas, and is then used to develop a thermos-mechanical erosion model that incorporates the changes in flow behavior (e.g., Newtonian fluid transitioning to pseudoplastic flow transitioning to a Herschel-Bulkley fluid).

We have also determined erosion rates for KREEP and Ti-rich lunar mare basalt for mechanical and thermal erosion. Due to the high viscosity of KREEP lavas even above their liquidus temperatures, total thermo-mechanical erosion rates are almost one order of magnitude lower than for lunar mare basalt. Thermal erosion is always more efficient than mechanical erosion within the first 80 degrees of undercooling. For both lavas, erosion potential strongly vanishes as soon as the lava is crystallized. Our data suggest that thermo-mechanical erosion is only a viable construction mechanism for sinuous rilles as long as lavas remain above or around their liquidus temperature. Assuming eruption temperatures and certain cooling rates of the lava, the effective length of sinuous rilles varies considerably between the two candidate lava compositions, whereby longer sinuous rilles can be expected to be a result of lunar mare basalt flowing in channels on the lunar surface.

1.2.2 Surface Roughness and Physical Properties of Lava Flows

Lava flow morphologies at Craters of the Moon National Monument and Preserve in Idaho resemble flow morphologies observed on the Moon and other planetary bodies. Of particular interest is the transition from smooth pahoehoe to rough \`a\`a, which is due to changes in the rheological properties of the lava as a result of changes in the physical properties (such as crystallinity and porosity induced by changes in emplacement temperature). However, no studies so far have provided a mathematic description of surface roughness and the quantifications of physical properties of the lava at the same time. This project addresses this problem and explores the correlation between surface roughness and physical properties so that it can be used as a remote sensing tool to characterize and understand the geologic history and the physical properties of volcanic terrains before robots or humans are deployed onto the surface.

Using our high-resolution DEM (of 5 cm per pixel, **Figure 1**) and quantifying the physical properties of 28 samples in the laboratory, we find good linear correlations between crystallinity and porosity at resolutions between 0.30 up to 2.5 meter per pixel, which corresponds to current resolutions of the lunar surface for example. The method used is the 2D/3D area ratio, however, we find that this mathematical description is only meaningful at resolutions down to ~20 cm per pixel. For instance, with higher resolution, the 3D area becomes increasingly large and large-scale surface morphology (controlled by the physical properties) is not resolved (e.g., too detailed of a view). We are currently investigating other means of quantifying the surface roughness, such as root-mean square deviations (RMSD) at various DEM resolutions.

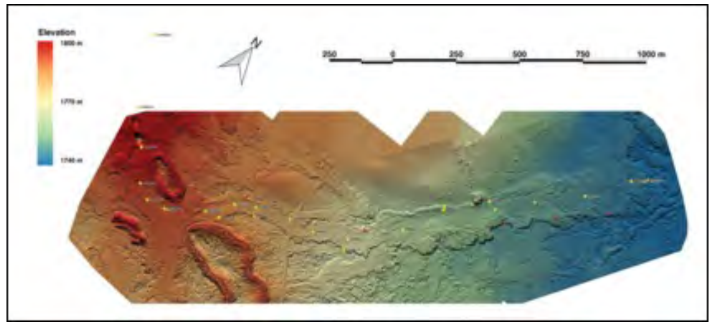


Figure 1. Digital Elevation Model (DEM) of the studied lava flow in Idaho. Data collected from FINESSE UAV flights. Small yellow and red stars represent sample locations.

1.2.3 Thermal Properties of Planetary Melts

Heat transport plays a crucial role in the thermal evolution of high-temperature, magmatic regimes on Earth and presumably on other planetary bodies, such as the Moon, Mars and Mercury. Thermal diffusivity (D) has been measured for terrestrial glasses and melts, spanning a compositional range from basalt to rhyolite. The observed low values for thermal diffusivity and viscosity for basaltic melts suggest that basalts transfer heat much more efficiently by advection than by conduction alone, and that partially molten zones in Earths' mantle quickly become more thermally insulating than non-molten zones, potentially contributing to melt localization during decompression melting.

In this project, we provide new thermal diffusivity and heat capacity data starting at room temperature up to ~1000 K (for D) and 1750 K (for CP) for a variety of synthetic planetary tholeiite glasses and liquids. Their viscosity and density were already measured, thus providing a comprehensive view of their transport properties.

One of the many findings is that the suite of planetary melts is generally less thermally insulating than terrestrial MORBs, an observation that has implications for melt generation and accumulation. In particular, lunar KREEP basalt and Mercurian NVP and IcP-HCT basaltic komatiites have low thermal conductivities. Consequently, partially molten regions producing these melts will also have low thermal conductivities, enhancing the productivity of decompression melting. This feedback mechanism may contribute to the large volumes of magma produced, and was observed as extended lava flow features (e.g., sinuous rilles located in the Procellarum-KREEP Terrane on the Moon) and flood style volcanism (Northern Volcanic Plains on Mercury).

1.2.4 Self Secondary Impact Features in Melt Flows

This research focused on impact features present in the Kings Bowl (KB) lava field of Idaho near the main vent which we refer to as “squeeze-ups” (**Figure 2**). These features were caused by the ejection of blocks during the phreatic eruption that formed the KB pit, and their subsequent impact into a partially solidified lava pond. We compare and contrast these features with analogous self-secondary impact features, such as irregular, rimless secondary craters (“splash craters”), observed in lunar impact melt flows. This was done by analyzing field measurements of feature dimensions and LiDAR analysis of feature distribution, and then comparing these data with self-secondary impact features on the Moon and related surface roughness constrained through Lunar Reconnaissance Orbiter observations.

Possible self-secondary impact features are formed when ballistic ejecta from the crater falls onto the ejecta blanket and melt surrounding the newly formed crater. The geologic setting, distribution, and morphology of lunar self-secondary impact features and KB squeeze-up features indicate they both formed in impact-melt or lava ponds before solidification, making them good analog comparisons.

Understanding how these features formed will help us to better understand surface processes and regolith evolution. For example, these self-secondary impact features on the Moon may complicate techniques used

Figure 2. Image of “squeeze up” features at Kings Bowl, Idaho which formed from the ejection of blocks during a phreatic eruption.

in crater chronology and geological dating. A surface has zero craters at the time of formation, but this may not apply to surfaces affected by self-secondary impact features. Further work is needed to help us better understand when we need to consider self-secondary impacts in crater chronology analysis.

1.2.5 Syracuse Lava Project

Nearly all analyses revealing the thermal and geochemical history of volcanoes on Earth require large volumes of material to be retrieved, prepared, and analyzed in a laboratory setting. To obtain the same level of information for lunar volcanoes, new techniques that require little to no sample collection must be developed. To that end, we have conducted experiments at the Syracuse Lava Project (SLP) to melt and resolidify basaltic rock to create experimental spatter bombs (**Figure 3**) which have been precisely measured over time in this controlled setting for temperature, time spent above 700 C (glass transition

Figure 3. Experimental spatter bombs created at the Syracuse Lava Project are shown being stacked with thermocouples between each clast. The cooled product mimics the appearance of natural spatter clasts (insert) from Idaho.

temperature), resultant vesicularity, void spaces, clast characteristics, etc. The SLP results have been correlated with numerical modeling to match emplacement temperatures and cooling trends plus accumulation rates, and then compared with Idaho-based field data and extrapolated to understand similar features on the Moon.

This project has expanded a method to determine the emplacement temperature and accumulation rate of volcanic deposits, which only requires measurements of outcrops to be applicable to lunar conditions. Thermal constraints for volcanic eruptions on the Moon will allow for better understanding of the thermal evolution of the lunar crust and mantle, as well as the loss of gasses from the lunar mantle. Higher temperatures and longer cooling times correlate to more connections and fewer void spaces between clasts. Furthermore, lower interior vesicularity and more oblate clasts were formed at higher temperatures and longer durations above the glass transition temperature.

We present a new method requiring no sample collection to assess the thermal evolution of lunar volcanic deposits, providing key information on eruptive history of volcanic areas on the Moon. There is currently no way to remotely sense these data from satellite imagery, therefore, landing on the Moon is critical to gain more understanding of the eruptive processes that shaped our nearest neighbor. With the correct measurements, the eruption duration, explosivity, and eruptive column height can be garnered from outcrops of scoria or spatter clasts.

1.2.6 Handheld Scientific Instrument Requirements for Human Exploration Missions

Handheld instrumentation capable of in-situ analyses are already used for geological exploration on Earth; however, their usefulness for human exploration missions to other planets needs to be evaluated. The FINESSE project has utilized several handheld spectrometers, a visible-near infrared (vis-NIR), a X-Ray-Fluorescence (XRF), and a Laser Induced Breakdown (LIB) spectrometer, as well as a forward looking infrared (FLIR) camera system. We studied how to best implement these new technologies, which were not available during the Apollo missions, during simulated exploration missions conducted on basaltic terrains in Idaho and Hawaii. To understand the data quality provided by these handheld spectrometers, we evaluated their performance under various conditions (measurement time, distance, angle, atmosphere, rock matrix), and compared data quality between handheld instruments and their traditional laboratory techniques. Our work provides guidelines and requirements on how to effectively incorporate these instruments in human exploration missions (**Figure 4**), and how future iterations

> Field testing handheld scientific instruments is critical for optimizing science on future planetary missions and demonstrates the complexity of integrating instrumentation into mission operations.

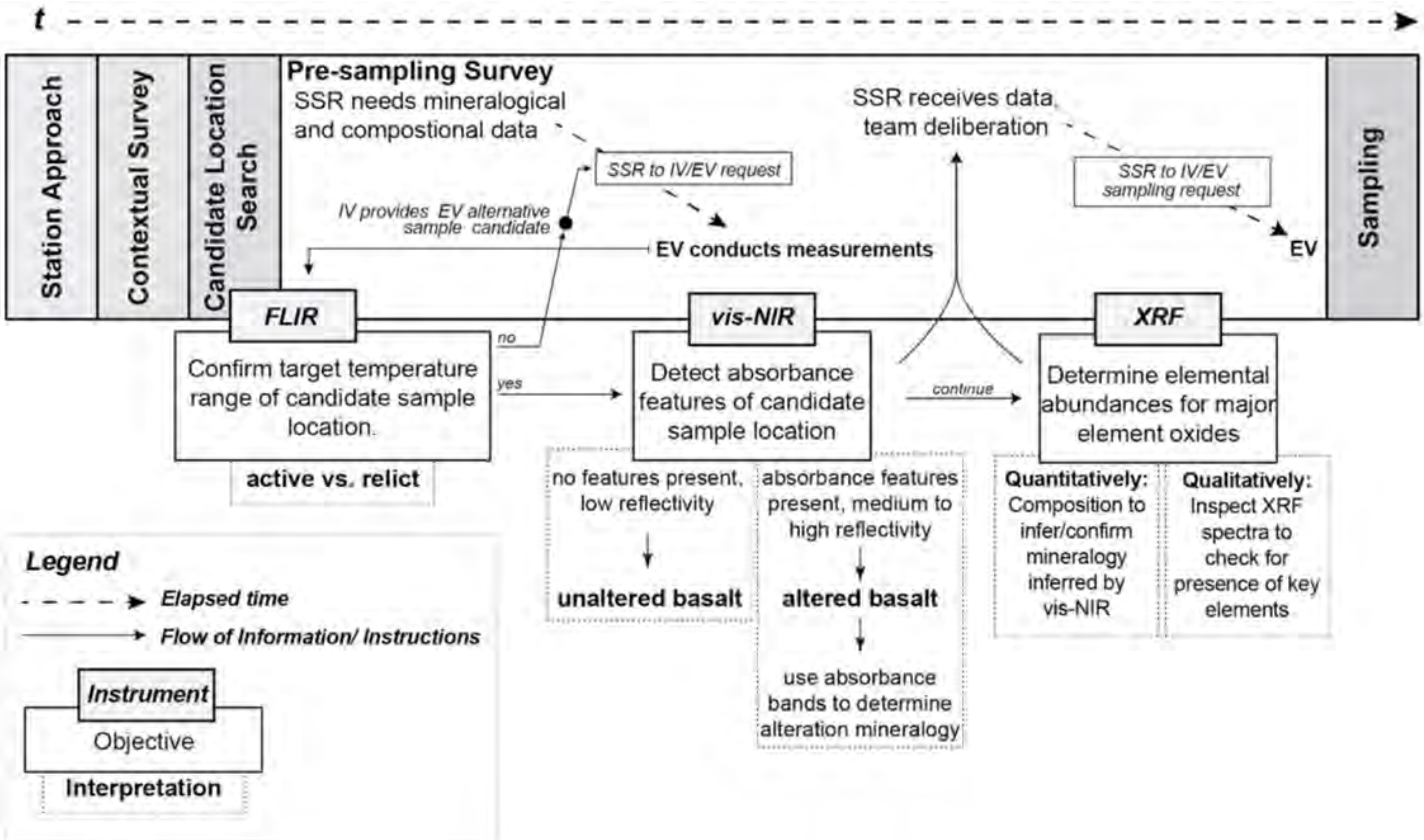


Figure 4. Integration of instruments into EVA architecture.

of these instruments will be beneficial for reliably collecting data and enhancing exploration missions.

1.2.7 Idaho Versus Eros Analog Study of Ejecta Blocks

One little explored way in which the Craters of the Moon National Monument and Preserve, Idaho field site is analogous to the surface of the Moon, the satellites of Mars and near-Earth asteroids is the presence of a large number of ejecta blocks. Ejecta blocks are common on the surface of the second largest NEA, 433 Eros, apparently produced by the impact that formed the Shoemaker crater, and on the Kings Bowl lava field in Idaho where they were produced by the phreatic explosion that formed the Kings Bowl crater.

We have performed a detailed analysis of the ejecta blocks at Kings Bowl (which occur only on the western side of the crater since wind-blown tephra buried those on the eastern side). We measured dimensions, locations, masses (where possible), and number densities on the surface, of over a thousand ejecta blocks. We have also measured the dimensions of boulders on Eros using three mosaics placed on the PDS by the NEAR-Shoemaker mission science team and we have gathered literature data in order to compare Eros ejecta blocks with those for the Kings Bowl crater. We have concluded that, despite considerable variety in texture and morphology of the Eros blocks, the boulders on 433 Eros have mechanical properties very similar to those of terrestrial basalt. The implication of this is that the Shoemaker impact penetrated the regolith and that Eros is a coherent rock, as suggested by morphological interpretations of global structures, rather than a rubble pile.

2 FINESSE Inter-team/International Collaborations

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), 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, as well as the publication of results regarding 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 Korea Institute of Geoscience and Mineral Resources (KIGAM)

FINESSE Collaborator Kyeong Kim is a researcher with the Korea Institute of Geoscience and Mineral Resources. Kim's research focuses on lunar science and the applications of XRF analysis on planetary surfaces. Kim deployed to Craters of the Moon with the FINESSE team this year (2017) and collected additional basaltic samples for XRF analysis, and presented 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

This year FINESSE team member Dr. Deepak Dhingra accepted a position as 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 Collaborations

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 (2015, 2016) which has led to several conference presentations with a manuscript publication underway. Matiella-Novak is a fully-integrated member of the FINESSE research team, and this collaboration has opened up new areas of research for both SSERVI teams, for mutual benefit and increased scientific productivity.

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. FINESSE also led a publication on Synchrotron X-ray computed tomography imaging with RIS^{4}E collaborators as a joint research effort.

2.2.3 NESS & CLSE

Both the FINESSE and CLSE teams have partnered with NESS to support a NASA Postdoctoral Program researcher through SSERVI to conduct research in the area of surface telerobotics to support future robotic missions to the Moon.

Figure 5. Spaceward Bound teachers and researchers use field portable instrumentation to measure lava flows in Idaho.

3 Public Engagement

3.1 Immersive, Authentic Field Experiences for Teachers and Students

Through FINESSE Spaceward Bound, a program we lead in partnership with the NASA Idaho Space Grant Consortium (ISGC), we bring students and teachers into the field to conduct science and exploration research in Craters of the Moon National Monument and Preserve. They work side-by-side with NASA researchers, operating field instruments, collecting data, participating in science discussions, and contributing to scientific publications. FINESSE has supported Spaceward Bound since 2014. Few NASA education programs engage teachers in similar experiences over multiple years, so we focused evaluation in 2017 on this long-term aspect. As compared to their first year participating in the program, teachers universally report greater confidence teaching science this year; sharing NASA resources with their students more often; talking with colleagues, administrators, and their communities about their experience in the program more often; feeling a deeper level of engagement in the program and a stronger connection to the FINESSE team, and an increased likelihood of participating in a similar program and other NASA educational programs in the future. *"I feel a deeper connection to science and math working in the real world and the field. This allows me to give my students a deeper understanding of the uses of math and science."*

Scientists reported feeling more comfortable working with the teachers this year than the first year they joined the field team, higher confidence that the teachers could support them and their research, and a deeper level of engagement with the teachers now than at the start of the program. They keep in touch with the teachers more, and are more likely to participate in a similar educational program in the future. *"Working with the teachers encourages me to be a better science communicator and to think of new ways to relate my active research to my own teaching. By having the same teachers over multiple years, it also creates opportunities to build lasting connections and possible pipelines for students via mentoring relationships."*

> "By teaming with teachers and bringing them into our world, we create opportunities for the fun, creative, messy sides of science to get back into the classrooms and inspire a new generation of scientists."

Chanel Vidal, a high school student that has participated in the program, presented her experience and how it motivated her to pursue a degree in geology and a career in space science research at the 2017 NASA Exploration Science Forum at NASA Ames: https://go.nasa.gov/2F6ng8v. FINESSE also worked with a team of 5 undergraduate students from the University of Idaho through a program called **TATERTOTS** ('Training in Advanced Technology and Exploration Research to Optimize Teamwork in Space'), awarded funding through NASA's Undergraduate Student Instrument Project (USIP) and also coordinated through the IGSC. The students joined the FINESSE team in the field at Craters of the Moon, where they launched a high altitude balloon in support of FINESSE planetary-analog lava tube research. They presented their work at the NASA Exploration Science Forum at NASA Ames, and were featured in the UI newspaper: http://bit.ly/2rzcC8l.

3.2 Team Outreach

The FINESSE team is committed to publicly sharing our research and interest in planetary science and exploration. We support a **SSERVI Seminar Series** for the NASA Museum Alliance and Solar System Ambassadors, who share this content with their audiences around the country and the world. In 2017, the FINESSE, RIS^{4}E, and DREAM2 SSERVI teams, SSERVI Central, and NASA's Lunar Reconnaissance Orbiter contributed. We also held a large public engagement event with Craters of the Moon staff and partners in Arco, ID for the August total solar eclipse, gave presentations at several universities and K–12 schools around the country, at a program for families at the Museum of Idaho, at the Fremont Peak Observatory Annual Members Meeting in California, and in a FINESSE-filled session at the National Association of Geoscience Teachers Pacific Northwest meeting. The team also supported International Observe the Moon Night and shared updates through the FINESSE website and social media accounts.

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, University of Idaho, volcanics, engineering
7. Hailey, Johnson, University of Idaho, volcanics, instrumentation
8. Avery, Brock, University of Idaho, volcanics; aerospace engineering
9. Mareyna, Karlin, University of Idaho, volcanics; instrumentation
10. Jonathan, Preheim, University of Idaho, volcanics; remote sensing
11. William, Miller, University 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 (2018), 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, Anthony Colaprete, Project Scientist
5. Resource Prospector, Richard Elphic, Deputy Project Scientist
6. Resource Prospector, Jennifer Heldmann, Science Co-I
7. Resource Prospector, Amanda Cook, Instrument Co-I
8. Resource Prospector, Matthew Deans, Co-I
9. Resource Prospector, 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, M^3 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 (Colour & 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)

1 IMPACT Project Report

1.1 Dust Accelerator Projects

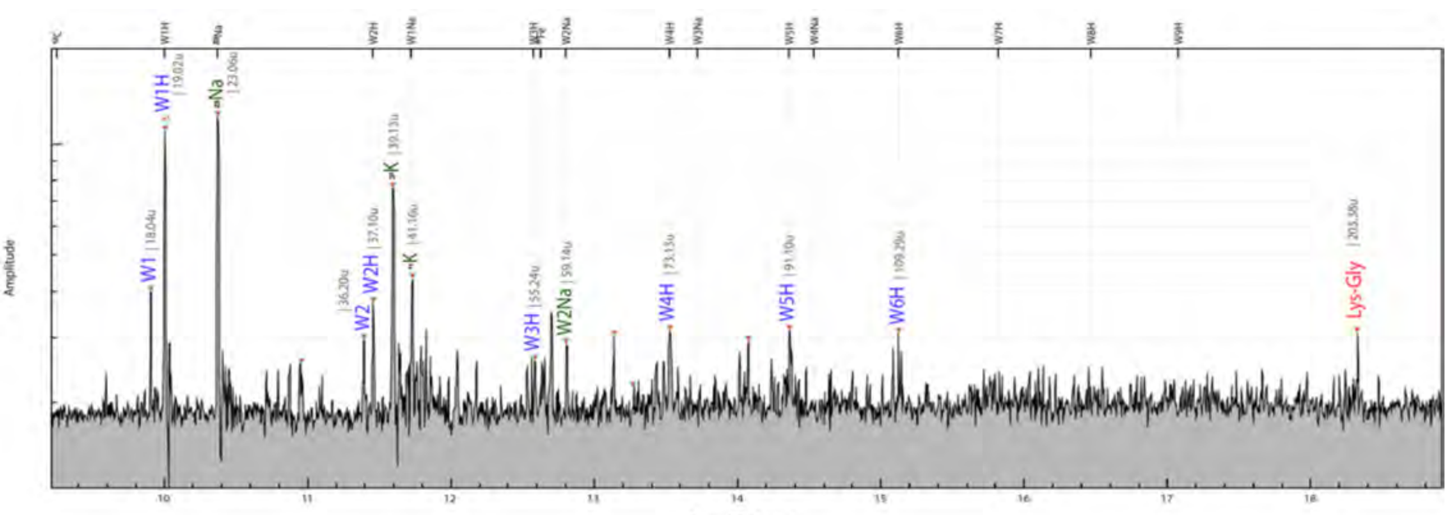
1.1.1 Ice-Target Impact Experiments

Modifications to the IMPACT cryogenic ice target have greatly improved its performance in terms of the quality and volume of mass spectrometry data produced, as well as the specificity of ice grown. The flash-freeze system has been used to create ice surfaces with homogeneously distributed amino acids and di-peptides (a chain of two amino acids). Even the more fragile Lysine-Glycine di-peptide survives dust impact and can be identified in mass spec data as shown in the attached spectrum, which was produced by a 4.8 km/s iron impactor.

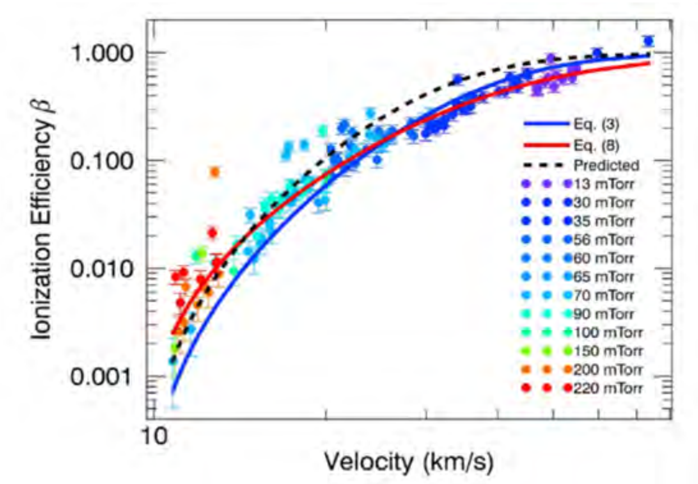
Additionally, improved system design has reduced the turnaround time between experiments and has allowed for a greater temperature control (down to 80 K) during ice growth. Further, a new heating system has been tested on a load which can be used to maintain the temperature of the target to within 1 K of a user-

> This discovery demonstrates that complex organic chemistry can survive micrometeoroid bombardment of icy planetary surfaces and be detected by impact ionization time of flight instruments.

specified value. Improved system design has also reliably increased the acceleration potential from 3 kV to 5 kV (thus increasing the charge yield and sensitivity of the instrument). Combined with improved experimental methods learned throughout the past year, the system performance has dramatically improved. In previous experimental runs, the flash-freeze system could be used to generate a up to ~100 usable spectra in a day, but the most recent experimental runs have reliably produced over 1000 spectra per day, with one day in



Time-of-flight mass spectrum produced by a single 4.8 km/s iron impactor into a flash-frozen Lysine-Glycine mixture.



Ionization efficiency for aluminum and air extended to the full velocity range of interest. From [SSERVI-2017-098].

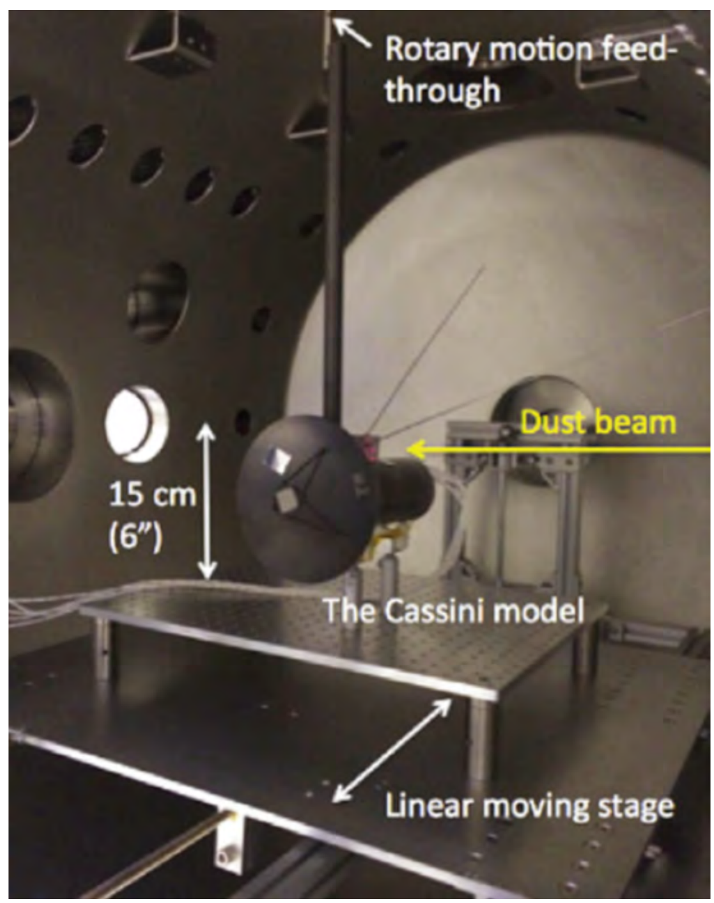
late January producing over 2700 spectra across two different ice mixtures. This volume of data can be used to add many spectra together to increase signal-to-noise ratio (SNR) and to perform statistical analysis in a way not previously possible.

1.1.2 Ablation Experiments

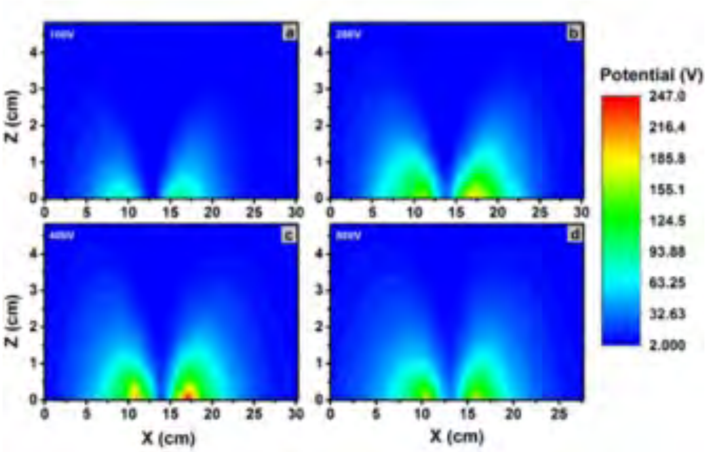
The ablation facility at the dust accelerator has been developed over the first half of the IMPACT funding period. The capabilities of the facility and its operation principle are described in a recently published article [SSERVI-2017-168]. Over the last year, the facility was used to conduct a number of experimental campaigns that led to two notable results. (1) The experimental measurement of the ionization efficiency has been extended close to the critical velocity (~10 km/s) as opposed to the past measurements reported for >20 km/s. The new data show that the ionization efficiencies are significant even at lower velocities that has a significant implication in accessing the sensitives of meteor radar measurements. The new results were published in a recent article [SSERVI-2017-098]. (2) A second experimental campaign was conducted to determine the drag coefficient that describes the efficiency of slow-down of micrometeoroids entering Earth's atmosphere. The surprising results here indicate drag coefficients that are considerable larger, about 1.3, than previously expected (in the range of 0.5-1.0). Furthermore, the experiments found no variation with the type of the gas the particles interact with (air, N_2, Ar, CO_2) that constrains the type of interaction between the impinging molecules and the surface of the micrometeoroid. To our best knowledge, these are the first experimental measurements of the drag coefficient, which are made possible by the unique capabilities developed at IMPACT. The implication for meteor radar measurements is that the atmospheric drag acting on the micrometeoroids is larger than expected which may explain why the measured ablation profiles are at higher amplitudes, compared to model calculations. The results were published at the AGU Fall Meeting (DeLuca et al.) and a manuscript is in preparation.

1.1.3 Dust Detection by Antennas

The dust accelerator facility enables the experimental investigation of the processes that make antenna instruments sensitive to dust impacts on spacecraft. There are two main results from the past year: (1) A large data set was collected using the dust accelerator to measure the response of antennas to dust impacts onto a scaled down model of the Cassini spacecraft. The measurements (a) confirmed that dipole antennas have greatly reduced



1:20 scaled model of the Cassini spacecraft exposed to dust impacts to study how sensitive antennas are to impact plasmas.



Measured potential contours above an insulating surface embedded in a vertical magnetic dipole field with the impact of the 100, 200, 400 and 800 eV plasma flow generated in CSWE.

sensitivities to impact on the SC body, (b) offered an explanation of the pre-peak phenomena observed in space as the charge separation of the fast electrons from the slower ions form the impact plasma, and (c) indicated the existence of a coupling mechanisms between dipole and monopole antennas that is yet to be explained. The results were published in [SSERVI-2017-203]. In addition, a numerical study has been performed to investigate the collection efficiency of electrons and ions from the dust impact plasma onto the antennas. This case study for the STEREO spacecraft showed that, contrary to the common belief, antennas are poor collectors of impact plasma. In light of this finding, the STEREO dust impact data has been revisited and the mechanisms generating the characteristic dust impact charges were evaluated. These results were published in [SSERVI-2017-202].

1.2 Colorado Solar Wind Experiment (CSWE)

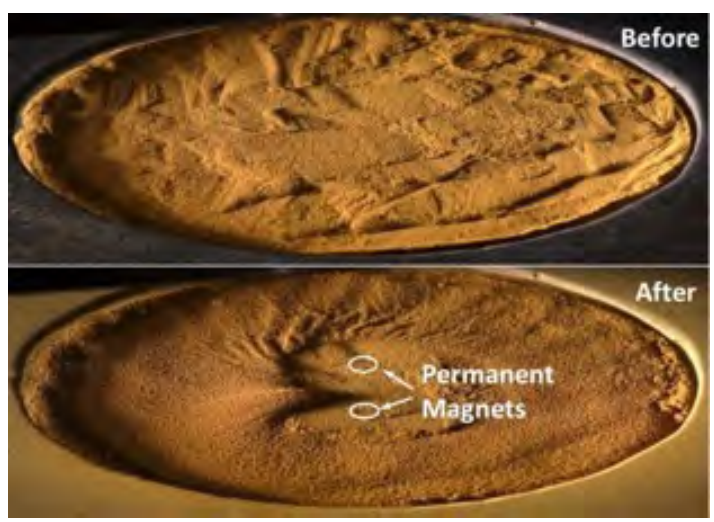
CSWE [SSERVI-2017-162] enables the laboratory investigations of solar wind interaction with lunar magnetic anomalies. We continued to explore the electrical environment above an insulating surface embedded in a magnetic dipole field with the impact of simulated solar wind plasmas. It was found that surfaces in the dipole lobe regions are charged to a relatively large positive potential due to electron shielding effects, but were not as positive as expected. Surprisingly, electrons were detected in the shielding region, and the detailed mechanism of their transport remains yet to be identified.

1.3 Tabletop Experiments

1.3.1 Electrostatic Dust Transport

We developed three new sets of experiments to address the nature of electrostatic dust transport on airless bodies: *1) Charging state of lofted dust.* It was found that all lofted particles were charged negatively under UV radiation. This surprising result can be explained by the newly developed “patched charge model,” recognizing the role of undersurface cavities in the charging process; *2) Dust lofting rate measurements.* We investigated the rate of dust lofting on the surfaces of airless bodies at 1AU in order to estimate the timescales of electrostatic dust transport. It was shown that this depends on surface compactness, dust size distribution, and the variation of porosity over the regolith depth; *3) Dust mobilization and transport in embedded magnetic dipole fields.* This experiment investigated the dust dynamics in the lunar magnetic anomaly regions and the possible contribution to the formation of lunar swirls.

> These experiments show that, contrary to expectations, dust particles exposed to UV radiation can become negatively charged due to the complex 3D undersurface structure of regolith surfaces in space.



Images showing surface changes due to dust mobilization under UV light.

1.3.2 Dust and Spacecraft Charging

We investigated the charging mechanism of objects with sizes ranging from smaller to larger than the Debye length, and measuring their floating potentials. It was shown that, in an identical plasma environment, the spacecraft potential can be twice as large as the dust particle potential.

New laboratory experiments showed experimentally for the first time the dependence of equilibrium surface potential on the ratio of object size over plasma shielding distance, in addition to the properties of the plasma environment.

1.4 Instrument and Technology Development

1.4.1 Development of Coating Materials for Langmuir Probes in Oxygen-rich Plasma Environments

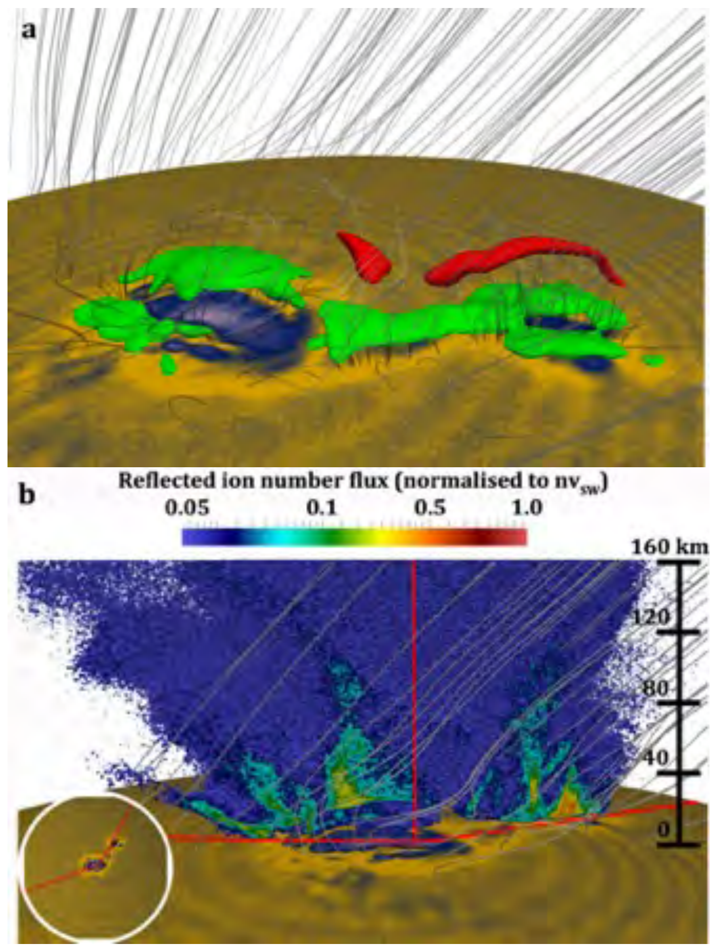
Current coatings of Langmuir probes have various problems (oxidation and/or erosion) in oxygen-rich environments, such as planetary atmospheres. We investigated several new coating candidates and found that Iridium outperformed all current customarily used coatings, with minimal degradation during long oxygen exposures.

1.4.2 CubeSat Electrostatic Dust Analyzer (CEDA)

We are developing a new dust instrument CEDA for in-situ measurements of electrostatically lofted dust particles on airless planetary bodies. CEDA is a 6U cubesat integrated with a 2U dust sensor, currently under development through a senior design class at the Department of Aerospace Engineering Sciences at the University of Colorado through the 2017-2018 academic year.

1.5 ISRU Experimental Probe

Extensive work was done to characterize the ISRU Experimental Probe (IEP) and its interaction with regolith simulants under temperature and pressure extremes. Close to 100 tests were performed on compacted and uncompacted, dry and icy JSC-1A lunar simulant, as well as in dry GRC-3 simulant. Numerous additions and modifications were made to the hardware assembly and control software throughout the course of these tests, successfully fine-tuning the experimental setup and enabling a high degree of test repeatability. Discrete-element modeling has begun and will be used to provide insight into the deformation mechanics of penetration into regolith in loose, compact, dry, and icy states at various temperatures and pressures. The development of this experimental capability led to the submittal of a paper to Review of Scientific Instruments.



a: Overview of the 3-D magnetic field structure surrounding the Reiner Gamma region. b: Side view of the reflected proton flux profile. The cut plane is indicated on the inset (top-down view). The structure of the reflected flux can be correlated with the underlying magnetic field topology.

1.6 Modeling/Theory Support

1.6.1 Fully Kinetic Simulations of the Solar Wind Interaction with Lunar Magnetic Anomalies

All lunar swirls, including Reiner Gamma, are known to be co-located with crustal magnetic anomalies, but the opposite does not hold. By coupling fully kinetic simulations with a surface vector mapping model based on Kaguya and Lunar Prospector magnetic field measurements, and without making any assumptions on the lunar surface properties, we show that solar wind standoff, an ion-electron kinetic interaction mechanism that locally prevents weathering by solar wind ions, predicts the shape of the Reiner Gamma albedo pattern. Our method reveals why not every magnetic anomaly forms a distinct albedo marking. The correlation between the predicted amount of surface weathering and the surface reflectance is highest when evaluating the proton energy flux, and characterizes the primary process for surface darkening [SSERVI-2017-013].

> Fully kinetic plasma simulations reveal plasma dynamics on short enough spatial and fast enough temporal scales to resolve the dynamics of electrons, leading to the recognition of their critical role in generating electric fields in magnetic anomaly regions, and preventing solar wind ions from reaching the surface, offering an explanation of the albedo features of lunar swirls.

1.6.2 Fully Kinetic Simulations of the Solar Wind Interaction with Weekly Outgassing Objects

Using a 3D fully kinetic approach, we disentangle and explain the ion and electron dynamics of the solar wind interaction with a weakly outgassing comet. We show that, to first order, the dynamical interaction is representative of a four-fluid coupled system. We self-consistently simulate and identify the origin of the warm and suprathermal electron distributions observed by ESA's Rosetta mission to comet 67P/Churyumov-Gerasimenko and conclude that a detailed kinetic treatment of the electron dynamics is critical to fully capturing the complex physics of mass-loading plasmas [SSERVI-2017-068].

2 Inter-team/International Collaborations

2.1 Dan Scheeres is a member of three SSERVI (IMPACT, ISET, and CLASS) teams with overlapping interest to study the mechanics of cohesive regolith surfaces. IMPACT funded activities have mainly focused on the development of improved simulation models of regolith, and on modeling of regolith flow on the surface of a small, rapidly rotating asteroid in order to characterize the degree to which regolith can be retained on such a body. Theoretical calculations and simulations show that regolith can be retained at the polar regions of a rapidly rotating body, even if no cohesion is modeled. Under the modeling of cohesion the location of where surface regolith first fails under increasing spin rates has been characterized and compared with simulations.

2.2 The IMPACT and DREAM2 teams collaborated on a book chapter The Dust, Atmosphere, and Plasma Environment of the Moon, to be published in the New Views of the Moon, edited by C. Neal et al., (https://www3.nd.edu/~cneal/NVM-2/).

2.3 IMPACT organized The Dust, Atmosphere and Plasma environment of the Moon and Small Bodies (DAP-2017) workshop (http://impact.colorado.edu/dap_meeting) with participants from nearly all SSERVI teams and many international partners, to discuss our current understanding of the surface environment of the Moon, the moons of Mars: Phobos and Deimos, and asteroids. About 30 referred papers from the meeting will be published in a special issue of Planetary and Space Sciences in 2018.

2.4 Tim Glotch and Jordan Young (RIS^{4}E) participated in a series of experiments at the IMPACT dust accelerator looking at infrared darkening of olivine from micrometeoroid impacts. This work will be presented in a co-authored presentation at LPSC 2018.

2.5 Deputy PI T. Munsat is involved with the SSERVI-TREX team, working with Co-I Greg Holsclaw to set up a new vacuum UV spectroscopy apparatus for looking at spectra of granular regolith simulants.

2.6 IMPACT members Horanyi and Munsat are both on the scientific advisory committee of the SSERVI-REVEALS team, participating in their initial all-hands meeting in Atlanta and planning an initial combined campaign of impact experiments.

2.7 IMPACT continued its close collaborations with Prof. R. Srama (Institut für Raumfahrtsysteme, Universität Stuttgart, Germany), and provides science and technical support for his dust instrument onboard JAXA's upcoming Destiny+ mission to flyby the meteor shower parent body 3200 Phaethon (https://www.lpi.usra.edu/sbag/meetings/jun2017/presentations/Araia.pdf).

2.8 IMPACT continued its collaboration with Prof. W.J. Miloch (Department of Physics, Oslo University, Norway) on developing new analysis tools for Langmuir probe measurements to improve our interpretations of data in dilute, and/or flowing plasmas. We have secured funding from the Norwegian Centre for International Cooperation in Education (SIU) for a 3-year project Probes in space science: a student exchange between USA and Norway (PNA-2017/10063).

2.9 IMPACT continued to work in close collaboration with Prof. Stas Barabash (Swedish Institute of Space Physics, Kiruna, Sweden) to develop the Surface, Environment, and Lunar Magnetic Anomalies (SELMA) proposal in response to the call for a medium-size Mission of Opportunity in ESA's Science Program (M5.). The selection results are expected in 2018, and the mission concept has been accepted for publication [SSERVI-2017-109].

3. Public Engagement

3.1 Junior Aerospace Engineering Program

IMPACT's Junior Aerospace Engineering Program finished a fall semester after school class. Ten middle and high school students at Casa de la Esperanza in Longmont have been learning about the forces of (rocket) flight, the engineering process, manufacturing, and data visualization over the last three months. The students built parachutes, raced multi-stage balloon "rockets," and developed egg-recovery systems for model rockets. The course concluded with the students building and launching a high-powered rocket on December 2 at Pawnee National Grassland. Model rocket experiments launched on the same day were responsible for destroying several eggs due to parachute failures. This five-year-long outreach program will conclude in Summer 2018 with a robotics camp tailored to expanding the students' unique

Middle and high school students from Casa de la Esperanza pose at Pawnee National Grassland on Dec 2, 2017 with the high-powered rocket they built in their IMPACT-sponsored after school class.

experiences with FIRST LEGO League and other robotics and electronics experiences.

3.2 International Observe the Moon Night (InOMN)

We held a successful InOMN event, one of over 600 similar events around the world. On the same evening, Boulder also had its annual Halloween-inspired "Mall Crawl," which boosted attendance into the hundreds, sometimes with 20 people at once waiting to look at the Moon (and Saturn!). Besides the two hand-built telescopes for observations, we also set up a table for members of the public to build their own take-home "Galileoscopes" and collect various lithographs of the Moon. Due to cloudy weather in other parts of the world, this Boulder InOMN location was also featured on a Twitch livestream running throughout the evening.

Top: The First Quarter Moon captured from one of IMPACT's hand-made telescopes on October 28 during International Observe the Moon Night (InOMN).

Bottom: A telescope points at the Moon (foreground) and visitors build "Galileoscopes" (left) while the Boulder's Pearl Street Mall is bustling with the Halloween "Mall Crawl" (background).

3.3 Lectures at the PILLAR Institute for Lifelong Learning

PILLAR Institute for Lifelong Learning is the only independent lifelong learning organization in the Pikes Peak region. It is a volunteer-driven membership organization that is open to all. PILLAR produces over 300 liberal arts and science classes each year for those young at heart. In addition, there are community lectures by community leaders, Living History portrayals, Reader's Theater performances, day tours and extended trips. In the spring of 2017, M. Horanyi of IMPACT gave lectures at PILLAR in Colorado Springs on Dust and Dusty Plasma in the Solar system.

3.4 Education Projects

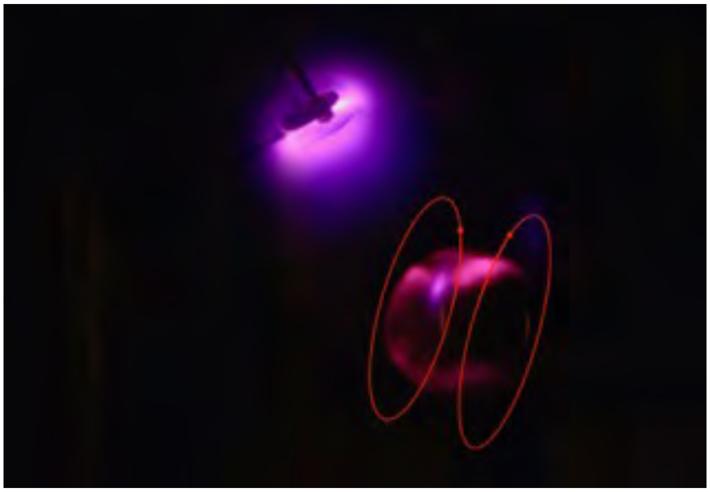
3.4.1 Glow Discharge Experiment

Two high school students built a glow discharge tube and learned to use diagnostic probes to characterize plasma properties and understand the processes leading to "striation;" a manuscript is in preparation with student first authors.

Glow discharge of 24 mTorr air plasma

3.4.2 Terrella Experiment

Two REU students over the past summer built a Terrella device to demonstrate the generation of Auroras, coronal holes and ring currents, due to the adiabatic motion of trapped electrons generating impact excitation and ionization in a partially evacuated glass chamber.



The formation of an Auroral oval over northern and southern hemisphere of a magnetic dipole in a student-built Terella experiment.

4. Student/Early Career Participation

Graduate Students **Project**

- Edwin Bernardoni Plasma theory
- Leela O'Brien Detector design and fabrication (graduated 2017)
- Evan Thomas Micrometeoroid ablation (graduated 2017)
- Marcus Piquette Surface/plasma interaction modeling
- JR Rocha Instrument development
- Ben Southwood Dust dynamics modeling (graduated 2017)
- Michelle Villeneuve Instrument development (graduated 2017)
- Zach Ulibarri Ice target experiments
- Lihsia Yeo Solar wind experiments
- Michael DeLuca Micrometeoroid ablation experiments
- Joseph Samaniego Langmuir probe measurements

Summer Interns

- Robin Varennes (Marseille, France) Terrella experiment construction
- Maria Radisch (Heidelberg, Germany) Plasma discharge tube construction
- Angelica Martinez Terrella experiment construction
- Dominic Fuentes Solar Wind Experiment Modeling
- Libor Nouzak (Czech Republic) Dust impacts on antennas

Undergraduate Students

- Forrest Barnes Control software development
- John Fontanese Small accelerator experiments
- William Goode Accelerator diagnostic design
- Andrew (Oak) Nelson Ice target development (graduated 2017)
- Andrew Seracuse Beam detector development
- Joseph Schwan Dust dynamics in plasma (graduated 2017)
- Robert Beadles Langmuir probes in sheath (graduated 2017)
- Juliet Pilewskie Dust dynamics modeling (graduated 2017)
- Michael Gerard Lunar swirls modeling (graduated 2017)
- Alexandra Okeson Dust instrument software development (graduated 2017)
- Jared Stanley LDEX modeling support (graduated 2017)
- Ethan Williams Instrument development
- Eric Junkins Instrument development (graduated 2017)
- Jia Han Solar wind experiments (graduated 2017)
- Zuni Levin SIMION studies
- Ted Thayer Antenna signals from dust impacts

- Elizabeth Bernhardt Accelerator experiments
- Max Weiner Mass-spectra
- George Ressinger Solar Wind Experiment
- Alex Doner Accelerator infrastructure engineering

High School Students

- Fiona Kopp DC Plasma discharge experiments
- Madeleine Nagle Heater system for cryogenic impact targets

Postdocs

- Jan Deca Computer simulations of plasma - surface interactions

5 Mission Involvement

5.1 JAXA Destiny

IMPACT scientists (Horanyi, Kempf, and Sternovsky) are members of the science team for the Destiny Dust Analyzer (DDA) onboard JAXA's Destiny+ mission to flyby the active asteroid 3200 Phaethon. DDA will be tested and calibrated at the IMPACT dust accelerator facility.

5.2 NASA Europa Clipper

IMPACT's new ice target facility for the study of meteoroid impacts effects on lunar permanently shadowed regions has been made available for development, testing and calibration of the Surface Dust Analyzer (SUDA) instrument that will fly onboard NASA's Europa Clipper flagship mission.

5.3 NASA New Horizons

IMPACT's dust accelerator facility has been used for follow-up tests of the Student Dust Counter (SDC) instrument flying onboard the New Horizons mission.

5.4 NASA Cassini

IMPACT's dust accelerator facility has been used to test the response of Cassini's MIMI/LEMMS to dust impacts, to aid in the analysis and interpretation of its observations taken flying through the plumes of Saturn's moon Enceladus.

5.5 NASA LADEE

IMPACT continued to work on the rich data set obtained by the Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Explorer Mission (LADEE). We have used the period of the Geminid meteoroid shower to directly compare ground based visual and radar observations of incoming dust particles ablating in the atmosphere and the temporal variability of the impact generated dust cloud engulfing the Moon [SSERVI-2017-069]. Similar approaches were used to constrain the ratio of micrometeoroids from short- and long-period Comets at 1 AU from LADEE observations [SSERVI-2017-124]. The models of the lunar dust ejecta cloud based on LADEE/LDEX measurements were also extended to other airless bodies in the Solar System [SSERVI-2017-110, SSERVI-2017-125].

William Bottke

Southwest Research Institute, Boulder, CO

Institute for the Science of Exploration Targets (ISET)

1 ISET Team Project report

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

The ISET team has deployed LIPAD—their novel accretion and fragmentation code—to study some fundamental aspects of planet growth. A large and time consuming suite of simulations continue to study the entire inner disk of the Solar System, focusing on the very basic stages of classical growth. This study has evolved into a critical take on the state of the last decade of planet formation modeling, finding that the initial conditions typically used are very flawed. We find that due to the interaction of collisional fragmentation and the continually evolving gas disk, growth is very inside-out and these initial conditions are never met. This study has ballooned from a short inspection of the fact that collisional grinding may explain the small mass of Mars, into a large parameters sweep across disk mass and gas disk lifetimes. The publication is being re-targeted from a singular short article to a large sweeping article or possibly two. Interest in this work remains high, as do prospects for wide reaching applications; K. Walsh was invited to talk about this project at a Chondrule- focused workshop at UBC, a “Disk Formation Workshop” in Leiden, and at the “First Billion Years of Accretion” conference hosted at LPI.

Additionally, the ISET team has continued building upon the novel planet formation model, Viscously Stirred Pebble Accretion, which last year was shown to be able to form the entire Solar System by a single, unified process. We have found that the growing giant planets will naturally scatter planetesimals from the region where the giant planets form (5-15 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. This work complements ISET work from Vokrouhlicky et al. (2016), who showed that objects from the primordial Kuiper belt were implanted in the main belt during a violent phase of late giant planet migration. Combining both implantation models, Bottke and Kretke have been working to identify plausible source regions for different kinds of carbonaceous chondrite meteorites. Preliminary work suggests CV/CO meteorites may come from the Jupiter zone, with links to K-type asteroids, CM and CI bodies may come from the Saturn-Neptune zone, with links to standard C-type asteroids, and CR meteorites come from the primordial disk beyond Neptune, with links to D- and P-type asteroids. We postulate CR and CM/CI meteorites may describe the targets of the Lucy/CAESAR missions (Trojans, comet 67P/Churyumov-Gerasimenko) and OSIRIS-REx mission, respectively.

Additionally, we have found that embryos temporarily scattered outward from the terrestrial planet region into the asteroid belt during the final stages of terrestrial planet formation can excite the asteroid belt. This means that earlier excitation by the giant planets is not necessary. This work has been carried out by SSERVI fellow K. Kretke, ISET members H. Levison, W. Bottke and K. Walsh with contributions from CLSE member D. Kring and two papers on these topics are to be submitted soon.

1.2 Theme 2: Origin of the Moon, Phobos and Deimos.

It has been suggested that Mars' moons are captured asteroids. However intact capture is difficult to reconcile with the moons' nearly circular and co-planar orbits, which instead suggest they accreted from an equatorial disk around Mars. Phobos today orbits at ~3 Mars radii (R_M), but it has evolved inward due to Mars tides, so that it likely formed at ~5 to 5.5 R_M, just inside synchronous orbit at 6 R_M. Deimos formed near its current position at 6.5 R_M. Thus an initial disk extending to about 6 to 7 R_M appears to be needed to produce a primordial Phobos-Deimos pair.

R. Canup and J. Salmon have extensively modeled the accretion of Phobos and Deimos as remnants from an impact-generated disk. Our state-of-the-art model treats material within the Roche limit as a continuous disk that spreads viscously, and outer material by individual bodies tracked by an N-body integrator. We find that if the initial disk mass exceeds 3×10^{-5} Mars masses (M_M), large interior moons grow and sweep-up all small moons near synchronous orbit, leaving no Phobos-Deimos like bodies. ***However, for smaller initial disk masses and strong early Mars tides, we find many giant impact cases can produce Phobos-Deimos type bodies near 6 R_M.***

Prior works on Phobos-Deimos origin have considered an impactor with a mass ~$0.03M_M$. However we find that such impactors produce disks that are much too massive to yield Phobos-Deimos. Instead, we find that forming Phobos-Deimos requires a much less massive Vesta-to-Ceres sized impactor with a mass ~10^{-3} M_M (**Figure 1**; Canup & Salmon 2018). ***Using impact simulations with an order-of-magnitude higher disk resolution than prior works, we show that these smaller-scale impacts produce disks whose outer edge is consistent with that needed to produce Deimos as Mars' outermost moon.***

We find that outer disk material originates overwhelmingly from Mars in all cases. Disk material is heated sufficiently to dehydrate OH-bearing minerals, and H_2O vapor is vulnerable to rapid escape once ejecta expands beyond ~5-6 R_M, which occurs after only a few hours (Nakajima & Canup 2017; Figure 1). This suggests that if Phobos and Deimos formed via impact, they would have dry endogenic compositions. Because their source

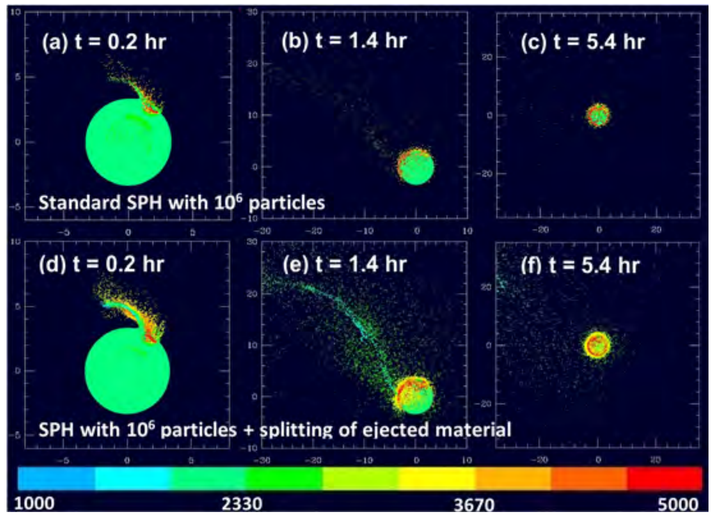


Figure 1: Simulations of the impact of a Vesta-mass body (5×10^{-4} M_M) with Mars. The impact velocity is $1.5v_{esc}$ (7 km s^{-1}), at a 45° impact angle. Color scales with temperature in Kelvin; distances shown in units of 10^3 km. (Top row) A 10^6-particle simulation with standard SPH. (Bottom row) The same impact modeled with SPH + particle splitting and an order-of-magnitude higher resolution of the ejected material. After 10 hr, the disk mass is 8.5×10^{-6} M_M, with ~$2M_{PD}$ having equivalent circular orbits at and beyond ~$5R_M$, consistent with subsequent accumulation of Phobos and Deimos in the 5 to $7R_M$ region. Outer disk material is 85% martian in origin. From Canup & Salmon (2018).

materials are predominantly martian in origin, their refractory elemental compositions would be Mars-like. These predictions should be directly testable by JAXA's MMX mission.

W. Bottke has also investigated the impact history of Phobos/Deimos, and Mars's Trojan asteroids. Nominally, such work is difficult because the nature of the impactor population striking these worlds during the planet formation era is unknown. In Bottke and Andrews-Hanna (2017), however, martian impact flux was derived all the way back to the Mars-changing Borealis impact. Scaling this martian flux to the above bodies, we find Phobos, Deimos, and Mars's Trojans are likely as old as the oldest martian features (i.e., Borealis and Hellas basins). This implies their origin may be linked to these impacts, as suggested by the runs of Canup and Salmon. A paper on this work is in preparation.

1.3 Theme 3: Solar System Bombardment

1.3.1 Impacts Over the Last Three Billion Years

The terrestrial impact crater record is commonly assumed to be biased, with erosion eliminating older craters even on stable terrains. Given that the same impactor population struck the Earth and Moon, however, terrestrial selection effects can be quantified using a new method that can date diameter D ≥ 10 km lunar craters younger than 1 Gyr. ***Using this method, we find that not only did the impact flux increase by a factor of 2.2 (-0.9, +4.4) over the last ~250 Myr, but that large terrestrial and lunar craters have similar age and size-frequency distributions over the past ~650 Myr. Accordingly, the dearth of large terrestrial craters between ~250-650 Myr on stable terrains is a byproduct of a lower impact flux, not preservation bias.*** Support for limited erosion in those regions comes from the ages and nearly-intact states of nearby kimberlite pipes. Conversely, the paucity of both craters and well-preserved kimberlites on > 650 Myr terrains indicate that extensive erosion took place during the Cryogenian period. In addition, given that we now reasonably understand the nature of the terrestrial crater record, we have been able to quantify the relationship of potential doublet craters on Earth and determine how many were formed by chance. This work is described in several submitted ISET papers: Mazrouei et al. (2018), Keller et al. (2018), and MacGregor et al. (2018).

We have also been interested in probing the terrestrial impact flux between 1-3 Ga, a formative time for the Earth and Mars biosphere. To this end, Kirchoff has finished determining 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 possibly for events starting near ~1.4 Ga). This work was presented at the NASA Exploration Science Forum and a manuscript is in preparation.

To examine a potential source for these impact spikes, Vokrouhlicky et al. (2017) examined the evolution of the Flora asteroid family. Formed from a catastrophic collision of a 150 km body, the LL-chondrite-like Flora family is located in the inner main belt. Using collisional and dynamical models to track the evolution of Flora family members, they found that (i) Flora formed ~1.4 Ga, (ii) it lost 90% of its initial km-sized members, and (iii) at its peak 100-200 Myr after the family-forming event, Flora family members filled NEO space with nearly 1000 km-sized bodies before fading to its present contribution of 35-50. Interestingly, there is potential evidence for an enhancement of impacts on Mars and the Moon near this time (while interesting things are happening on Earth at this time as well).

D. Nesvorný has been working on constraining the flux of NEAs in Nesvorný et al. (2018). Models of asteroid delivery suggest that the current impact flux of D > 10 km asteroids on the Earth is ~1 impact per Gyr, while studies of the NEA population find a much higher flux. We show this problem is rooted in the extrapolation of the impact probability of small NEAs, which is well characterized, to large NEAs. The actual impact rate is 0.8+/-0.3 per Gyr. This presents a conundrum; the odds of getting the observed K/T-size craters on Earth/Venus from D > 10 km impactors are exceedingly small. This prompted Bottke et al. (in prep) to calculate empirical crater scaling laws by mapping the shape of the NEA size-frequency distribution (SFD) into the shapes of crater SFDs from Mercury, Venus, the Moon, and Mars. Their results indicate these crater SFDs are congruent with each other and can be readily fit to the NEA SFD provided the projectile diameters are multiplied by a factor $f = 24 \pm 5$. Testing this relationship using constraints from terrestrial craters Chixculub, Popagai, Manicouagan, and Sudbury, they found projectile diameters consistent with those derived from Ir/Os abundances. This suggests large craters come from smaller projectiles than previously thought.

Finally, 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 threshold is uncertain due to unique properties of the lunar surface’s roughness). The database was presented at the Lunar and Planetary Science Conference, where many lunar researchers promoted the usefulness of the database. It was also presented at the Planetary Crater Consortium. ***It contains 2.0 million craters over the entire lunar surface (1.3 million are ≥1 km).*** The paper is currently in review with JGR-Planets.

1.3.2 Early Bombardment

Marchi and Canup investigated the Earth's earliest collisional history using new high-resolution smooth particle dynamics (SPH) impact simulations (Marchi et al. 2017). They showed that substantial portions of a large planetesimal's core could penetrate all the way down to merge with Earth's core, or ricochet back into space and escape the planet entirely (**Figure 2**). Both outcomes reduce the apparent total mass added to Earth's mantle, which implies ***the amount of material delivered to Earth may have been 2-5 times greater than previously thought.***

They also demonstrated that some puzzling isotopic anomalies observed in terrestrial rocks can be explained as products of collisions following the Moon's formation. Some of the oldest terrestrial rocks found in Greenland and South Africa exhibit tungsten (W) signatures that are remarkably different than average, mantle rocks. An example of this anomalous behavior is provided by komatiites. The process of heterogeneous projectile mixing may also have broad implications for the origin of the Moon. Previously it was thought that the isotopic anomalies observed in some ancient terrestrial rocks were produced by processes that occurred before the Moon-forming giant impact. ***Preservation of such anomalies then required that the Earth's mantle was not well-mixed during the giant impact, a problematic constraint for some lunar origin models.***

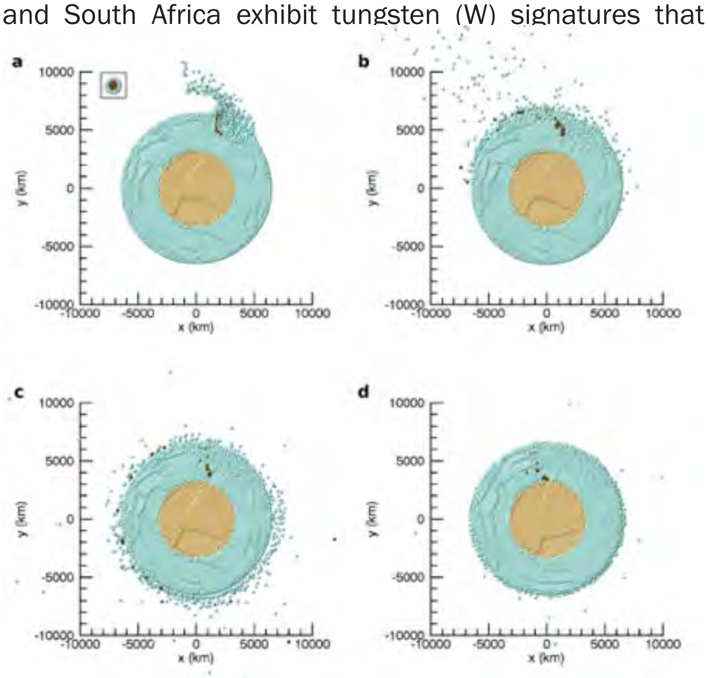


Figure 2: Projectile's core interaction during large terrestrial collisions. Panels (a)-(d) show four time steps in an SPH simulation (at 0.2, 1, 2.7 and 23 hr), with impactor mass Mi = 0.001M⊕, (~1400 km diameter projectile), 45° impact angle, and impact velocity of 18 km/s. Green particles represent silicate material (Earth and projectile), light brown particles indicate Earth's core, and dark brown particles indicate the projectile's core. The projectile size is shown for reference in the top-left corner of (a).

A. Evans and J. Andrews-Hanna submitted results of their work on the chronology of lunar basins for publication in JGR. The work in that manuscript builds on previous work by them (also funded in part by this SSERVI grant) that used gravity data from GRAIL to map a population of buried craters and basins not visible on the surface (Evans et al. 2016). They now use that population of buried craters to re-evaluate the crater retention ages of all major lunar basins and crustal terranes. One of the noteworthy results in that manuscript is the conclusion that the age of the South Pole-Aitken basin must be >4.3 Ga, based on its older crater retention age than the PKT and constraints on the absolute age of the final crystallization of KREEP. ***They also find evidence that the large lunar basins Imbrium and Serenitatis are similar in age, contributing to the debate over the still contentious age of Serenitatis.*** If true, many lunar basins formed at a time similar to ~3.9 Ga, the likely age of Imbrium.

Bottke and Norman (2017) published an extensive review of the Late Heavy Bombardment (LHB), where they argued that the LHB was not a narrow spike as defined by the so-called "Terminal Cataclysm" model. Instead, they advocated for two early bombardment components: one early (> 4.4 Ga) and one late (< 4.0 Ga). Follow up work by Bottke indicates Mars and the ancient farside of the Moon show signs they were hit by two distinct impactor populations. If so, the easiest scenario to explain this behavior would be two phases of impacts at different times from different sources.

Nesvorný and Marchi developed new impact chronologies to interpret the crater record on Ceres and Vesta, the two largest asteroids in the main belt that were both visited by NASA's DAWN mission. The results reproduce the largest craters on Vesta but not on Ceres, where viscous relaxation may have removed them.

1.4 Theme 4: Properties and Populations 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. New analyses performed and presented this year include the identification and analysis of a natural end-of-life disaggregation phase for small, rubble pile asteroids with some level of cohesive force. ***Once these bodies reach a small enough size, the spin rates for disruption ensure that the body components will immediately escape, leading to a convergent series of spin-up events that rapidly disaggregate the rubble pile into its core constituents.***

Other analysis explored the retention of regolith on fast spinning small bodies, simulating the flow of material on the surface and identifying the polar regions of a rapidly spinning body as still being able to retain regolith (see **Figure 3**). Additional work on the YORP effect identified a fundamental symmetry for the dynamical evolution of asteroid poles and spin rates, which was presented at conferences and will be submitted to a journal.

Additional research was focused on small body exploration, with an emphasis on deployment of surface packages to small bodies and on the martian moon Phobos. Papers on

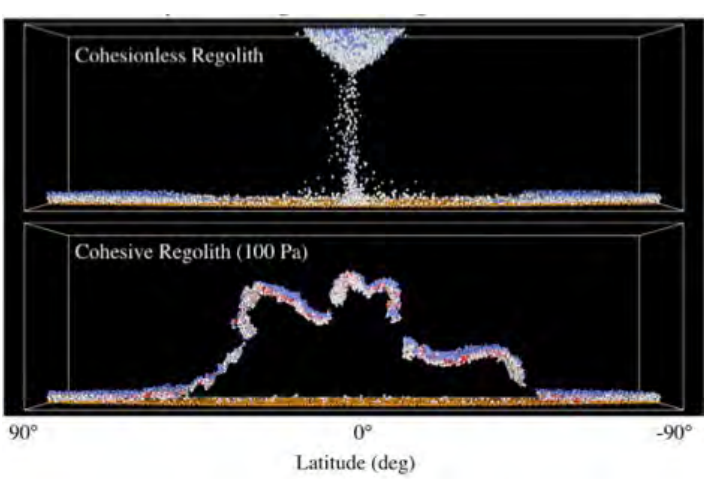


Figure 3: Simulations of regolith loss from rapidly spinning bodies. Note that polar regions retain regolith, even in the cohesionless case.

both topics were presented at conferences and submitted to journals for publication. This work has involved support from Senior Research Scientist Paul Sanchez, post-doc Alex Golubov, and graduate student Stefaan Van wal.

Jedicke's paper "An Investigation of the Ranges of Validity of Asteroid Thermal Models for Near-Earth Asteroid Observations" (Mommert et al., 2018) was submitted and accepted in 2017. This work was originally motivated by our desire to measure the thermophysical properties of minimoons. We found that the Near Earth Asteroid Thermal Model (NEATM) that is typically used for calculating asteroid diameters and albedos is best for solar phase angles of <65 deg, but the Fast Rotating Model (FRM) is better at larger phase angles. We were surprised to find that there was no diameter-dependence on the applicability of the two models.

We submitted a proposal to contribute a minimoon chapter to a special *Frontiers* book on the Earth-Moon dynamical system "Earth's Minimoons: Opportunities for Science and Technology" (Jedicke, Bottke, Chyba, Fedorets, Granvik, and Urrutxua). The book will be published in 2018 and our intention is that this chapter will provide the definitive overview of our current understanding of minimoons. The author list includes all major contributors to minimoon research at this time.

We have only made slow progress on analysis of the Subaru minimoon survey (Jedicke et al., 2017). The data is all in-hand and much of the reduction and analysis software has been written but we lack the resources to bring the analysis to completion. It is unlikely that the survey would have detected a minimoon but it should allow the first intentional, well characterized upper limit on the population's number density, and will be a template for future minimoon surveys.

Finally, we are excited by the temporary capture in 2017 in the Earth-Moon system of asteroid 2018 AV2. This ~10 m diameter object could be the first example of a "temporarily captured flyby" (TCF; Granvik et al., 2012; Fedorets et al., 2017), an asteroid that is gravitationally bound to the Earth-Moon system for some period of time but does not complete a revolution around Earth. We are involved in acquiring observations of this object to determine whether it is artificial or natural. If it is indeed the first known TCF, some discussion of its properties will be included in our *Frontiers* chapter.

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.

David Kring (CLSE) and William Bottke have been sharing SSERVI postdoc Katherine Kretke over a variety of projects related to linking dynamical models of planet formation with evidence from meteorite samples. Kretke has been concentrating on so-called pebble accretion, the process by which planetesimals can grow to giant planet cores via the accretion of small, rapidly drifting sub-meter-sized bodies known as "pebbles." This work has shown that growing giant planets will naturally scatter planetesimals from the region where the giant planets form into the modern day asteroid belt, which could provide an origin for the C-complex asteroids. Results are being gathered in two papers that will be submitted for publication shortly.

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 in the **Phobos and Deimos: The Moons of Mars Academic Graduate-Level Course** as part of the CLASS SSERVI team, and will contribute a planned seminar in February 2018 as part of the CLASS-SSERVI seminar series.

Scheeres and Sanchez have collaborated with the STRATA-I space station experiment with support of the CLASS team.

Scheeres and Sanchez have had meetings to coordinate research activities with researchers from the Colorado School of Mines as part of the IMPACT team.

D. Nesvorný and S. Marchi collaborated with A. Morbidelli at the Observatoire de la Cote d'Azur (Nice, France) and L. Elkins-Tanton of the SEED team, to propose a new model for the earliest bombardment history of the Earth and Mars. They showed that the bombardment in the 3-4Gy period can be explained in the accretion tail scenario, in which the lunar bombardment declined since the era of planet formation and the latest basins formed in its tail-end. The accretion tail scenario requires a global resurfacing event on Mars ~4.4Gy ago, possibly associated with the formation of the Borealis basin. Results have been accepted for publication in Icarus.

S. Marchi and R. Canup collaborated with R. Walker of the CLSE team on constraining the early bombardment of the Earth. They showed that the amount of highly siderophile elements delivered to the Earth during an impact with large planetesimals had been previously underestimated, implying that the amount of material delivered to Earth may have been 2-5 times greater than previously thought. Results were published in Nature Geoscience.

William Bottke worked with Marc Norman (CLSE) on a comprehensive review of the late heavy bombardment for Annual Reviews of Earth and Planetary Science that was published in summer 2017. We argued that the most parsimonious solution to match constraints from the Earth, Moon, Mars, asteroids, and meteorites is a bombardment model that includes discrete early, post-accretion and later, planetary instability-driven populations of impactors.

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.

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, 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.

3 Public Engagement

3.1 Summer Science Program (SSP)

Our collaboration with SSP continues to be a success. Kretke, Dones, Kirchoff, and a new participant, Walsh, served as science instructors (with 36 high-school students each) in New Mexico and Colorado in July, 2017. ISET members guided the students through a SSERVI-rich participatory experience using the numerical integrator Swift (developed by ISET member Hal Levison) 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 (**Figure 4**). This was the first opportunity many of these high-school students have had to participate in a scientific presentation. We also provide scientific lectures to the students on asteroid populations and their dynamical evolutions, including chaos theory.

A new survey about their experience with the ISET research project was generated by Shupla and given to the students in Colorado. In this survey, 100% of the students either agreed or strongly agreed that participating in the research project expanded their knowledge and skills. In addition, greater than 90% agreed or strongly agreed that the discussions and interactions with the ISET scientists were valuable. We think these two student comments summed up the experience best: "I found most interesting the introduction to real-world astronomical computer modelling, and the analysis of the chaotic system that results." and "I liked how we were able to simulate the fates of the asteroids we studied."

3.2 Helping Informal Educators Bring Solar Eclipse Science to Their Clients

Shupla and colleagues at the Lunar and Planetary Institute (LPI) expanded the "*Explore Marvel Moon*" this summer to include "*The Vanishing Sun*" (Figure 5). This module includes a dozen publicly available multicultural eclipse stories, researched and recorded by professional storytellers, along with activities for viewing and understanding science related to eclipses. The website, www.lpi.usra.edu/education/explore/eclipse, was disseminated in the weeks leading up to the August 21st eclipse through blogs, flyers, and announcements with the American Camp Association, the American Library Association, and the NASA Eclipse teleconference committee, as well as through LPI emails to 3,000 educators nationally. This website was also linked from the NASA eclipse website

To further promote the new module, LPI staff, along with Kirchoff, conducted "*Explore the Vanishing Sun*," a webinar for out-of-school time programmers, such as librarians and camp program facilitators, on July 11. The 30-minute webinar included presentations by LPI educators on shared eclipse activities and tips for incorporating "*The Vanishing Sun*" in programs, and a scientific presentation about the August total solar eclipse by Kirchoff. Approximately 50 informal educators participated in the live webinars. Participant feedback was very positive. Greater than 90% of those responding to the survey indicated that the webinar was useful and that it provided them with new information.

3.3 Sharing Results

Six ISET scientists participated in the 2017 Denver Comic Con, including SSERVI-related science talks. The most rewarding sessions with our team members were "Women

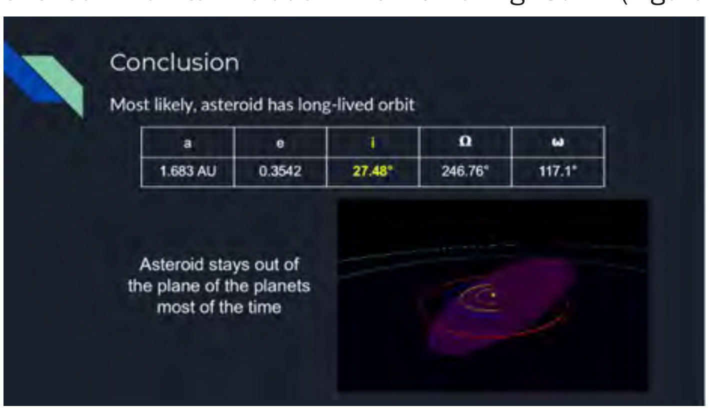


Figure 4: An example conclusion slide from a student team.

Figure 5: The video folktale, "Shooting Down the Sun" is available on the Vanishing Sun website.

in Science and Engineering" and "How to Have a Career in NASA." Bottke talked about postulated "Planet 9," "Upcoming NASA Missions," and lead panel discussions between scientists, authors, and artists that compared known worlds to worlds in science fiction. Kirchoff and Kretke ran a "*Superheroes on other Planets*" activity for elementary children.

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 will graduate in May 2018 and 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.

Postdoctoral Fellows

3. Katherine Kretke, Southwest Research Institute, Planetary Science

Katherine is a SSERVI postdoc fellow and has been working with B. Bottke and Hal Levison of the ISET team and David Kring of the CLSE team. She has been working on further modeling the formation of giant planets via pebble accretion and on its influence on the asteroid belt. Kretke presented her results at six conferences and workshops. Two papers are in preparation.

4. Alex Evans, Southwest Research Institute, Planetary Science

Alex Evans has been working with ISET member Jeff Andrews-Hanna. Alex has been continuing work on the chronology of lunar basins. Results were presented by A. Evans at the Lunar and Planetary Science Conference in March. A paper has been submitted for publication in Journal of Geophysical Research.

Early Career Scientists

5. 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 IMPACT team.

6. 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.

7. 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.

8. Julien Salmon, Southwest Research Institute, Planetary Science

Salmon has been working with R. Canup on performing accretion simulation of Mars's moons Phobos and Deimos. Results have been submitted for publications in Science Advances. He also started a new project on assessing the dynamics of the accretion of the Moon in a multi-impact framework.

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 the 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 the 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 the ESA 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. Hayabusa, Daniel Scheeres, Astrodynamics Science Team Co-I.

Scheeres was a Co-I on the Astrodynamics Science team of the Japanese Hayabusa mission to asteroid Itokawa. He contributed to the analysis of the physical and dynamical environment about that body and developed the first maps of the surface potential and slope, helping to identify the unique properties of that body. He also contributed to the mass determination of the asteroid.

16. 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)

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 second 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 2017, the RIS⁴E Theme 1 team primarily focused on two areas of research designed to provide a quantitative framework for the analysis of remote sensing data from airless bodies. These were (1) development of light scattering codes designed to provide a realistic physical simulation of the scattering of electromagnetic radiation by planetary regoliths, and (2) space weathering experiments, including dust impact experiments in collaboration with the IMPACT team.

1.1.1 Development of Light Scattering Models

Stony Brook graduate student Gen Ito has been pushing the state of the art in modeling the interaction of infrared light with planetary regolith particulates. Ito et al. (2017) demonstrated that a hybrid T-matrix/Hapke model provides a much better match to laboratory thermal infrared spectra than traditionally used Mie/Hapke models. The improvement comes from the ability of the T-matrix model to faithfully calculate solutions to Maxwell's equations at every wave/particle interface, which is not possible with the single particle Mie model. Ito et al. (2018) further improved upon this code by incorporating the static structure factor correction into the light scattering calculations. This correction accounts for the single-particle scattering properties of particle clusters and effectively allows us to model "clusters of clusters," providing a high fidelity simulation of light interaction with fine-grained particulates (**Figure 1.1**). Next steps include modeling clusters with polydisperse size fractions and extending the modeling efforts to visible and near-IR wavelengths. Stony Brook graduate student Carey Legett has already started to tackle this problem.

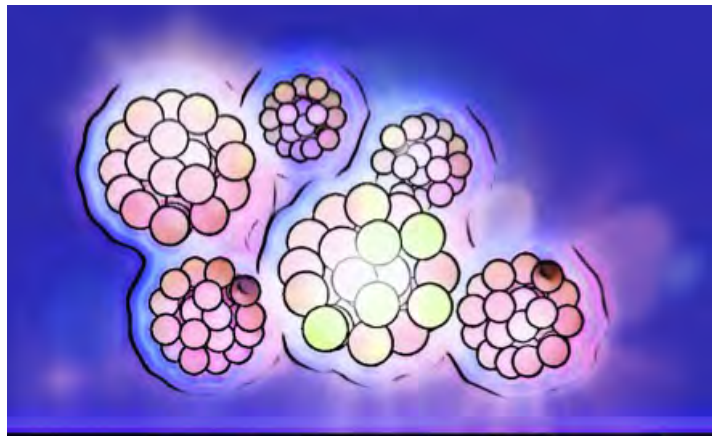


Figure 1.1. Visualization of light scattering by particles in clusters and the close packing of the clusters themselves. Mutual influence among the clusters is depicted.

1.1.2 Space Weathering Experiments

In 2017, Stony Brook graduate students Jordan Young and Carey Legett, and postdoctoral researcher Sarah Nicholas, demonstrated that dust impacts into single crystal mineral targets result in the formation of glassy materials surrounding the resulting micro-craters and visible/near-infrared spectra consistent with the effects of space weathering on airless bodies in the Solar System. In collaboration with the IMPACT team, we prepared several single crystals of olivine for space weathering experiments. One sample was irradiated by 12 keV protons at the

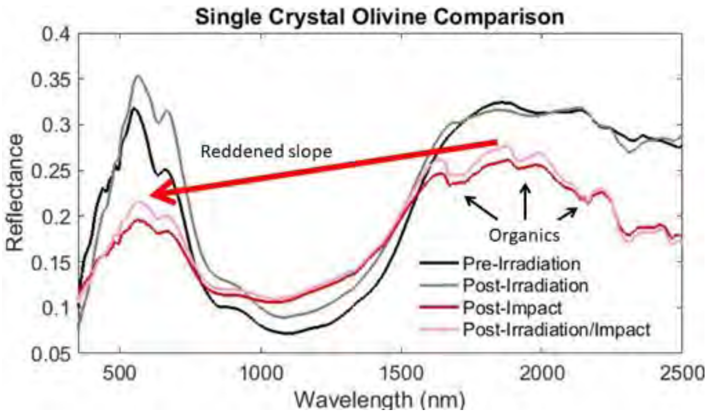


Figure 1.2. VNIR spectra of olivine single crystals subjected to 12 keV proton irradiation and/or dust impacts. Post-impact spectra have lower overall albedos, reduced band depth, and red slopes compared to pre-impact spectra.

Brookhaven National Laboratory Tandem Van de Graaf accelerator to simulate interaction with the solar wind, while another was left unirradiated. Both samples were then subjected to ~10,000 dust impacts at ~1-10 km/s velocities at the University of Colorado Dust Accelerator Laboratory. Visible/near-IR spectra of the samples before and after irradiation and impact are shown in **Figure 1.2**. Post-impact samples exhibit lower albedos, red slopes, and reduced band strength compared to pre-impact spectra. They additionally exhibit organic spectral features due to a conductive polymer coating on the impacting dust grains. We are currently conducting transmission electron microscopy and synchrotron X-ray spectroscopy measurements on impacted samples and are preparing new samples for further impact experiments.

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

During 2017, the RIS^{4}E Theme 2 team was highly productive. The central achievement of the team was the completion of a 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. The study included an aspect of science operations associated with understanding timeline impacts of currently available, field portable instruments during extravehicular activities (EVAs). To this purpose the NASA Astronaut Office assigned Barry "Butch" Wilmore to the field study in support of the EVA work. Apollo astronaut and geologist Jack Schmitt also attended this deployment in order to provide feedback on instrument use (**Figure 1.3**). This deployment also included the second field interaction with the Stony Brook School of Journalism. Five journalism students and two professors accompanied the field team to the site and learned to cover science in action as journalists embedded within a team. This is discussed in detail in Section 3 of the report. In addition to the primary field campaign to the Potrillo Volcanic Field, RIS^{4}E has continued to support the Human Research Program as requested by HEOMD to provide high fidelity field tasks for HISEAS crew members. RIS^{4}E has deployed two instruments at the site, which HISEAS crew have operated throughout their 8-month study. Crewmembers interact with RIS^{4}E instrument team members via e-mail on a communications delay so that HRP can assess operations between crew and instrument

Figure 1.3. Astronauts Jack Schmitt (left) and Butch Wilmore (right) explore the Kilbourne Hole maar crater with the RIS4E field team.

scientists during long duration missions.

Based on our field deployment data, we make recommendations to instrument design teams about how to optimize instrument precision, operation time, user interface and data presentation. Through collaboration with rover team and instrument team members from the MER and MSL rovers at GSFC and JSC (who have identified similar data integration issues across multiple instruments) we continue to examine how best to make data available to crew in real time or near-real time, and how assimilation of in situ data will effect both sample high-grading and traverse-flexible execution. Data display to crew members will likely involve some form of wearable computing to enable data sharing. Data transfer and visualization of this nature can depend upon "disruption tolerant networking" and enables us to help explore the manner in which this technology might be applied to data management for crew and suit software development. Our LiDAR data are contributing to hazard and navigation instrument development, with a focus on assessing whether surface materials are indurated enough to support vehicles, which are studies best conducted at sites that involve both loose and competent materials such as are observed at our field locations. Finally, our work with the NASA EVA Tools group and the Exploration EVA office at JSC means that relevant constraints for ongoing instrument and operational concept designs are being consistently integrated into our field testing, and that RIS^{4}E field planning and results directly reflect current architecture and concept of operations thinking. Our involvement with other analog projects like HISEAS and the NASA NEEMO missions also means that our results can be consistently integrated into other ongoing projects and that the EVA community is quickly made aware of our results after investigating scientifically-motivated EVAs. Additionally, the composition of RIS^{4}E field teams and the cadence of field campaigns give RIS^{4}E the ability to contribute to the AES portfolio in a meaningful way. RIS^{4}E team members were integral members of the Deep Space Gateway Science Workshop Organizing Committee and are currently serving on the Program Committee. Furthermore, team members have supported a JPL and GSFC Astrophysics TIM focused on DSG science operations to provide feedback as to how astrophysics needs might align with planetary science goals from an infrastructure perspective.

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

The Theme 3 team continues to build on work we have done over the past decade to develop a wide variety of assay techniques that are designed to assess the identity and concentration of reactive oxygen species (ROS) produced by interactions between regolith simulants pulverized in the laboratory and various liquid media. This work has enabled us to determine which assays are most effective for the characterization of low concentrations (nanomolar to millimolar) of common ROS species. After developing these assays, many of which are suitable for eventual miniaturization for use by astronauts, we have been carrying out new investigations in three critical areas in 2017.

1.3.1 Reactions at Mineral Surfaces

We are developing a mechanistic understanding of the reactions that occur at the interface between mineral surfaces and liquids. These reactions result in the production of the ROS observed and quantified by our assay techniques. This aspect of our research involves the use of surface spectroscopic techniques, such as X-ray photoelectron spectroscopy (XPS) to probe the surface speciation of pulverized minerals and regolith simulants, before and after reaction with liquid media, in order to ascertain which surface chemical species are participating in ROS-producing reactions. For example, **Figure 1.4** shows the surface speciation of O-bearing species on forsteritic olivine after crushing, but prior to reaction with liquid. Comparison to the spectra collected after reaction will enable us to assess changes in surface speciation and understand the chemical reactions that produce ROS. Armed with this understanding, we will be able to predict which mineral and regolith species have the greatest potential to produce harmful ROS, and understand why ROS are produced.

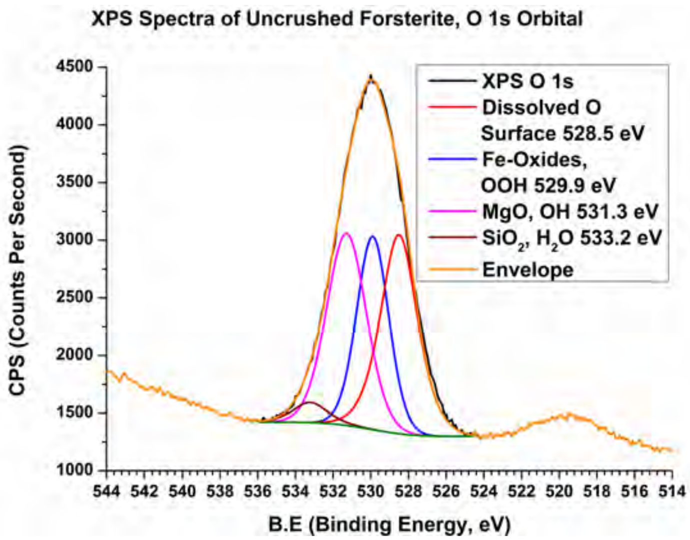


Figure 1.4: XPS spectrum from crushed forsteritic olivine showing mineral surface speciation prior to reaction with liquid media and ROS production.

1.3.2 Effects of Pulverized Materials on Biological Compounds and Processes

This aspect of our research involves collaborative research between geoscientists and medical researchers; forging an important link between scientists that understand the properties of planetary surfaces and those that understand the human body and its vulnerabilities. Our work has included studies of oxidative stress induced by mineral and lunar regolith simulants in lung tissue (**Figure 1.5**), programmed cell death in proliferating and terminally differentiating lung epithelial cells, and of cytotoxicity and activation of peripheral macrophages. These studies are enabling us to better understand how planetary regolith and the human body interact with one another, and which

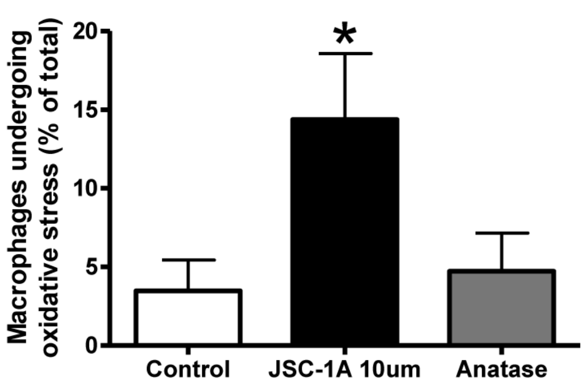


Figure 1.5 (bottom): Oxidative stress in mouse lung tissue macrophages after exposure to the JSC-1a lunar regolith simulant, compared to non-reactive anatase powder, and a control with no particulates.

planetary materials have the greatest potential to harm astronauts.

1.3.3 Increasing Simulation Fidelity

Finally, we are continually increasing the fidelity of our simulations to maximize the benefits of our research on the potential impacts of exposure to regolith on astronaut health. This will ultimately enable effective mitigation strategies and engineering controls to be designed to prevent exposure to the most harmful particulates. Looking ahead to 2018, these efforts will grow to include experimental simulations of space weathering processes and their effects on regolith reactivity and toxicity, and assessments of the ROS-producing capacity and toxicity of Apollo lunar regolith samples, as well as the sensitization of cells exposed to these samples to inflammatory inputs.

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

Research projects from RIS^{4}E Theme 4 seek to enhance the value of observations and returned samples using cutting edge laboratory capabilities. Ongoing development by our team splits into two technologies: synchrotron x-ray absorption and transmission electron microscopy.

1.4.1 Synchrotron X-ray Absorption Spectroscopy

In 2017, we continued our work in the application of X-ray absorption fine structure (XAFS) spectroscopy methods for defining the valence states of multi-valent elements in minerals and glasses and the application of these methods to the study of extraterrestrial materials. With improved XAFS methodologies and calibrations, we are working to develop improved valence-state oxybarometers to constrain the evolution of oxidation states of igneous systems on the Moon, Mars and achondrite parent bodies. We have continued to make advances in using multivariate prediction models to more precisely measure ever-smaller variations in elemental valence. Applied to V XAFS spectra in glasses, we have developed an MVA calibration model that directly relates the measured spectra to predicted fO_2, improving the precision in calculating fO_2 with more robust error analysis (**Figure 1.6**). These machine learning-based algorithms also allow

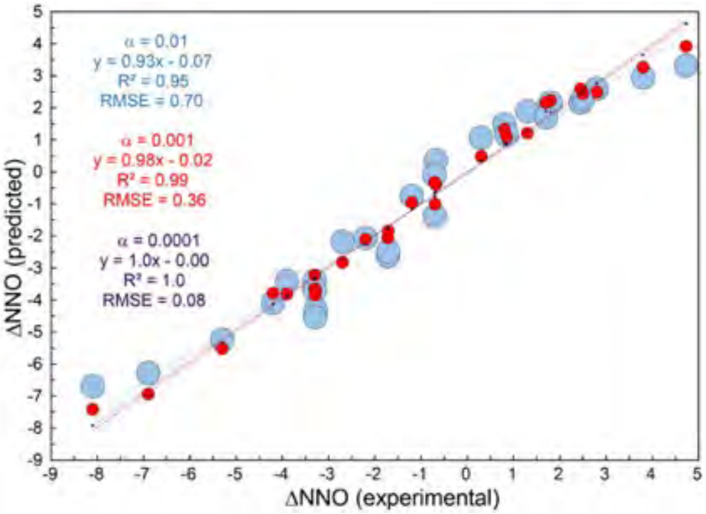


Figure 1.6. Predicted vs. experimental oxygen fugacity using XAS data.

for XAFS to be collected in an imaging modality to spatially map elemental redox states within samples (Lanzirotti et al., 2017).

Studies of lunar glass beads showed the first direct measurements of Fe^{3+} in natural lunar picritic glasses (McCanata et al., 2017). We found that lunar glass beads from the Apollo sample collection contain up to 60.0% Fe^{3+}. No correlation with melt chemical properties, such as Mg# or weight % TiO_2, or physical properties, such as bead diameter, was observed. $Fe^{3+}/\Sigma Fe$ was found to be negatively correlated with NBO/T. Elevated $Fe^{3+}/\Sigma Fe$ values are interpreted to reflect eruption and post-eruption oxidation due to magmatic degassing of H or OH. Glass beads observed to be zoned to lower $Fe^{3+}/\Sigma Fe$ rims may represent a subsequent reduction in the lunar vacuum prior to cooling through the glass transition temperature.

1.4.2 Scanning Transmission Electron Microscopy and Electron Energy Loss Spectroscopy (STEM-EELS)

Our STEM-EELS work continued in three main themes: (1) scanning transmission electron microscope-based imaging and spectroscopy to understand the nanoscale effects of space weathering in lunar soils, (2) coordinated synchrotron X-ray and STEM-based analysis of primitive Solar System materials, and (3) STEM-based spectroscopic studies of the incorporation of volatiles into nanodiamonds. Dr. Kate Burgess analyzed space weathered rims of the lunar soil grains, specifically helium from the solar wind in an ilmenite/chromite/silicate glass grain (**Figure 1.7**). She also continued analysis of oxidized material present in the space weathered rims and examined helium and hydrogen in vesicles in interplanetary dust particles (IDPs), which builds on her lunar work.

The Theme 4 team also examined primitive materials.

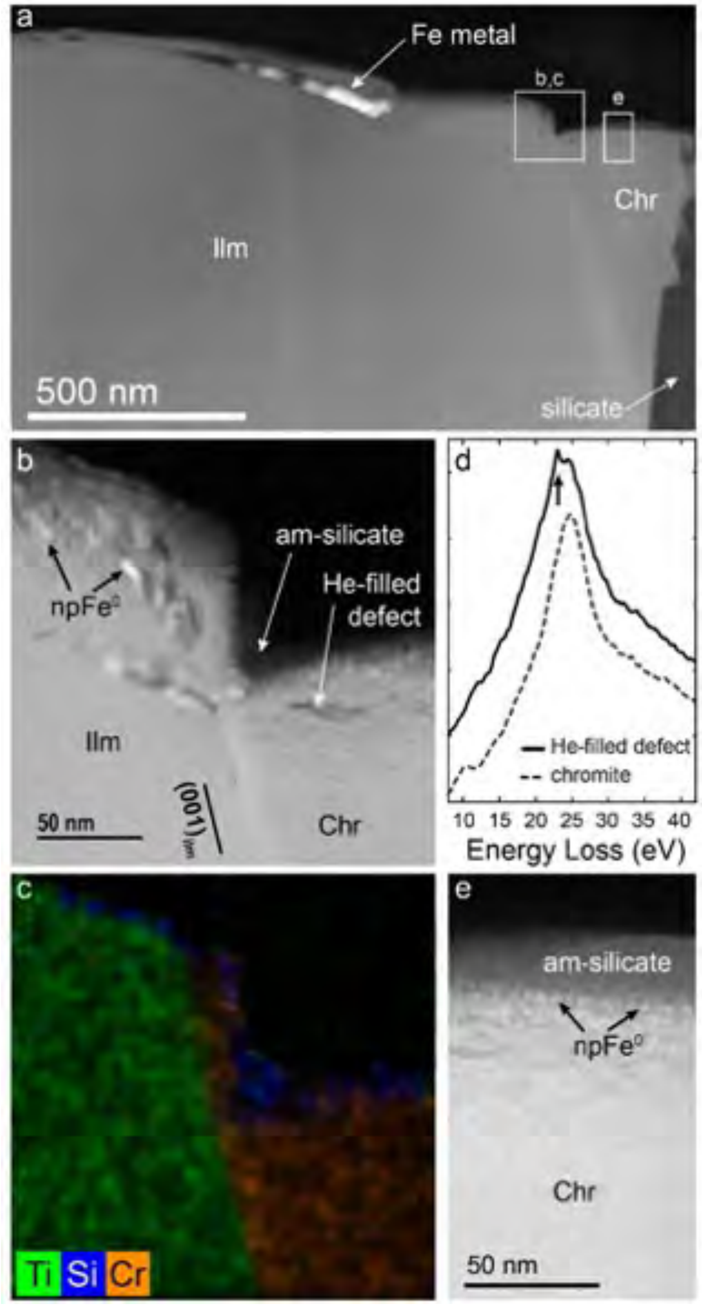


Figure 1.7. Differences in space weathering features in ilmenite and chromite in a lunar soil grain. Helium is present in vesicles and defects in the ilmenite and chromite, and can be analyzed and quantified using electron energy loss spectroscopy. Nanophase iron inclusions are present at the surface of the chromite and in the rim of the ilmenite, and silica-rich vapor deposited material is seen coating both phases in this region. From Burgess & Stroud (2018).

Using Fe-XANES data from FIB sections of a primitive carbon-rich clast from chondrite LAP 02342, Dr. Bradley De Gregorio quantified the Fe oxidation state variation at the 50 nm level, showing how the abundance of Fe^{3+}-rich materials is lower within the clast than within the surrounding fine-grained matrix. Fe-bearing materials at the edge of the clast, where fluids were actively mixing with clast-derived fluids, produced a mixed valence state.

2 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

Following the SSERVI site visit to the University of Colorado in October, 2015, PI Glotch and IMPACT PI Mihaly Horanyi began discussions that lead to a successful collaboration. 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. Glotch, his former postdoctoral researcher, Mehmet Yesiltas, and graduate students Jordan Young and Carey Legett prepared mineral samples, a reflectance standard, and a portable VNIR spectrometer for integration with the CU dust accelerator facility. Young traveled to the University of Colorado in February 2017 to finalize the design of our joint experiment. We prepared several single crystal olivine samples for analysis. Prior to the impact experiments, which occurred in early July 2017, two samples were irradiated with low energy protons at the Brookhaven National Laboratory Tandem Van de Graaf accelerator to simulate solar wind bombardment. The irradiated sample and an unirradiated sample were subjected to ~10,000 dust impacts each at the CU dust accelerator. The samples were subsequently analyzed using visible/near-IR reflectance spectroscopy, thermal IR emission spectroscopy, Raman spectroscopy, X-ray Absorption spectroscopy, and transmission electron microscopy. The results of these analyses are presented in Section 1.1. RIS^{4}E postdoctoral researcher Sarah Nicholas is currently preparing a new suite of samples for experiments at the CU dust accelerator. Results from these experiments will be directly compared with samples subjected to laser irradiation experiments meant to simulate micrometeoroid bombardment. We anticipate that this comparison will provide a calibration for the laser wavelength and energy density required to most accurately simulate micrometeoroid bombardment.

2.2 Collaboration with the SEEED Team

The pigeonite mineral standards that our experimental petrologists have synthesized are of great interest to numerous scientists. Following Mössbauer spectroscopic analyses by Co-I Dyar, portions of each of the synthetic samples were turned over to SEEED PI Carlé Pieters for VNIR spectral analysis in the Brown RELAB facility. PI Glotch has also worked with SEEED Co-I Jack Mustard on a book chapter focused on the theory of reflectance and emittance spectroscopy. This chapter, which has successfully completed peer review, is part of a new “Remote Compositional Analysis” book to be published by Cambridge University Press in 2018.

2.3 Collaboration with the TREX and ESPRESSO Teams

The RIS^{4}E 2017 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). As the TREX and ESPRESSO teams prepare for their own field seasons, Wright and Lewis were invited to join the RIS^{4}E team to observe the planning and execution of our field investigations and to participate in the scientific investigation of Kilbourne Hole and Aden Crater.

2.4 International Collaborations

Dr. Ed Cloutis (University of Winnipeg) is a RIS^{4}E collaborator and a Canadian Lunar Research Network (CLRN) team member, providing a link between the two teams. In each of the first four years of our SSERVI collaboration, he has hosted a U.S. undergraduate student as a SSERVI summer research fellow.

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

Former RIS^{4}E postdoctoral researcher Dr. Mehmet Yesiltas is now a professor at Kirklareli University in his home country of Turkey. He is now a RIS^{4}E collaborator, working with PI Glotch and SBU graduate student Jordan Young on Raman spectroscopic measurements of ordinary and carbonaceous chondrites.

3. Public Engagement

Throughout 2017, the RIS^{4}E team continued to support public engagement through a plethora of activities noted below.

3.1 RIS^{4}E Science Journalism Program

2017 marked the second RIS^{4}E Science Journalism Program course and field season. This program includes a semester-long special topics course at Stony Brook University School of Journalism taught by Co-I Elizabeth Bass and invites the journalism students to accompany the RIS^{4}E scientists into the field.

3.1.1 Journalism Special Topics Course at Stony Brook University

The special topics course at Stony Brook University School of Journalism hosted a class of eight students from a wide range of backgrounds. The students were able to learn about RIS^{4}E science and exploration activities from members of the RIS^{4}E team. RIS^{4}E scientists visited the classroom and the students visited RIS^{4}E team members at their labs, including Brookhaven National Laboratory and Goddard Space Flight Center (**Figure 3.1**). RIS^{4}E team members also participated in one-on-one interviews, both on- and off-camera. During the semester, the students improved their interview and reporting skills and prepared for the working environment and physically harsh conditions they could expect to encounter in the field.

Figure 3.1. Stony Brook journalism students visit RIS^{4}E Team members at NASA Goddard Space Flight Center.

Figure 3.2. Stony Brook journalism students observe RIS4E scientists in the field in Potrillo, NM.

3.1.2 Journalism Students Field Excursion in Potrillo, NM

The second portion of the RIS^{4}E Journalism program teamed journalism students with the RIS^{4}E field team in the volcanic fields of Potrillo, New Mexico. Five students took advantage of the field excursion and were able to observe the entire multi-day field campaign, from set-up through weather-motivated changes in plans, data analysis and investigation of new questions that arise as a result of field discoveries. The students observed the scientists formulating and testing hypotheses in real time. Throughout the trip, they put their camera and interview skills to the test in the harsh desert conditions (**Figure 3.2**).

The product from the RIS^{4}E Science Journalism program is ReportingRIS4E.com. Blog posts, articles, photos and videos documenting the students' time in the field can be found on the website from both the 2017 and 2015 RIS^{4}E Science Journalism Programs.

The RIS⁴E Science Journalism Program serves two complementary purposes. We simultaneously train the next generation of science journalists while providing researchers with the opportunity to practice communicating their science to a general audience.

3.2 Social Media

As a joint effort, multiple team members help to give the public a taste of RIS⁴E science going on throughout the year over several social media platforms, including Twitter (@RIS4E_SSERVI) and Facebook (RIS⁴E Science and Exploration). Updates from the field, outreach events, and the exciting science happening throughout the RIS⁴E team are shared with the general public in short, digestible bursts in order to excite the public about RIS⁴E science. This year the RIS⁴E field team was also featured on YouTube, https://www.youtube.com/watch?v=BWhPKXf1jUQ, highlighting the RIS⁴E Potrillo, NM fieldwork conducted this summer.

3.3 Public events

The RIS⁴E team supported public engagement at many events, including talks, interviews and hands-on activities. RIS⁴E team members supported outreach at multiple events across the country during the 2017 Solar Eclipse. Team member Jacob Bleacher assisted with one of the large Minor League Baseball events at the South Carolina Charleston River Dogs game, where talks, interviews, activities, and a live view of totality during the game were experienced. Several RIS⁴E team members spent time at Union Station in Washington, DC giving talks and helping with hands-on activities for Earth Day 2017, with students, teachers, parents, and passersby. RIS⁴E team members supported the 4.7-mile long Planet Walk which attracts families and people of all ages as they explore a scale model of the Solar System. The participants can 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. For the third year in a row, several Stony Brook graduate students presented RIS⁴E science and exploration activities at the Port Jefferson Mini Maker Faire.

4 Student / Early Career Participation

Undergraduate Students

1. Dylan McDougall, Stony Brook University, Diviner data analysis
2. Alexander Kling, Stony Brook University, Thermal IR spectroscopy of airless bodies
3. Melvin Li, Stony Brook University, Macrophage response to lunar soil simulants
4. Katie Luc, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants
5. Rami Areikat, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants
6. Lucia Mallozzi, Stony Brook University, Raman spectroscopy of ordinary chondrites
7. Oliver Lockwood, Stony Brook University, Mineral synthesis and characterization
8. Kristina Finnelli, Stony Brook University, Infrared spectroscopy of basalts from Hawaii and New Mexico
9. Sarah Byrne, Mount Holyoke College, Spectral data analysis
10. Isabel King, Harvey Mudd College, Mineral sample preparation and characterization
11. Jane Watts, Harvey Mudd College, Mineral sample preparation and characterization
12. Josephine King, Harvey Mudd College, Mineral sample preparation and characterization
13. Andrea Bryant, Emory University, X-ray absorption spectroscopy

14. Rebecca Wilks, University of Winnipeg, Underdense regolith simulations

Graduate Students

15. Gen Ito, Stony Brook University, Light scattering models and infrared imaging
16. Melissa Sims, Stony Brook University, Novel high pressure/temperature mineral physics experiments
17. Melinda Rucks, Stony Brook University, Synthesis and characterization of tissintite
18. Katherine Shirley, Stony Brook University, Thermal IR spectroscopy in a simulated lunar environment
19. Carey Legett IV, Stony Brook University, Light scattering models and space weathering experiments
20. Jordan Young, Stony Brook University, Space weathering experiments and Raman spectroscopy
21. Donald Hendrix, Stony Brook University, EPR and XPS spectroscopy of lunar analog dust
22. Tristan Catalano, Stony Brook University, Pigeonite synthesis and electron microprobe characterization
23. Douglas Schaub, Stony Brook University, Plagioclase synthesis and electron microprobe characterization
24. Nicholas DiFrancesco, Stony Brook University, Olivine and plagioclase synthesis and characterization
25. Marcella Yant Roth, Stony Brook University, Field and laboratory spectral studies of Hawaiian basalts
26. Kaitlyn Koenig Thompson, Stony Brook University, Lung inflammation processes
27. Nathan Smith, Northern Arizona University, Phobos thermal modeling
28. Marina Gemma, Columbia University, Simulated asteroid environment spectroscopy of ordinary chondrites
29. C. J. Carey, University of Massachusetts Amherst, Machine learning techniques for spectral analysis

Postdoctoral Fellows

30. Sarah Nicholas, Stony Brook University/Brookhaven National Laboratory, X-ray spectroscopy
31. Steven Jaret, Stony Brook University, Spectroscopy and geochronology of impact shocked materials
32. Rachel Caston, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants

New Faculty Members

33. Jillian Nissen, SUNY Old Westbury, Molecular and cellular pharmacology
34. Mehmet Yesiltas, Kirklareli University (Turkey), Raman spectroscopy of chondrites

Job Changes/Promotions/Awards

35. Steven Jaret, Stony Brook Grad/Postdoc, now Postdoctoral Researcher at Mount Holyoke College (RIS^4E team)
36. Marcella Yant Roth, Stony Brook grad student, now Postdoctoral Researcher at Johns Hopkins University (ESPRESSO team)
37. Rachel Caston, Stony Brook University grad student, now Stony Brook Postdoctoral Researcher (RIS^4E team)
38. C. J. Carey, UMASS grad student, now software developer at Google
39. Melinda Rucks, Stony Brook University grad student, successfully renewed her NASA Earth and Space Science Fellowship (NESSF) award
40. Melissa Sims, Stony Brook University grad student, was awarded beam time at the Advanced Photon Source

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, Lora Bleacher, E/PO Lead Solar System

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

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

10. ORISIs-REx, Ed Cloutis, Co-I/Asteroid scientist—spectroscopy

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

12. 2001 Mars Odyssey, Deanne Rogers, THEMIS, Co-I Pending

13. 2001 Mars Odyssey, Christopher Edwards, THEMIS, Co-I Pending

14. 2001 Mars Odyssey, Scott McLennan, GRS, Co-I

15. Mars Science Laboratory, Christopher Edwards, Participating Scientist

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

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

Carlé Pieters

Brown University, Providence, RI

SSERVI Evolution and Environment of Exploration Destinations (SEEED)

Organization and Objectives: Our SSERVI Evolution and Environment of Exploration Destinations (SEEED) team is hosted at Brown University with major contributions from Co-Is at MIT and five additional academic institutions. We partner with individuals from another four institutions as well as seven foreign countries. Altogether, SEEED participants include 24 Co-Is and 18 Collaborators. This report covers the fourth year of SSERVI activities [January 2017 - December 2017]. SEEED activities focused on expanding scientific knowledge associated with the key designated targets: The Moon, asteroids, and the moons of Mars. In addition to scientifically relevant results, our goal is to attract some of the best minds into the field, keep them involved, and produce the next generation of knowledgeable and committed planetary scientists and engineers. The examples below are representative of recently completed or ongoing research within SEEED themes and community involvement. During 2017, SEEED members produced 39 peer-reviewed research publications and >40 extended abstracts (LPSC). A more complete list of SEEED publications (peer-reviewed and extended abstracts) can be found at http://www.planetary.brown.edu/html_pages/brown-mit_sservi_pubs.htm.

1 SEEED Science and Infrastructure Themes

Described below are several SEEED accomplishments during 2017. Full citations for references to 2017 peer-reviewed publications are provided in the SSERVI 2017 publication list or through the above SEEED publication website.

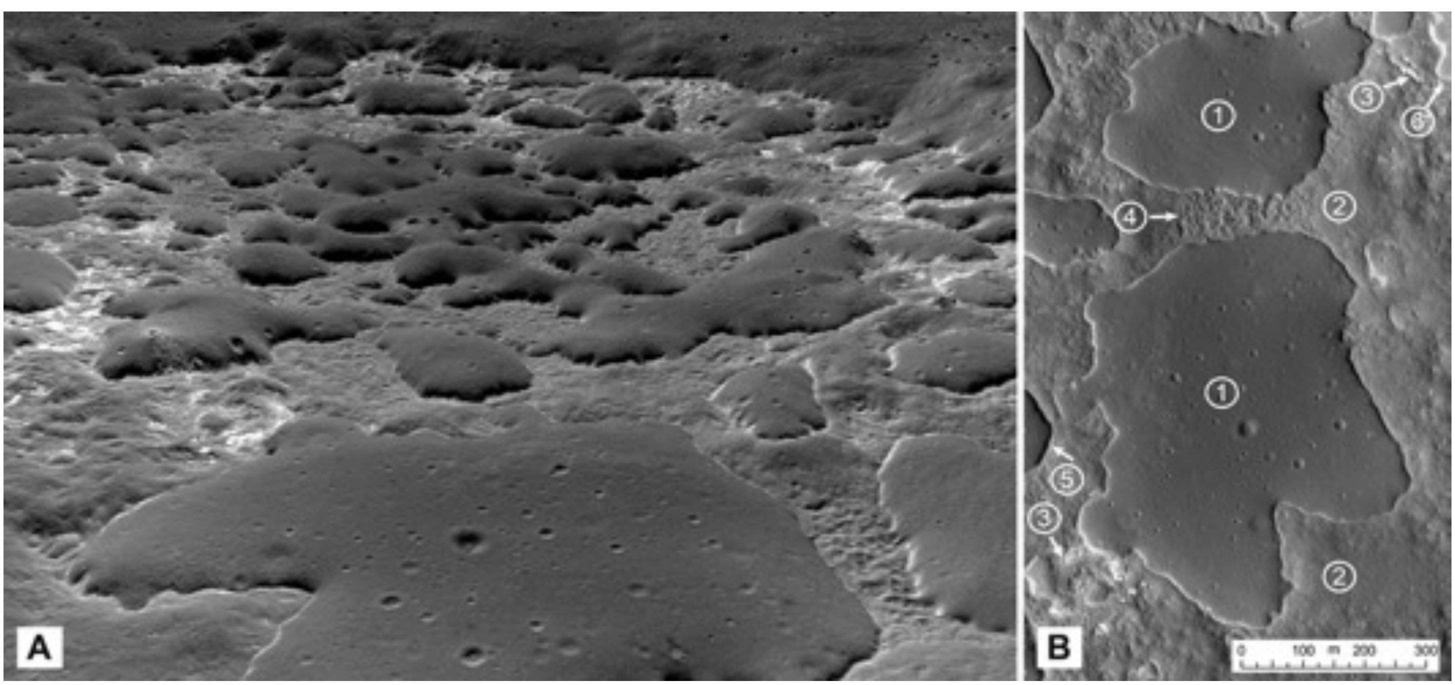
1.1 Thermal/Chemical Evolution of Rocky Bodies [How do planetary bodies form and evolve?]

1.1.1 Magmatic Processes on the Moon [International]

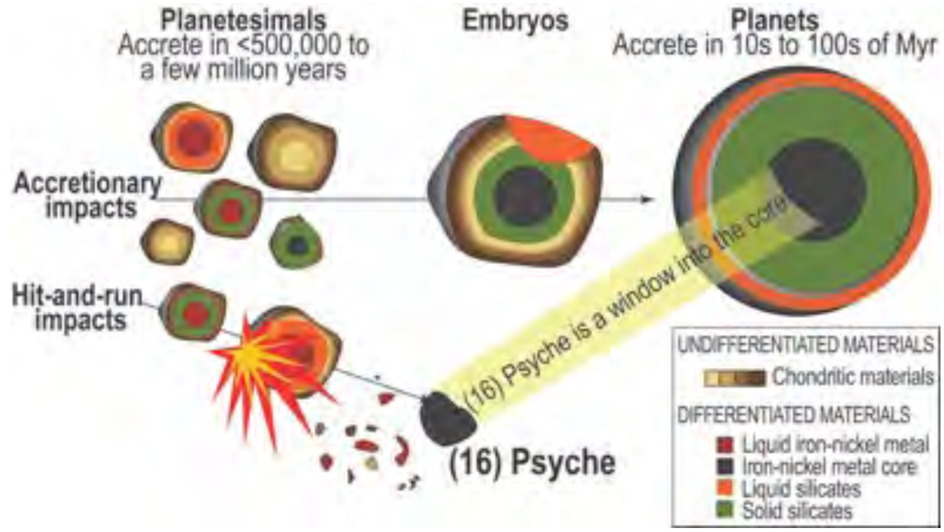
Deputy PI Jim Head and International Collaborator Lionel Wilson completed a comprehensive model of the generation, ascent and eruption of magma on the Moon and published them in two papers they affectionately call “doorstops” (See Icarus: Wilson and Head, part-1 2017; Head and Wilson, part-2 2017). Using new data on crustal thickness and density, magma properties, surface topography, morphology and structure, they show that: (1) essentially all lunar magmas were negatively buoyant everywhere within the crust; (2) positive excess pressures of at least 20–30 MPa must have been present in mantle melts at or below the crust–mantle interface to drive magmas to the surface; (3) such pressures are easily produced in zones of partial melting by pressure-release during mantle convection or simple heat accumulation from radioisotopes; (4) magma volume fluxes available from dikes forming at the tops of partial melt zones are consistent with the 10^5 to 10^6 m^3 s^{-1} volume fluxes implied by earlier analyses of surface flows; and (5) eruptions producing thermally-eroded sinuous rille channels involved somewhat smaller volume fluxes of magma where the supply rate may be limited by the rate of extraction of melt percolating through partial melt zones. As the Moon cools with time, the lithosphere thickens, magma source regions become less abundant, and rheological traps become increasingly deep; the state of stress in the lithosphere becomes increasingly contractional, inhibiting dike emplacement and surface eruption. Implications from this integrated analysis are very broad.

1.1.2 Irregular Mare Patches (IMPs): Very Young or Old? [International]

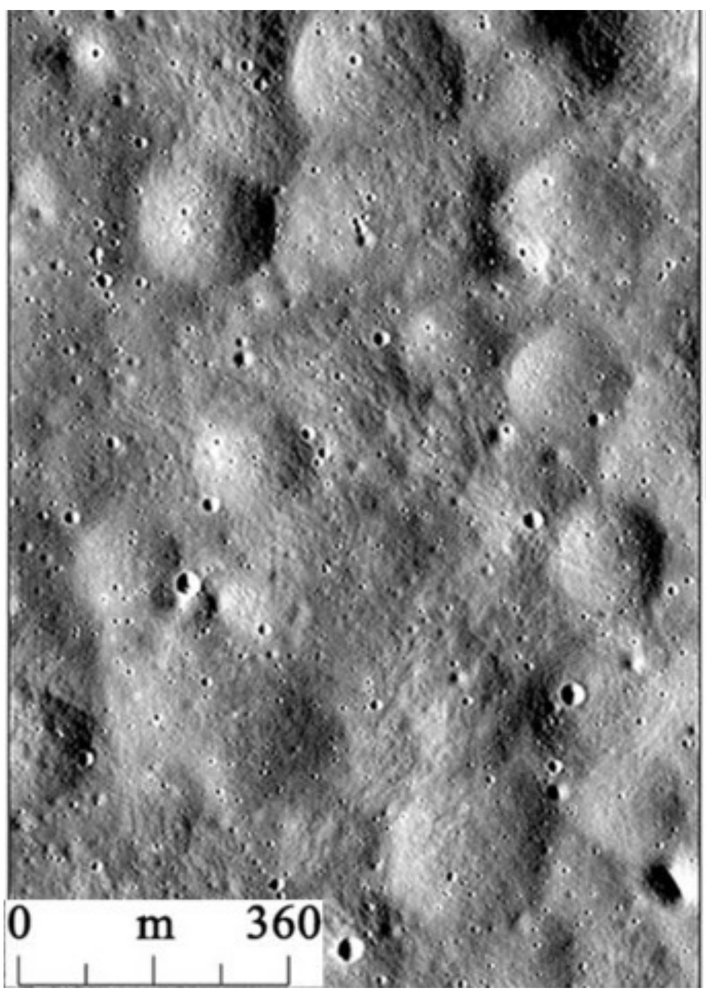
Volcanic eruptions on the Moon take place in conditions of low gravity and negligible atmospheric pressure, very different from those on Earth. These differences can lead to the production of unusual eruption products neither predicted nor observed on Earth in the terminal stages of eruptions. These include the unusual mounds and rough (hummocky, blocky) floors of some small-shield summit pit crater floors, and elongated depressions and mare flows (often called “irregular mare patches” or IMPs. SEEED Co-Is Head, Wilson and colleagues (Wilson and Head, 2017, JVGR; Qiao et al., 2017, Geology) examined the ascent and eruption of lunar magma in the waning stages of the eruptive process in small-shield summit pit crater floors and show that many characteristics observed at IMPs can be plausibly explained by expected basaltic magma behavior: as the rise rate of the ascending magma slows to zero, volatiles exsolve in the dike and lava lake to form a very vesicular foam, and the dike begins to close. Stresses in the very vesicular and porous lava lake crust produce fractures through which the foam extrudes. Waning-stage extrusion of such viscous magmatic foams to the surface produces convex mounds whose physical properties inhibit normal impact crater formation and regolith development, resulting in an apparent young crater retention age. This mechanism for the production and extrusion of very vesicular magmatic foams provides a candidate explanation for many irregular mare patches. It also implies that IMPs and associated mare structures (small shields, pit craters and fissure flows) formed synchronously billions of years ago. This interpretation is in contrast to very young ages (less than ~100 million years) inferred for the same IMPs by other researchers using different assumptions. Analysis of this critical question concerning lunar volcanism processes and timing continue to be debated.



1.1.3 Ring-moat Dome Structures [International]



Building on a discovery made decades ago by SEEED Co-I Peter Schultz, but largely unknown to the community, SEEED investigators found evidence for widespread development of a distinct morphological feature documented at high resolution by the Lunar Reconnaissance Orbiter (LRO) on the lunar surface designated Ring-Moat Dome Structures (RMDS). These low domes (a few meters to ~20 m height with slopes <5°) are typically surrounded by narrow annular depressions or moats. In this multinational research project (US, England, Russia, Italy, Japan, China: Zhang et al. 2017), we mapped about 2,600 RMDSs in the lunar maria with diameters ranging from tens to hundreds of meters. Four candidate hypotheses involving volcanism for their origin were discussed. Currently, we favor a mechanism for the formation of the RMDS related to modification of the initial lava flows through inflated flow squeeze-ups and/or extrusion of magmatic foams below a cooling lava flow surface. These newly documented features provide additional insights into the nature of emplacement of lunar lava flows, suggesting that in the waning stages of an emplacement event, magmatic foams can be produced, extrude to the surface as the dike closes, and break through the upper lava flow thermal boundary layer (crust) to form low-density viscous mounds and surrounding moats.



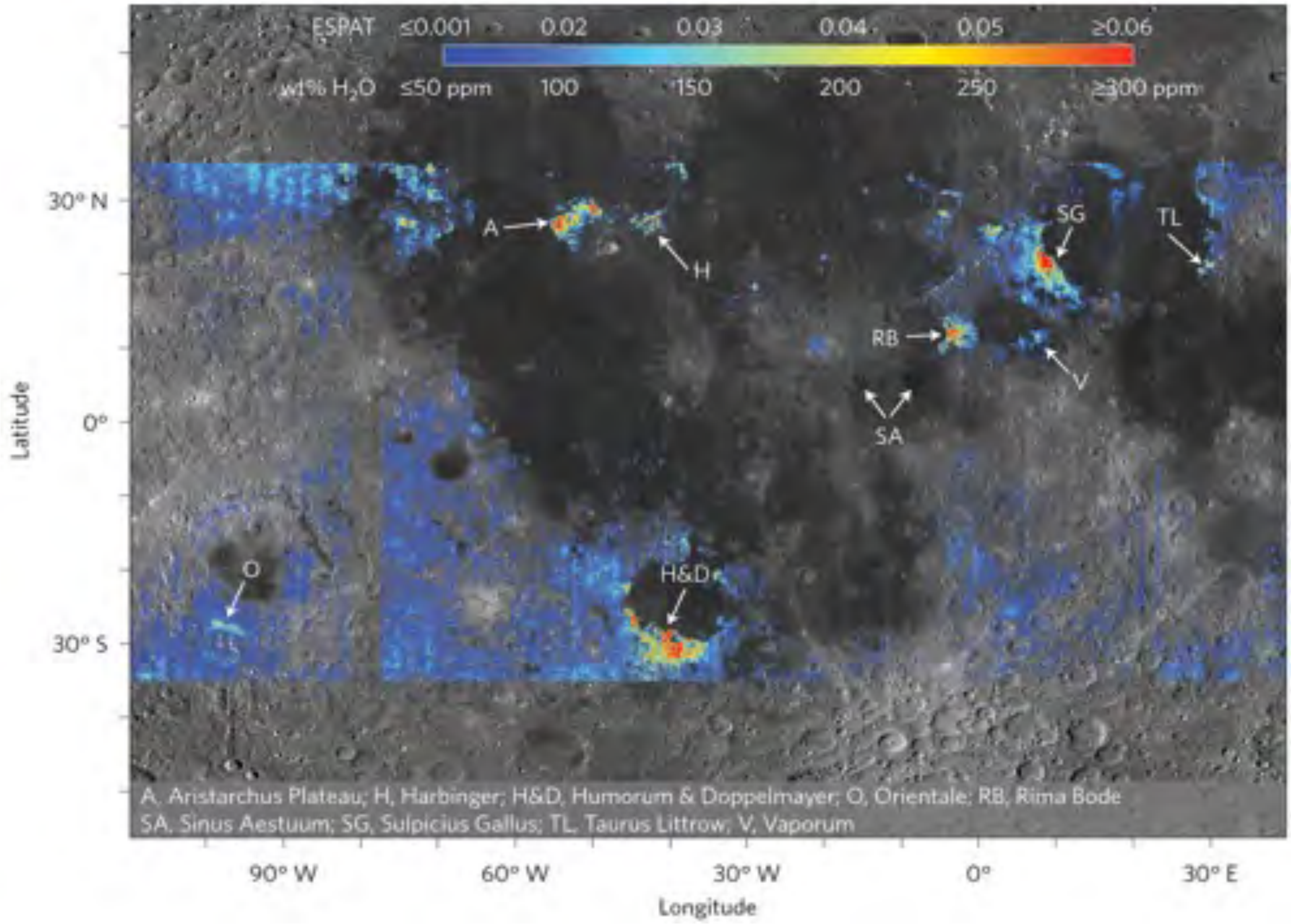
1.1.4 Psyche: A Proto-planet Core?

After being awarded a Phase A study in 2016, SEEED Co-I Lindy Elkins-Taunton successfully led her team as PI of Psyche to being selected in 2017 for implementation as a Discovery Mission. Current evidence suggests asteroid 16 Psyche is metal-rich and could represent a core-like remnant of planetary accretion processes. SEEED Co-Is Ben Weiss will lead the Magnetics experiment and Maria Zuber will lead Radio Science for Psyche.

1.2 Origin and Evolution of Volatiles in the Solar System

1.2.1 Hydrous Lunar Pyroclastic Deposits Detected from Orbit

Two SEEED 2017 peer-reviewed publications [Li and Milliken; Milliken and Li] investigated M^3 analyses of



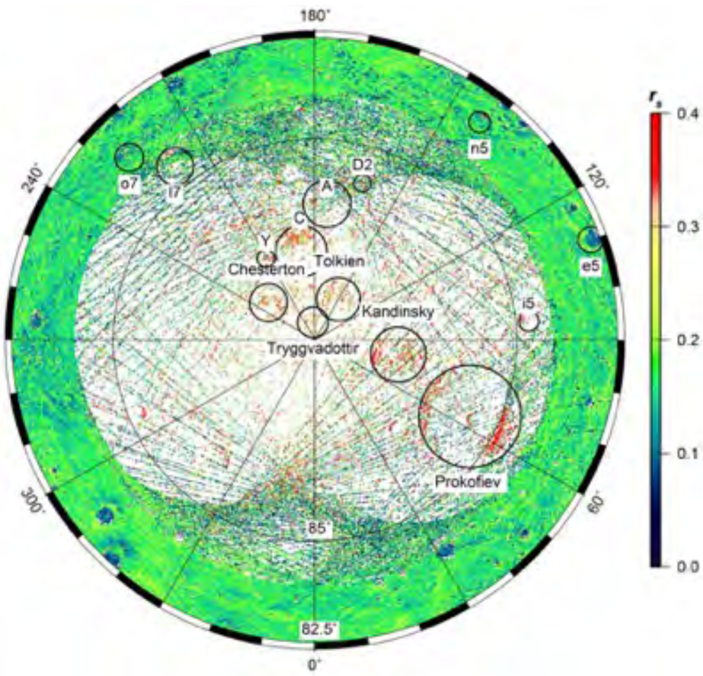
hydrated lunar surface material at mid-latitudes using an empirical lunar-sample based thermal correction. Global assessment of the remotely acquired results identified enhanced water at both sampled and many un-sampled pyroclastic deposits (indigenous water-bearing materials from the lunar mantle studied previously by SEEED Co-I Saal et al. [2008] in lunar samples). Interestingly, the extensive dark Rima Bode (RB) deposits in the central nearside exhibit enhanced water, whereas the nearby similar Sinus Aestuum (SA) has dark deposits to the south that contain unusually abundant spinel [Pieters et al., 2014, Am Min] and appears to be dry.

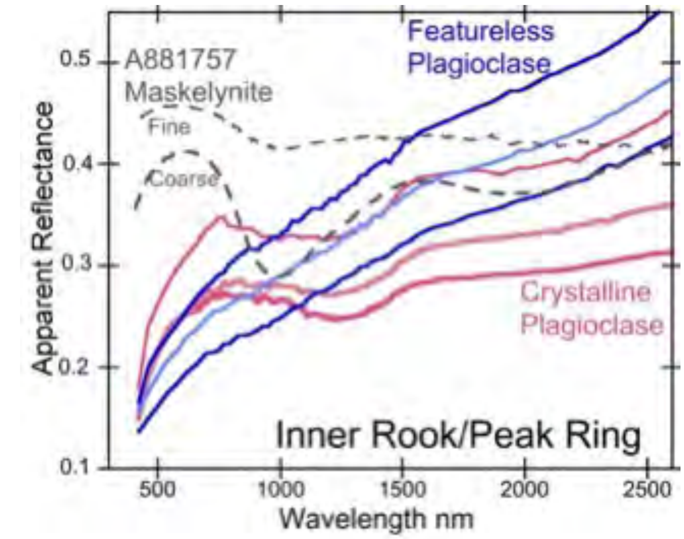
Of additional interest are the vast pyroclastic deposits found on the Aristarchus plateau (A) that is currently being studied by graduate student Erica Jawin as part of her PhD thesis.

1.2.2 Mercury Polar Ice Deposits Characterized [Young Scientist led]

Radar-bright deposits at the poles of Mercury are located in permanently shadowed regions, which provide thermally stable environments for hosting and retaining water ice on the surface or in the near subsurface for geologic timescales. Typical radar-bright polar water-ice deposits observed below 85° N are veneered with low albedo material (presumed lag deposits), but high reflectance ice deposits are relatively rare. By closely evaluating the sparse data above 85° N, Deutsch et al., (2017, GRL) identified new craters that are radar-bright with high surface reflectance indicative of exposed ice. The observed exposed ice deposits are believed to result from a temperature dependence stability above 85° N. Furthermore, an overall brightness increase toward the pole is hypothesized to be due to small scale microcold traps.

The thickness of the polar deposits, and thus their total mass and volume, remain poorly constrained. Graduate Student Ariel Deutsch led colleagues in deriving thickness estimates for selected water-ice deposits using small, simple craters visible within the permanently shadowed, radar-bright deposits (Deutsch et al., Icarus in press 2017). Using the ice thickness estimates to calculate the





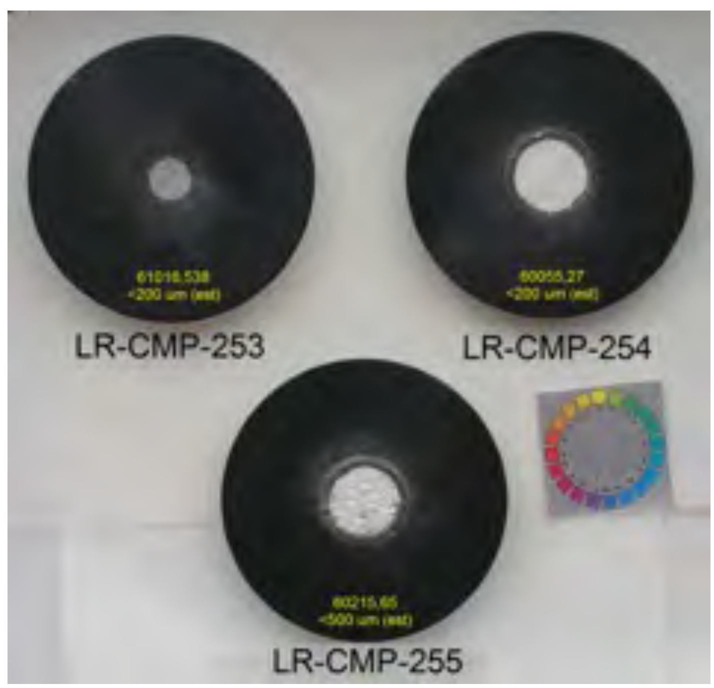
M[3] spectra of crystalline and 'featureless' plagioclase found along the Orientale Inner Rook mountains. Shown for comparison are offset laboratory spectra of a maskelynite separate from the gabbroic lunar meteorite A881757.

total amount of water ice currently contained in Mercury's polar deposits results in a value of ~10^{14}–10^{15} kg. This is equivalent to ~100–1000 km^3 ice in volume. This volume of water ice is consistent with delivery via micrometeorite bombardment, Jupiter-family comets, or potentially a single impactor.

1.3 Regolith of Airless Bodies and Space Weathering

1.3.1 Origin and Distribution of 'Featureless Plagioclase' on the Moon

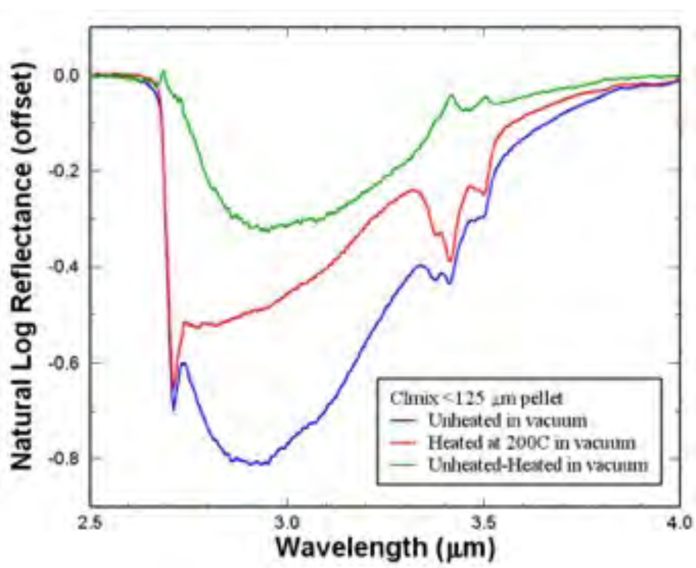
Crystalline plagioclase with a diagnostic 1.25 μm feature has been detected using modern spectroscopic instruments orbiting the Moon and is found to be widespread across the highlands. At high spatial resolution, such pure crystalline anorthosite (PAN) is usually found associated with the much more common 'featureless plagioclase' (no mafic mineral signatures) in remote observations, which has been assumed to be a processed or shocked form of anorthosite. In order to characterize the global lunar crust, it is essential to be able to link these (presumed) two forms of primary crustal plagioclase. The challenge for remote compositional analyses is that no 'featureless plagioclase' has been identified in lunar samples to validate interpretations of the remote data, while on the other hand no outcrops or mountains exhibiting pure maskelynite (highly shocked plagioclase) properties have been identified in remote spectra of the surface. We have been making progress in both aspects of this issue (analyses of remotely acquired spectra and laboratory spectra of lunar samples). Although analyses are not yet complete, new allocations of carefully selected lunar anorthosite samples hold promise of understanding this mystery.



Three new lunar anorthosite samples prepared for RELAB spectral measurements. Preliminary results indicate two exhibit the diagnostic 1.25 μm crystalline plagioclase absorption, but one (intriguingly) does not.

1.3.2 Survey of Hydrated Carbonaceous Chondrites [International]

In anticipation of spectroscopic remote sensing and sample return analyses of two near-Earth primitive asteroid bodies being visited by US and JAXA spacecraft, SEEED Co-Is Hiroi and Milliken have initiated several studies concentrating on the spectroscopic analysis of primitive meteorites in order to have quality laboratory spectroscopic data of candidate materials available for comparison. The difficulty of such measurements in Earth-based laboratories, however, is that terrestrial contamination prior to measurement is unavoidable, and it is well recognized that such spectra cannot be directly compared to asteroid surfaces in their natural environment. In collaboration with colleagues from Japan, Hiroi and Milliken are measuring a suite of carbonaceous chondrites and testing different techniques to extract fundamental compositional information from the spectra. One promising approach illustrated here (and to be reported at LPSC49) involves measuring samples in vacuum before and then after heating to remove loosely bound OH (in this case to 200°C). Modeling of features observed in each is underway to isolate the most diagnostic absorptions and useful approach for compositional analyses.



Spectra of CI meteorites (CImix) measured in vacuum. Blue= unheated. Red= heated to 200°C. The Green spectrum is the ratio of the two and captures the character of the loosely bound adsorbed water for this sample.

1.4 Science and Engineering Synergism

1.4.1 Is Phobos on the Pathway to Mars? [Young Scientist led]

As a result of our SSERVI-Sponsored Phobos and Deimos Course, Brown University graduate students undertook a class project to evaluate whether Phobos was on the Pathway of Humans to Mars. They presented their results at the end of the seminar to the class and to the visiting NASA Associate Administrator for Space Science John Grunsfeld during a visit to Brown. They then prepared and recently published their findings in a paper (Deutsch et al., 2018 Advances in Space Research). Despite decades of revolutionary Mars exploration and the desire to send humans to the surface of Mars in the 2030's, there are many strategic knowledge gaps regarding the moons of Mars, specifically regarding the origin and evolution of these bodies. While addressing such knowledge gaps is itself important, it can also be seen that Phobos and Deimos are well positioned to support martian surface operations as a staging point for future human exploration. The students present a science exploration architecture that seeks to address the role of Phobos and Deimos in the future exploration of Mars. They recognize these small moons are potentially valuable destinations, providing a wealth of science return, as well as telecommunications capabilities, resource utilization, radiation protection, transportation and operations infrastructure, and could have an influence on the path of the martian exploration program. They suggest a human mission to the moons of Mars would maintain programmatic focus and public support, while serving as a catalyst for a later successful human mission to the surface of Mars. When this paper completed the review process, it was specially flagged by Elsevier's social media campaign, and made available open-access for three months.

1.4.2 Space Horizons 2017 [Young Scientist led]

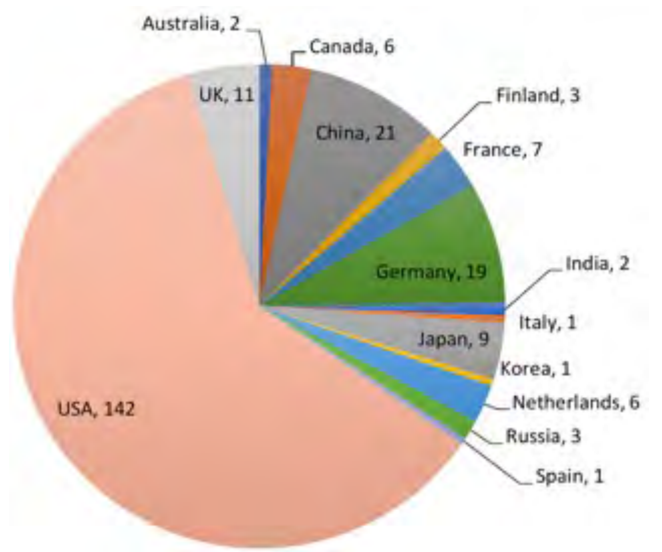
SEEED has worked with our colleagues in the Brown School of Engineering as a SSERVI co-sponsor of Space Horizons. This is an exciting student-led annual workshop that looks at intriguing ideas that capture the imagination within the space and exploration fields. The students ask "if this is so cool, why isn't it happening?"

Previous workshops targeted chipsats, chipsat launch vehicles, clouds of satellites, safe cubesat propulsion, infrastructure, McMurdo Base on the Moon, and the International Lunar City. They ask 'why don't we have those things?' Working with a core of experts and surrounded by professionals, the students put the future under a microscope and for one day try to understand how to make it happen. In 2017 they looked at "a dream humans have dreamed probably since we have dreamed–flying to a star," or more specifically, exploring the engineering and micro-technology challenges that need to be solved for VERY long space flights. Alpha Centauri, became the 2017 focus since Stephen Hawking suggested that traveling the 4 light year distance with a 1 gram satellite on a chip accelerated by photon propulsion and achieving 20% the speed of light could get to our nearest stellar neighbors in just 20 years. It was an invigorating discussion!

2 SEEED Community Involvement and Inter-team and International Collaborations

2.1 Micro 58: the Woodlands, Houston, March 18-19

Our SEEED-SSERVI sponsored 2017 Microsymposium focused on Surface Exploration and Sample Return: A New Era in Planetary Sciences and stimulated excellent discussions of the importance of sample science and multinational plans for the future. It attracted 234 attendees, more than 1/3 of whom were international participants from 15 countries. The full program of topics,



discussion leaders, and speakers can be found at:

http://www.planetary.brown.edu/html_pages/micro58program.htm

2.2 SEEED-CLSE Virtual Lunar Seminar Course

An academic course on the origin and evolution of the Moon is being jointly prepared to be held Fall 2018 (Mondays, 3 PM EST). The course will consist of 15 weekly lectures and discussion by experts in the field. It is structured similar to http://www.planetary.brown.edu/planetary/geo287/PhobosDeimos/, and will provide recommended readings, be accessible remotely in real time, and be recorded. Recognizing the call from the current administration for a return to the Moon, our intent is to provide the next generation of planetary scientists and engineers a scientific understanding of the Moon while also introducing the breadth and excitement of current lunar science issues.

2.3 New Views of the Moon 2 [cross-team; international]

SEEED members participate in several chapters of this important new book [now international; expected completion in 2018] discussing important results and discoveries about the Moon since 2006 when New Views of the Moon was originally published. SEEED Co-Is are responsible for leading three important chapters: Volcanic Features and Processes, Lunar Magnetism, and Evolution of the Lunar Crust.

2.4 60th Sputnik Anniversary and 8M-S3 [International]

2017 marked the 60th anniversary of the launch of Sputnik, and international symposia were held in Moscow and St. Petersburg in celebration of the space age that it opened, to reflect on accomplishments, and to discuss international plans for the future. Continuing a decades-long scientist-to-scientist collaboration, SEEED PI, Deputy PI, and students participated in the Moscow Sputnik celebration, the associated St. Petersburg symposium, and the 8th Moscow Solar System Symposium (8M-S3). Links to the program, activities, and abstracts can be found at: http://www.iki.rssi.ru/conf/2017/oct4_e.htm and https://ms2017.cosmos.ru/

Full scale Lunokhod rover

2.5 International Meetings and Publications in 2017

SEEED investigators actively participated in several additional international conferences and workshops: European Lunar Symposium, Münster, Germany (May); Goldschmidt Origin ...of Volatiles, Paris (August); International Forum on Lunar and Deep Space Exploration, Beijing (September); Astrobiology-2017, Chile (November). Of 39 SEEED peer-reviewed publications in 2017, 16 were co-authored with international colleagues.

2.6 Santa Fe Impact structure [Cross-team]

A field trip to the Santa Fe impact structure was led by SSERVI team members from Australia [Aaron Cavosie, Curtin Univ.] and TREX [Shawn Wright, PSI] in July. The impact crater itself is long gone (age is > billion years), but exquisite shatter cones in resistant granite remain and document the event.

3 SEEED Public Engagement Highlights

3.1. Leadership Alliance Summer Research: Early Identification Program

Graduate Student Erica Jawin worked with the Leadership Alliance Summer Research-Early Identification Program as a mentor for traditionally underrepresented students, focusing on principles underlying the conduct of research in STEM.

3.2 Association for Women Geoscientists

Graduate Student Erica Jawin was elected to the Board of Association for Women Geoscientists (AWG) for a three-year term. AWG is a professional organization which promotes the professional development of its members, provides geoscience outreach to girls, and encourages women to become geoscientists.

3.3 SEEED/CLASS Education and Public Engagement Team activities:

Continued productive ongoing work on 1) infusing arts into traditional science, technology, engineering and mathematics lessons (STEAM); 2) integrating formal, informal and out-of-school experiences to foster content retention; and 3) broadening audience reach to include ALL learners, especially those with disabilities. Highlights include:

• Publishing and distributing nearly 4,000 copies of Getting a Feel for Eclipses to Schools for the Blind, state and local libraries and the Library of Congress. Requests for the book continue.

• Finalizing a new tactile book, Small Worlds in the Solar System is in layout, ready to go to press.

• Field testing and editing The World Ender, a middle school curriculum focusing on asteroids, meteorites and small bodies in our Solar System.

• Hosting and/or co-hosting more than 10 workshops across the country to share SSERVI content. Example locations include California, Florida and North Dakota and South Carolina Schools for the Blind, SC State Parks, 3 National Monuments, Roper Mountain Science Center and more.

4 SEEED Student / Early Career Participation

Graduate Students

1. Cannon, Kevin*, Brown University, now at CLASS; Thesis: Nature and Evolution of the Martian Crust and Regolith: New Insights from Meteorites, Experiments and Remote Sensing (PhD 2017). Earned 2017 Dwornik award for best Oral presentation Honorable Mention.

2. Cassanelli, James, Brown University; Analyzing the nature of impact melt seas in lunar basins and their cooling properties to assess the vigor of convection and the probability of the melt seas undergoing differentiation.

3. Caswell, Tess, Brown University; Evaluating the physical and rheological properties of ices in the Solar System. Earned 2017 Dwornik award for best Poster presentation.

4. Daly, Terik, Brown University, now at APL; Thesis: Preserving Projectiles During Impacts on Asteroids and Planets (PhD 2017). Earned 2017 Dwornik award for best Oral presentation.

5. Deutsch, Ariel*^, Brown University; Assessing the nature of polar and circumpolar ice deposits on the Moon and Mercury.

6. Hahn, Tim, University of Tennessee, now at Washington University; Evaluated constraints of HED meteorites on magma ocean evolution.

7. Jawin, Erica*^, Brown University; Examining lunar pyroclastic deposits in the Aristrachus and Prinz regions and documenting one of the largest volcanic complexes on the Moon, Cobra Head and Schroeter's Valley. 1st place winner for ESF posters; Received travel award for LEAG meeting.

8. Kaplan, Hannah, Brown University; Performing detailed analyses of the spectral signature of organic bearing materials [associated with Astrobiology Institute]. Thesis: Reflectance Spectroscopy of Organic-Bearing Rocks with Applications to Laboratory and Spacecraft Data. Earned 2017 Dwornik award for best Poster presentation Honorable Mention.

9. Liu, Boda, Brown University; Developing a statistical method [Markov chain Monte Carlo, MCMC] for analysis of geochemical problems related to trace element fractionation during partial melting and magma crystallization.

10. McGraw, Lauren, University of Tennessee; Worked with the highly shocked Novosibrisk meteorite.

11. Roberts, Sarah, University of Tennessee; Analyzed the NWA 10986 meteorite from the lunar highlands.

Postdoctoral Fellows

12. Boukaré, Charles-Edouard, Brown University; Research with magma ocean models; aims to better understand the very early dynamics of planetary mantles.

13. Jean, M. M., University of Tennessee; Working with SNC meteorites and mantle processes.

14. Li, Shuai, Brown University, now at University of Hawaii; Thesis: "Water on the Lunar Surface as Seen by the Moon Mineralogy Mapper: Distribution, Abundance, and Origins."

15. Moriarty, Daniel, Brown University, now at Goddard; Thesis: "A Compositional Assessment of the Enormous South Pole-Aitken Basin Grounded in Laboratory Spectroscopy of Pyroxene-Bearing Materials."

16. Potter, Ross, Brown University, now working in UK; Modeling and evaluating the properties and effects of major lunar basins.

17. Robertson, Kevin, Brown University; Testing detailed models for characterizing mineral abundance from spectra of mineral mixtures.

18. Wang, Hua, MIT; Working with magnetics of meteorites and implications for evolution of the Solar System.

*SSERVI cross-team origins or links

^acted as productive and successful note-taker for major SSERVI workshops (Water; Lunar Landing Site)

5 SEEED Co-Is Separate Mission Involvement (Moon, asteroids, Phobos/Deimos) Over Last ~10 years

Mission	SEEED Investigator	Instrument/ Experiment	Role
Chandrayaan-1	Pieters, Carle	Moon Mineralogy Mapper	PI (Discovery M of O)
Chandrayaan-1	Head, Jim	Moon Mineralogy Mapper	Co-I
Chandrayaan-1	Mustard, Jack	Moon Mineralogy Mapper	Co-I

- Chandrayaan-1 Taylor, Larry Moon Mineralogy Mapper Co-I
- Chandrayaan-1 Runyon, Cass Moon Mineralogy Mapper Co-I
- Dawn Pieters, Carle Science Team Co-I
- Dawn Zuber, Maria Science Team Co-I
- Mars Express (Phobos) Head, Jim HRSC Co-I
- LCROSS Schultz, Peter Science Team Co-I
- Hayabusa 1 Hiroi, Takahiro spectral instruments Affiliate
- Kaguya Hiroi, Takahiro spectral instruments Affiliate
- Kaguya Pieters, Carle spectral instruments Visiting Scientist
- Lunar Reconnaissance Orbiter Zuber, Maria LOLA Co-I
- Lunar Reconnaissance Orbiter Head, Jim LOLA Co-I
- Lunar Reconnaissance Orbiter Donaldson Hanna, Kerri DIVINER Co-I
- MESSENGER Head, Jim Science Team Co-I
- GRAIL Zuber, Maria Discovery Mission PI
- GRAIL Head, Jim Science Team Co-I
- GRAIL Johnson, Brandon Science Team Affiliate
- OSIRIS REx Binzel, Rick Science Team Co-I
- Hayabusa 2 Hiroi, Takahiro NIRS3 [JAXA invited] Team Member
- Hayabusa 2 Milliken, Ralph NIRS3 [JAXA invited] Team Member
- Psyche Elkins-Taunton, Lindy Discovery Mission PI
- Psyche Weiss, Ben Magnetometer Instrument PI
- Psyche Zuber, Maria Radio Science Instrument PI
- Psyche Binzel, Rick Asteroid Composition Co-I

Andy Rivkin

Johns Hopkins University/ Applied Physics Lab, Laurel, MD

Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES)

1 VORTICES Team Project Report

1.1 Regolith Development and Maturity

Regolith is the fragmental layer formed on the surfaces of most planets, and certainly on those that lack atmospheres (e.g., Moon, small bodies). It is the material of the regolith that is observed by remote sensing techniques which provides information on bedrock composition and history. It is also the material that interacts directly with space, being bombarded by solar and galactic radiation and the population of impact projectiles. In turn, the effects of the radiation and impact processes change the regolith and thereby influence the formation, transport and storage of volatiles on and across the surface. Perhaps the most frequently studied target is the Moon and how volatiles interact with its surface and how they are ultimately sequestered into the polar cold traps that are among the coldest locations in the Solar System.

1.1.1 Physical Processes

Regolith particles are initially formed by the mechanical comminution of rock. That comminution has classically been considered to be produced by impact. Large impacts (10s m to 100s km) excavate and shatter bedrock. Small impacts (10s μm to 10s mm) break those larger fragments down into fine-grained regolith. At some level, those small impacts weld individual particles together forming agglutinates. The observation that small bodies have regoliths, when some theoretical models suggest they shouldn't, precipitated a new idea of particle fragmentation mechanisms—thermal fatigue. Rocks on the surface of rotating body are diurnally heated and cooled causing stresses that can fracture a rock into small pieces. The magnitude of the thermal stress is a function of the diurnal time scale (minutes to months) and the temperature amplitude.

Simulations that provide accurate predictions of the outcome of a high-speed impact on small airless bodies must consider two regimes having drastically different timescales: the mechanical response (from a few microseconds up to some tens of seconds), and the gravity response (from hours to months). Hybrid numerical methods have been used to bridge these diverse timescales. The approach typically consists of a hydrocode coupled with an N-body code. K.T. Ramesh and C. El Mir have been examining the stresses induced by thermal cycling and how the inhomogeneous fabric of the rock influences the propagation and focusing of stress. A key aspect of the recent work has been to examine the size-frequency distribution of the particles produced by thermal fatigue.

In terms of ejecta distribution, they are conducting a series of simulations to examine the development of ejecta as a consequence of the impact of one asteroid into another. The model examines how the ejecta is redistributed and how the body reaccumulates. Initial results with their new approach, examining impact onto 25 km size asteroids in the main belt, show remarkable differences from conventional understanding of the consequences of such impacts. One feature of many of the classical particle-based asteroidal impact simulations was that essentially every particle became a fragment during large impacts, so that subsequent gravitational re-accumulation dominated the final fragment distribution. In the Ramesh group's simulations, in contrast, impacts produce a large, damaged but coherent core which then dominates the gravitational reaccumulation phase, and the final fragment distributions are thus quite different from those currently suggested by the literature. They have also begun to examine the effects of mechanical impact on regolith generation and evolution.

J. Plescia has been examining the size-frequency distribution of particles on the lunar surface to understand how it varies with target material (highlands v. mare) and how it changes with time. The current population of particles represents an integrated history of modification extending back billions of years. But the original target material (e.g., mare basalt) is not a massive homogenous body. Rather the original mare material is jointed and fractured and thus before any modification by impact and thermal fatigue, the target has a size-frequency distribution. Bedrock exposed in rille walls and rolling downslope provide insight into the size distribution before disaggregation begins. The complete particle size-frequency distribution of the regolith can be used to constrain models of impact fragmentation and thermal fatigue fragmentation.

1.1.2 Thermal Conditions

P. Hayne has continued examining regolith thermal properties and produced a thermal model used to simulate surface temperatures on the Moon and other bodies. That model is open source. He has also considered lateral temperature variations produced by small-scale shadows (i.e., those produced by rocks and topography). The results demonstrate that small shadows cover significant area (as a function of latitude and time of day) resulting in a more heterogeneous surface temperature regime than produced simply by long-wavelength topography and latitude.

C. Magri and E. Howell have continued to examine the influence of the shape and spatially variable physical properties of small bodies on the surface thermal environment by advancing the complexity of the SHERMAN thermal model. The model has been modified to include infrared beaming and a rigorous treatment of subsurface heat transport. Multiple ground-based thermal observations provide tight constraints on the sizes and physical characteristics of spatially varying thermal regions on small bodies. Modeling the thermal conditions using complex shape models and spatially variable physical properties leads to a significant improvement of our understanding of the regolith properties of small bodies. The inclusion of data from a variety of local times increases the precision of the analysis. Asteroids (8567) 1996 HW1, (162421) 2000 ET70 and 1627 Ivar exhibit thermal signatures indicative of complex, non-homogenous regolith covered surfaces.

B. Greenhagen continued to investigate the near-surface thermal gradients found in the lunar epiregolith (upper mm), collaborating with VORTICES Collaborator N. Bowles (Univ. Oxford) to make new lab measurements. After a period of inoperability due to a cooling system failure, the Simulated Lunar Environment Laboratory (SABEL) at APL has been brought back to full operational status. P. Prem joined the Diviner team at APL in 2017 and is developing a model that will help quantify the epiregolith thermal gradients produced in SABEL. Together, these new measurements and models provide the most complete picture to date of the thermal structure of the epiregolith. Ultimately, improved understanding of these physical properties will be applied to lunar and asteroid thermal models to improve interpretation of remote sensing datasets.

1.2 Regolith Volatile Interaction

In addition to physical bombardment, the regolith is bathed by galactic and solar radiation. That radiation damages and modifies the crystal structure of regolith grains. Radiation damaged grains have different volatile adsorptive and absorptive properties compared with undamaged grains. Understanding how radiation effects the grains is necessary to understand how the regolith acts as volatile reservoir and transport system.

C. Hibbitts has developed a laboratory capability to simulate space weathering by solar protons and understand how such weathering influences the regolith's transport properties. The UV-VIS-NIR-MIR spectra and hydration bands at 140 to 8000 nm can be examined as function of the irradiation of the sample by protons and deuterons (1-40 keV). Analysis is conducted under vacuum (10^{-8} to 10^{-10} torr) and the temperature (100K-650K) and flux can be varied to simulate different locations in the Solar System.

Proton bombardment of the regolith has been modeled by A. Kulchitsky along with D. Hurley. The DEM model examines the depth of penetration of solar wind particles into the lunar regolith using a combination of analytical, Monte-Carlo, and ray tracing techniques. The depth of penetration is found to be a function of void ratio, solar wind incidence angle, and regolith grain size. The model allows a prediction of how deep solar radiation influences the regolith. He and D. Hurley analyzed the depth that solar wind protons penetrate into the regolith inbetween grains and found the depth distribution can be fit with a gamma function, characterized by the void ratio and the grain size distribution; some protons find paths through the pore space to reach grains buried 4-5 grains below the surface, and the protons that reach the deeper grains are often clustered.

J. Cahill, B. Greenhagen and A. Hendrix are examining far UV to understand the extent of H_2O/OH hydration as a function of latitude. The analysis not only includes examination of the LAMP UV data, but also Diviner thermal data to derive surface and subsurface temperature.

T. Orlando and his group are reexamining the temperature programmed desorption (TPD) characteristics of lunar samples. They completed the construction and testing of a new TOD system allowing direct examination of the role of associative recombination (or recombinative desorption) of minerals containing hydroxyl (OH) sites in the production of water. A modeling effort on the diurnal variation of the 2.8 μm optical signature of "water" has been completed. The effort was a collaboration with the REVEALS team involving Co-Is Hibbitts and Dyar. The model demonstrates that the diurnal variation of water can be understood by taking into account the recombinative desorption (RD) of H2O from OH terminated metal-oxide surfaces such as those expected to be present within the regolith. The pre-factors and energetics of RD from anorthite and the JSC-1A regolith have been measured with VORTICES support. The results indicate that the activation energies are below 100 kJ/mol and are within the range which allows this second-order process to be important in controlling the terminal OH densities and hence the observable 2.8 μm feature reported in the observational data.

1.3 Surface and Subsurface Composition

The geologic and volatile history of a body is a function not only of the physical properties of its surface, but also the composition of the underlying bedrock. Volatiles are stored in the regolith over various time periods and to different depths. The composition of the regolith controls the volatile interaction processes. The volume of volatiles in the regolith is an integral aspect of the story. Compositional information is derived from analysis of visible to infrared reflectance and from neutron and gamma ray data.

R. Klima has been integrating her lunar water research, started through SSERVI, with a new research project funded by the LDAP program to explore several locations of potential mantle exposures on the lunar surface. One of the outstanding questions about apparent regional enhancements of OH is whether it is associated with specific lithologies, and, if so, if similar lithologies formed from different processes (e.g. pyroxenes and olivines from a melt sheet, igneous intrusions, or even mantle) show different OH signatures. Together with an undergraduate intern, Jordan Bretzfelder, Klima is mapping the bulk composition of deposits surrounding the Imbrium Basin, characterizing their mineralogy, likely depth of origin, and OH band strength using LROC, M^3 and Diviner data. The OH-related analysis will be conducted in the coming year, once new thermal models can be applied to the data. This has spurred potential inter-team work with the team at Open University to consider pyroxene as a reservoir for internal water in the Moon.

D. Lawrence, J. Wilson and J. Cahill have deconvolved neutron data to examine exposures of primitive flotation crust surrounding the Hertzprung Basin. Similar analysis was conducted for the Compton-Belkovich region. Analysis of the Orientale Basin and its unique epithermal neutron signature is being examined in the context of S-band circularly polarized radar. Lunar Prospector (LP) bulk hydrogen content for a number of craters correlates with the radar signature; low H corresponds to areas of high radar CPR. A possible explanation for this correlation is that areas having high CPR represent immature (high rock abundance) regions that have not had sufficient time to acquire a background of implanted H. Indications that H implantation is not a geologically instantaneous process is provided by the H content of returned lunar samples. J. Plescia has reviewed the Apollo H content data and noted that it shows that samples with surface exposure ages of millions of years (e.g., Shorty Crater) have little or no H (as measured in the laboratory).

An intrinsic limitation of orbital gamma ray and neutron data is that the spatial resolution is of the same scale as the orbit height. This results in compositional pixels that are often much larger than individual geologic features, resulting in a blurry understanding of the relationship between surface geology and composition. J. Wilson has carried out a comprehensive analysis of LP neutron and gamma-ray data using the Pixon reconstruction technique to enhance the ability to correlate specific geologic features with neutron and gamma-ray derived composition.

J. Cahill and D. Blewett are collaborating on a study to measure the optical constants of unoxidized vs. oxidized Fe and Ni materials in the far-ultraviolet (160 nm) to the NIR (4100 nm) portions of the spectra. This was supplemented with modeling and analysis of mineral assemblages with a range of submicroscopic Fe and Ni abundances and particle size.

A. Rivkin has examined the NEO population that exhibits hydrated mineralogy in reflectance spectra to understand their potential for resource exploitation. A key aspect of the potential for resource exploitation is the energy required to reach the object, and thus he has examined the ΔV requirements to reach various hydrated asteroids compared with the Moon, to better characterize the efficiency of in-situ resource utilization. Initial results suggest that hundreds of hydrated objects over 100 m diameter may be present in the near-Earth population and have easier round-trip access than the surface of the Moon.

A. Rivkin and R. Klima have also been working with M. Horanyi and J. Szalay of the IMPACT team and B. Cohen of the FINESSE team in order to model the size-frequency distribution and density of particles in dust clouds generated by micrometeorite impacts onto inner- and main-belt asteroids. A related investigation looks into understanding the minimum amount of dust samples that are necessary to accurately and correctly extract the overall bulk composition of an object.

M. Dyar has been working with a graduate student at the University of Massachusetts studying machine learning approaches to asteroid taxonomy. Initial results suggest that such approaches may provide more robust results than current techniques which focus on principal component analysis. Dyar plans to continue this work with additional students and with increased involvement from Rivkin in an asteroid advisory role.

1.4 Synthesis

The research conducted by individual members of the team provides insight and understanding of a range of topics related to volatiles and regolith on the Moon and small bodies. However, by its nature such work is focused on a small area. A more important aspect of the research is an integration of a body of related research to better understand the complete scope of the problem. To this end, several members of the VORTICES team are leads on the New Views of the Moon 2 book: D. Hurley and M. Siegler are co-leads for the “Surface Volatiles” chapter, P. Spudis is a co-lead for the “Development of the Moon and Cislunar Space” chapter and J. Plescia is one of the co-leads for the “Surface Processes” chapter. Many members of the VORTICES team are also major contributors to the individual chapters.

2 VORTICES Inter-team/International Collaborations

A. Rivkin has been working with F. DeMeo at MIT on the characteristics of the NEO population. He and others have been working with Z. Landsman and P. Metzger of the CLASS team.

C. Hibbitts, R. Klima, and A. Rivkin have been working with K. Stockstill-Cahill of the TREX team to make sure that when data is obtained in the Hibbitts Spectroscopy Laboratory for VORTICES projects (focusing on the infrared wavelengths) it is also obtained in the UV spectral region (of interest to many TREX projects). This will facilitate easy collaboration between teams on samples of mutual interest as well as make more efficient use of laboratory time.

K.T. Ramesh and C. El Mir has been working with Derek Richardson from the University of Maryland on using the pkgrav numerical model.

As mentioned above, B. Greenhangen is collaborating with P. Prem, who is funded in part through the DREAM2 team under D. Hurley, a VORTICES and DREAM2 Co-I. The SSERVI team and DREAM2 team continue to have additional collaborations, most notably involving D. Hurley and P. Hayne.

Dyar is a Co-I on the RIS^{4}E team as well as the VORTICES team, and the machine learning asteroid taxonomy work reported above is an offshoot of a larger project addressing spectral modeling with machine learning approaches that is supported by RIS^{4}E.

There are several collaborations between VORTICES and the CAN 2 teams: Co-I Orlando is the PI of the REVEALS team, which has Hibbits as a Collaborator and Rivkin as a member of the advisory board. Rivkin, Klima, and Hibbitts are Collaborators on the ESPRESSO team. Stockstill-Cahill of the TREX team is located at APL and has been using the spectroscopy lab of Hibbitts, with several collaborative projects underway.

As mentioned above, Rivkin and Klima have been working with Horanyi, Szalay, and Cohen on understanding the dust population around main-belt and near-Earth asteroids. This involves members of the VORTICES, IMPACT, and FINESSE teams.

Rivkin presented at the SSERVI/ASI Workshop at the Italian Embassy in Washington DC.

Hibbitts presented two invited talks at the Korea Aerospace Research Institute (KARI) and the Korea Astronomy and Space Science Institute (KASI) focused largely on water on the Moon. He also gave an informal lecture at Kyong Hee University on the same subject.

3. VORTICES Public Engagement

Student engagement activities included an event with the Magic Planet at Old Mills Middle School in Millersville, MD. About 200 students were taken on a tour of the Solar System, with science and exploration themes being discussed. For another student engagement activity in the summer, about 50 students participating in the Maryland Summer Center for Gifted and Talented Students Space Camp at the Applied Physics Laboratory saw a Magic Planet presentation. During this presentation, students learned about planetary mission planning, how scientists and engineers work together to determine Solar System exploration science questions, as well as how they build mission spacecraft to explore and answer those questions.
VORTICES also held its 2nd Solar System Exploration Institute with students from Howard University and minority-serving institutions in Texas. SSERVI research scientists gave presentations, and there was also a tour of Johnson Space Center. This institute also gave these students the opportunity to use what they had learned about Solar System science to engage the public with various activities and hands-on demonstrations (pictured below left). Stipends to attend the institute were provided by VORTICES, the D.C. Space Grant Consortium, and the Texas Space Grant Consortium.

For public engagement, the VORTICES team organized an International Observe the Moon Night (InOMN) event at the Maryland Science Center on October 27. Over 50 participants, including families and out-of-town tourists, were engaged with lunar science and exploration. There were hands-on lunar science activities and the Magic Planet was displaying lunar data such as Mini-RF data and M^3 data. Science posters on the formation of the Moon and future lunar exploration were on display, as well as Moon maps provided by SSERVI Central. These posters aided in generating discussions between VORTICES scientists and InOMN participants. Three VORTICES scientists supported the event and we also partnered with a scientist from the TREX team (K. Stockstill-Cahill), bringing the number of SSERVI scientists supporting the event to four.

The eclipse glasses sent to VORTICES by SSERVI Central were all distributed by team members, with members of the public putting them to use across North America.

They were particularly pleased to be able to use glasses with an official NASA imprimatur, given that some faulty glasses had been distributed by others in the weeks leading up to the eclipse.

4 Student/Early Career Participation

Undergraduate Students

1. Jordan Bretzfelder, University of Southern California, Spectroscopy

Graduate Students

2. Charles El Mir, Johns Hopkins University, thermal fatigue and gravitational reaccumulation

3. Jenna Crowell, University of Central Florida, thermal and shape modeling of NEOs

4. Parker Crandall, University of Hawaii

5. Francisco Garcia, University of Massachusetts, Amherst

Postdoctoral Fellows

6. Jack Wilson, APL, neutron spectroscopy

New Faculty Members

7. K. Hazeli now faculty at University of Alabama in Huntsville

8. H. Kaluna now faculty at University of Hawaii in Hilo

5 Mission Involvement

1. LRO / LROC, J. Plescia, Co-I, geology

2. LRO/Mini-RF, L. Carter, Participating Scientist

3. LRO/Mini-RF, B. Bussey, PI

4. LRO/Mini-RF, P. Spudis, Co-I

5. LRO/Mini-RF, A. Matiella Novak, Co-I

6. LRO/Mini-RF, J. Gillis-Davis, Co-I

7. LRO/LAMP and Mini-RF, J. Cahill, Participating Scientist and Co-I

8. LRO/LAMP, D. Hurley, Co-I

9. LRO/Diviner, B. Greenhagen, Deputy PI

10. LRO/Diviner, P. Hayne, Co-I

11. LRO/Diviner, M. Siegler, Co-I

12. LRO/Mini-RF and LAMP, A. Stickle, Science Team Member

13. DART, A. Rivkin, Investigation Team Co-Lead

14. DART, A. Stickle, Co-I

15. MRO/CRISM, A. Matiella Novak, Team Member

16. LADEE/NMS, D. Hurley, guest investigator

17. Dawn/FC, A. Rivkin, Associate Team Member

18. Dawn/GRaND, D. Lawrence, Participating Scientist

19. MESSENGER/GRNS, D. Lawrence, Instrument Scientist and Participating Scientist

20. MESSENGER/GRNS, R. Vervack, Participating Scientist

21. MESSENGER/MASCS, R. Klima, Team member

22. OSIRIS-REx, E. Howell, Spectroscopy Collaborator

23. MGS/MAG-ER, D. Hurley, Associated Scientist

24. Europa Clipper, R. Klima, Project Staff Scientist

25. New Horizons/LORRI, A. Rivkin, Team member

26. Rosetta/Alice, R. Vervack, Team member

27. Psyche/GRNS, D. Lawrence, Instrument PI

28. MMX/MEGANE, D. Lawrence, Instrument PI

29. NEA Scout, A. Rivkin, Co-I

30. Lunar Flashlight, B. Greenhagen, Co-I

31. Lunar Flashlight, P. Hayne, Co-I

In addition to this, several VORTICES members have been involved in PSDS3 studies, notably Plescia who is PI of the APEX study and Hibbitts who leads Lunar WATER, with Klima and Plescia also members of the team. Rivkin is a Collaborator on the Chariot PSDS3 study, and Rivkin and Hurley are Co-Is on the PRISM study.

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

1.1 Development of the Airborne Space Environment Chamber

Project ESPRESSO is developing a large (approximately 1200 liter) vacuum chamber that will be integrated inside a reduced gravity aircraft. This Airborne Space Environment Chamber (ASEC) will provide access to the gravity and pressure environments analogous to those on the surfaces of asteroids and the Moon, enabling large-scale tests of regolith processes and regolith/hardware interactions in a truly relevant environment. In 2017, the ASEC team completed preliminary design of the ASEC chamber and associated mechanical simulations to assess structural loads on the chamber frame and aircraft floor rails. Given the baseline design of the chamber, PI Alex Parker traveled to the Canadian NRC-CNRC Flight Research Laboratory to conduct a fit check of a volume- and mass-simulant mockup of the ASEC chamber on board their Falcon 20 reduced gravity research aircraft (**Figure 1**). The mockup chamber segments were moved into the aircraft cabin and fitted successfully. Detailed chamber design is now in progress, with chamber fabrication expected in the first half of 2018.

Throughout 2017, Project ESPRESSO team members interacted with investigators interested in low-cost access to a robust chamber that provides a space-like gravity

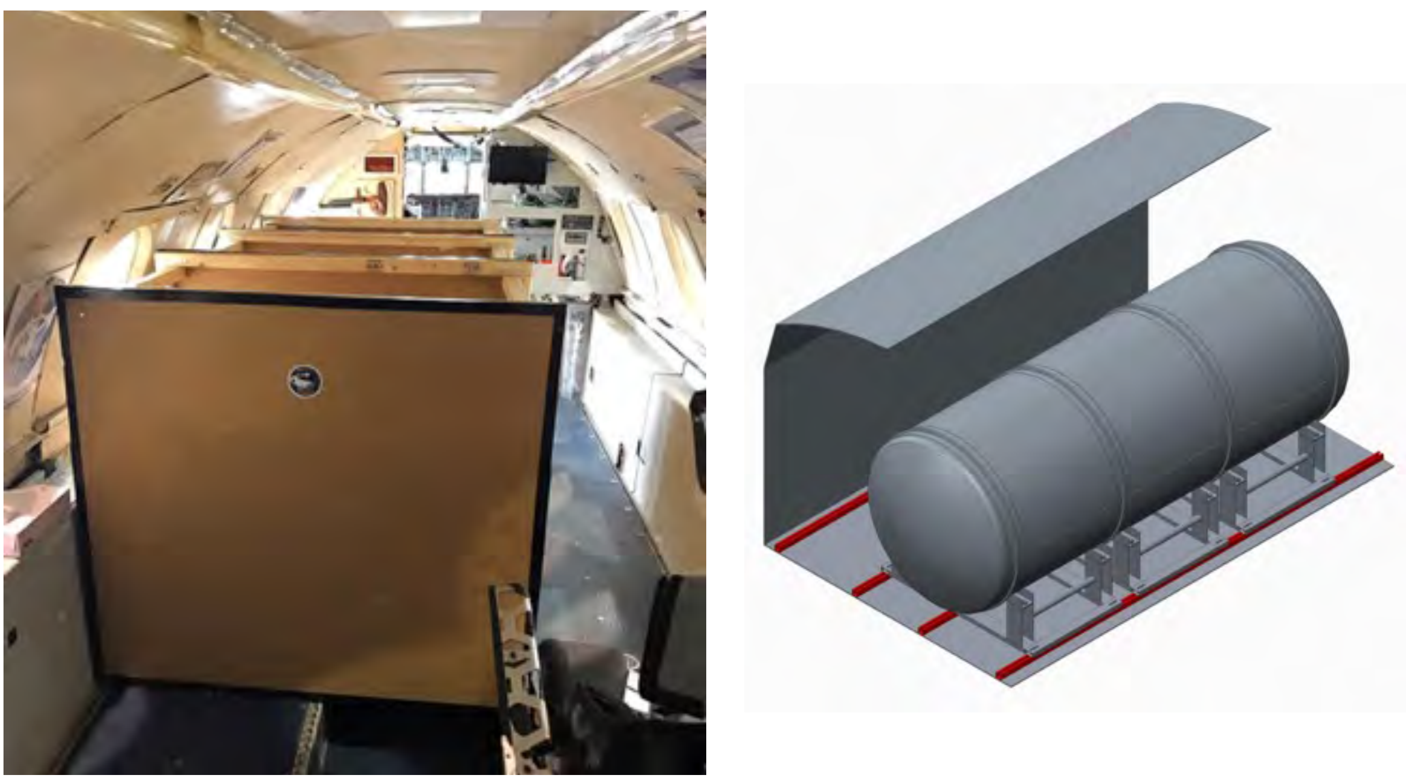


Fig. 1: (left) ASEC chamber mock-up in the cabin of the NRC-CNRC Falcon 20 reduced gravity research aircraft during an October fit check. (right) Preliminary design of the segmented ASEC chamber, enabling installation of a very large chamber volume in a small aircraft.

Preliminary design and mechanical analysis of the Airborne Space Environment Chamber is complete, and culminated with a successful fit check aboard the NRC-CNRC Falcon 20 reduced gravity research aircraft.

and pressure environment for scientific or engineering experiments. Feedback from these discussions have further informed our baseline chamber design, and we are encouraged by the strong response of community members who have expressed an interest in flying their experiments aboard the ASEC.

1.2 Development and Testing of the Grain Velocimetry and Tomography Analysis System

The Grain Velocimetry and Tomography Analysis System (GraVeTAS) is a key component in Project ESPRESSO's planned investigations of the dynamics of impact ejecta on the surfaces of asteroids and the Moon. GraVeTAS uses multiple beams of laser light of unique wavelengths, each encoded with interference fringes, to illuminate particles passing through its aperture. The light scattered by these particles is collected by an array of high speed photodiodes, each filtered for detecting a single laser's

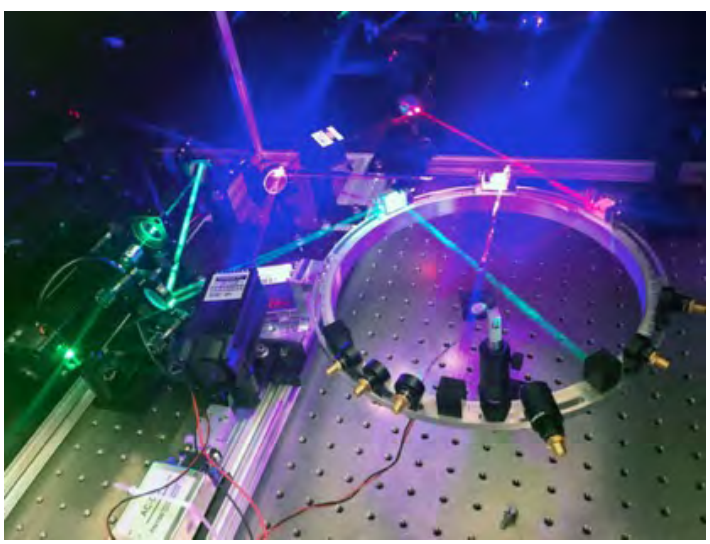


Fig. 2: First illumination of GraVeTAS aperture in full three beam mode. Each beam is encoded with an orthogonal array of fringes generated by novel miniaturized laser interferometers.

wavelength. Using Fourier reconstruction techniques, the 3D shape and trajectory of grains passing through the aperture can be reconstructed from the time series recorded by these detectors, even at extremely high velocities and for micron-scale grains. In 2017, Co-I Keith Nowicki fabricated the first prototype of GraVeTAS (**Figure 2**), and testing of the prototype is underway at SwRI using calibrated grains of silicon carbide. The GraVeTAS team is on track to demonstrate the first simultaneous reconstruction of the 3D shapes and dynamics of microscopic particles in free flight in early 2018.

GraVeTAS is on track to demonstrate the first simultaneous measurement of the 3D shapes and trajectories of free-flying microscopic particles in early 2018.

1.3 Setup of Optical Constants Measurement Facility

The primary laboratory facility for the measurement of optical constants of materials relevant to the surfaces of asteroids and the Moon is a newly-installed Bruker Vertex 70v FTIR spectrophotometer, located in Co-I Sarah Hörst's laboratory at Johns Hopkins University. Calibration and fine-tuning of detector configurations is underway to enable measurement of full optical constants (real and imaginary indices of refraction n and k) across a broad range of visible and IR wavelengths commensurate with current and near term observational capabilities (including full overlap with JWST's spectroscopic capabilities). "First light" reflectance spectra of two samples is illustrated in **Figure 3.** Full measurement of optical constants will commence upon completion of calibration and detector setup in early 2018.

1.4 Development, Fabrication, and Testing of Miniaturized Impact Probes

Developing the means to reliably estimate the mechanical properties of a surface before committing an astronaut or spacecraft to interacting with it is a key goal of Project

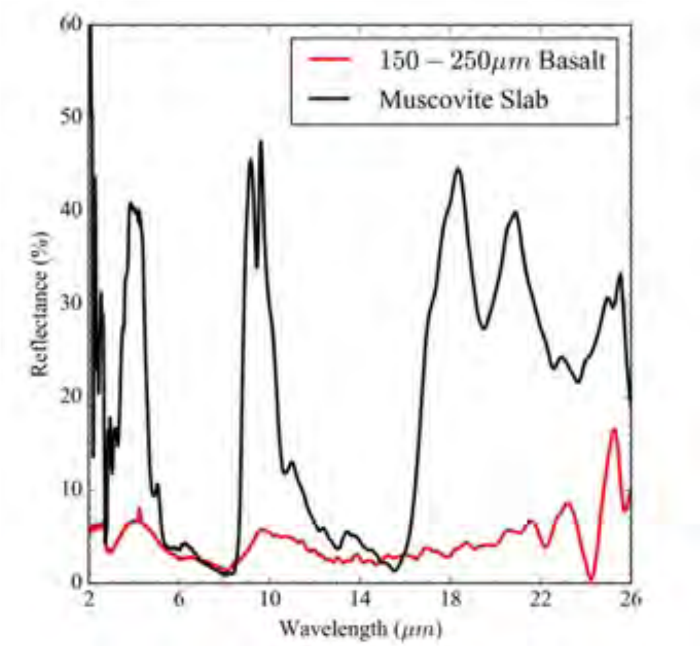


Fig. 3: “First light” reflectance spectra of two samples from new JHU optical constants facility.

ESPRESSO. In 2017, Co-Is Kevin Walsh and Dan Durda designed, fabricated, and began testing a 3D-printed prototype miniature impact probe instrumented with a multiple high-speed, high-g inertial motion unit (IMU) to record the profile of an impact into a target surface in high fidelity. The team is developing a procedure set for synchronizing IMUs within the impactor and across many tens of subsequent drops, as well as for pipelining the data that they produce for subsequent analysis. By comparing the impact acceleration traces returned by these IMUs to predictions from theory and to computational models, estimates of surface mechanical properties can be made. Dr. Walsh conducted a large suite of pkdgrav simulations of impacts into granular media in 1g for calibration and comparison to literature drop tests. In these numerical simulations, Dr. Walsh has been able to reproduce a suite of canonical experimental results of the interaction of low velocity impacts into granular media, and is now proceeding with modeling the suite of granular media that will be used in Project ESPRESSO’s planned 2018 impact tests and the prototype impactors.

1.5 Preparation for LIBS and Raman Field Campaigns

Co-I Kevin Lewis conducted preliminary tests of the handheld Laser Induced Breakdown Spectroscopy (LIBS) device that our team will be using in future field investigations of the exploration role of handheld laser-activated spectroscopy devices, including LIBS and Raman. Given the positive outcome of these tests, orders have been placed for SciAps Z300 and Inspector 300 hand-held LIBS and Raman devices as part of the SwRI institutional contribution to Project ESPRESSO. Preparations for instrument calibration have been made, including expanding the suite of geochemical standards available at JHU, and planning for the first field deployments (spring of 2018) exploring the roles of these devices for geochemical mapping of lunar terrain analogues is underway.

2 Inter-team/International Collaborations

2.1 Inter-team Collaborations

Co-I Alejandro Soto has begun working with Debra Needham and David Kring from the Center for Lunar Science and Exploration SSERVI team. Needham and Kring have previously published work showing that volcanism likely created a transient atmosphere on the Moon [1]. Dr. Soto, an expert in the dynamics of transient atmospheres, is building on this previous work by investigating the climate conditions that may have resulted from the outgassing identified by Needham and Kring (2017). Dr. Soto plans to use an idealized general circulation model (GCM) to simulate the 1 kPa lunar atmosphere predicted by Needham and Kring (2017). This will allow him to simulate the large-scale circulation of this ancient lunar atmosphere. Ultimately, Dr. Soto will work with Needham, Kring, and other SSERVI scientists to investigate the poleward transport of volatiles for these transient lunar atmospheres. The goal is to derive parameterizations of the poleward transport of volatiles that will allow the simulation of a possible evolution of volatile distribution under a lunar atmosphere. This effort will allow Project ESPRESSO’s instrumentation teams to ensure that their methodologies will enable future mapping and characterization of volatiles emplaced under this and other scenarios.

Co-Is Kevin Walsh and Dan Durda have interacted with team members of the Center for Lunar and Asteroid Surface Science (CLASS) SSERVI node in developing our instrumented impactors and preparing for regolith impact experiments at both CLASS's and Project ESPRESSO's facilities.

Co-I Kevin Lewis joined members of RIS^{4}E on a field deployment to get familiarized with team field strategies and to identify how to best complement existing efforts in future joint field deployments. Future Project ESPRESSO field efforts will welcome participation of members of other SSERVI teams in much the same manner.

2.2 International Collaborations

During the Airborne Space Environment Chamber / Falcon 20 aircraft fit check in October of 2017, PI Alex Parker met with staff of the Canadian NRC-CNRC Flight Research Laboratory (FRL) to develop a strategy for operating the chamber in the coming years. Substantial enthusiasm was generated by the chamber concept and the investigations and experiments it would enable, as well as the overall mission of SSERVI and Project ESPRESSO. Going forward, we will seek to build a strong relationship with the NRC-CNRC FRL to enable responsive access to the ASEC facility, and to explore means of engaging student groups in the United States and Canada in future ASEC flights.

In 2017, Co-I Mika McKinnon has engaged with our collaborators at the University of British Columbia, Canada. Their group has an unparalleled knowledgebase related to the development and application of landslide modeling tools and hazard analysis. UBC summer students will be recruited for term projects related to landslide hazard modeling on low-g, airless bodies.

3 Public Engagement

In 2017, Project ESPRESSO launched a public website and Twitter account for disseminating information about the team's progress and information about opportunities for public and student engagement. The team website is hosted at https://www.espresso.institute, and the team's Twitter handle is @ESPRESSO_SSERVI.

Project ESPRESSO team members have been involved in a variety of public outreach and education events in 2017. Co-I Mika McKinnon delivered several invited public talks about the goals of Project ESPRESSO at Dragon Con (Atlanta, GO) and Skepticon (Springfield, MO); she also delivered three high school science classes in Vancouver, BC on the theme of "What do we need to know before we can mine asteroids?" PI Parker and Co-I Soto jointly delivered an invited session at Denver's MileHiCon, a meeting of science fiction authors, on Project ESPRESSO and the near-future of human space exploration.

4 Student / Early Career Participation

1. Dr. Marcella Yant, JHU, Laboratory Measurement of Optical Constants.

a. Dr. Yant (PhD 2017) has joined the Project ESPRESSO team at Johns Hopkins University to lead laboratory efforts to measure the UV, Optical, and NIR optical constants of materials relevant to the surface of the Moon and asteroids. Additionally, she will be working with our BLASTERLab field campaigns to explore the roles of astronaut-operated handheld Raman and LIBS devices for informing sample selection and handling procedures on the surface of the Moon. Dr. Yant recently received her PhD from Stony Brook University, where she was involved in the RIS^{4}E team.

2. Dr. Silvia Protopapa, SwRI, Infrared Spectroscopy and Laboratory Measurement of Optical Constants.

a. Dr. Protopapa (PhD 2009) was hired to SwRI into the position of Principal Scientist, where she will work closely with the SwRI team on measuring optical constants of key Solar System processes.

3. Dr. Alex Parker, SwRI, Project ESPRESSO PI.

a. Dr. Parker (PhD 2011) was promoted to a permanent position at SwRI with the position of Senior Research Scientist after the selection of Project ESPRESSO.

5 Mission Involvement

1. New Horizons, Alex Parker, Co-Investigator

2. New Horizons, Silvia Protopapa, Co-Investigator

3. New Horizons, Will Grundy, Co-Investigator

4. New Horizons, Kelsi Singer, Co-Investigator

5. OSIRIS-REx, Kevin Walsh, Co-Investigator, Regolith Development Working Group lead

6. OSIRIS-REx, Jamie Molaro, Participating Scientist

7. Curiosity/Mars Science Laboratory, Kevin Lewis, Participating Scientist

8. OSIRIS-REx, Cristina Thomas, Collaborator

9. Dragonfly (New Frontiers 4, Phase A), Sarah Hörst, 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 Extrasolar Space Weather

Efforts on the extrasolar weather key project were executed largely on two fronts by Co-I Hallinan and his group:

i) VLA observations of brown dwarfs were used to push radio observations of substellar objects to lower masses culminating in the detection of radio emission from an object of mass 12.7 ± 1 M_{Jup}, right at the boundary between planets and brown dwarfs. This object is now the benchmark object for understanding dynamos in the mass gap between planets and stars. These observations confirmed magnetic field strengths of 3000 Gauss on this same object, orders of magnitude larger than predicted by theory for an object of this age (200 Myr) and mass.

ii) Development continues of the OVRO-LWA, which serves as a pathfinder array for a future lunar farside experiment. This includes design development for the final stage of construction, anticipated to commence in late 2018, as well as early science with the current (Phase II) array. Early science involves monitoring observations of 4000 stellar systems in an effort to detect radio emission from both stellar Coronal Mass Ejections (CMEs) and exoplanets. Study of this sample will help identify key targets for continuous monitoring with a lunar farside array. Light curves are generated in Stokes I and Stokes V, under the assumption that substantial circular polarization will be present in the case of many stellar and planetary bursts. This effort includes substantial effort to develop the

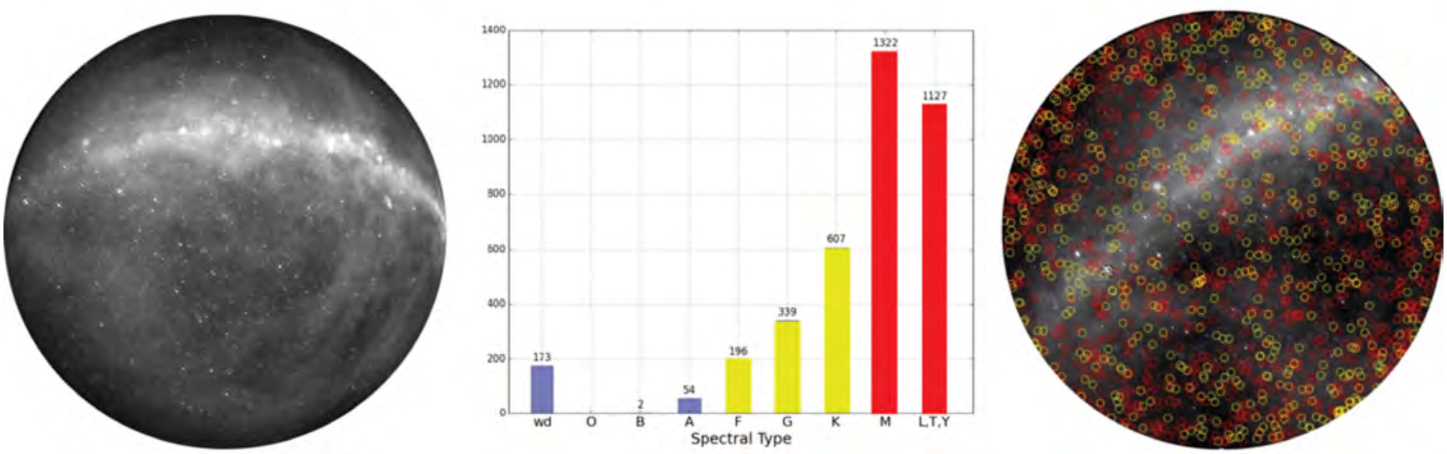


Figure 1: (Left) A single 13-second snapshot integration using 224 antennas in the LWA core and the 32 antennas of the long-baseline demonstrator array (LBDA) detects >10,000 discrete extragalactic sources. The completed 352-antenna OVRO-LWA will detect >50,000 sources in each snapshot image. (Center) The spectral type distribution of the ~4,000 known stellar/planetary systems within 25 pc. The OVRO-LWA will continuously monitor each of these systems while above the horizon, corresponding to ~2,000 systems at any one time, with particular focus on systems potentially suitable for habitability (highlighted in yellow and red). (Right) A 13-second snapshot integration highlighting the location of the F, G and K type dwarf stars (yellow) and the M, L, T and Y dwarfs (red) above the horizon. Flux measurements are made at each location in each integration. Prime systems for regular detectable space weather events will be identified for prioritization with a lunar farside array, alongside the existing planned sample of Alpha and Proxima Centauri. This research is from Co-I Hallinan and his group.

capability for automated detection of enhancements in the radio light curves of this sample, to enable near real-time detection of extrasolar space weather events.

1.2 Hydrogen Cosmology: Dark Ages, Cosmic Dawn and Epoch of Reionization

The 21-cm spin-flip line of neutral hydrogen provides a powerful method to study the currently unexplored end of the Dark Ages, Cosmic Dawn, and the beginning of the Epoch of Reionization. This signal from the early Universe is highly redshifted before it arrives to us as low-frequency radio waves. We plan to measure these signals from orbit above and on the surface of the lunar farside at night to avoid contamination from the Earth ionosphere, solar emissions, and human-generated radio frequency interferences.

1.2.1 Instrument Design and Data Analysis Pipeline Development

In the first half year of NESS, we have worked on the design of mission concepts for low-frequency radio antennas shielded by the Moon (Dark Ages Radio Explorer; Dark Ages Polarimeter PathfindER), and the development of the corresponding data analysis pipeline. In Burns et al. (2017), we showed how the sky-averaged 21-cm spectrum can be measured, and the astrophysical parameters of the first stars and black holes constrained, in the presence of large foregrounds. We illustrated the ability to distinguish between two relevant physical models, one with primordial Population II stars (richer in metals) and the other containing also Population III stars (metal-poor). Our results rely strongly on the pioneering use of the polarization induced by the anisotropic foregrounds when interacting with the large beams of our antennas as described in Nhan, Bradley & Burns (2017), which facilitates the separation from the isotropic and thus unpolarized 21-cm signal. In Tauscher, Rapetti, Burns & Switzer (2018), we fully implemented this technique into our analysis, confirming preliminary results. This paper also describes in detail the novel utilization of a pattern recognition algorithm in combination with information criteria, as well as rigorous statistical tests, to properly and efficiently extract the global 21-cm signal from systematics.

To experimentally demonstrate the validity of the induced polarization technique, which is to be employed later on in lunar orbit, Colorado graduate student Nhan, supervised by Co-I Bradley (NRAO) and Burns, deployed a prototype of the Cosmic Twilight Polarimeter. Observations were taken and a tentative detection of the periodic projection-induced polarization from the foreground spectrum was reported by Nhan et al. in a poster presented at the recent AAS meeting in Washington. For this presentation, Nhan was awarded an Honorable Mention Chambliss Prize.

1.2.2 Theoretical Predictions of the 21-cm Signal of Neutral Hydrogen

Another key component of this project is to provide theoretical descriptions of the 21-cm signal. One of the chief advantages of lunar or cis-lunar telescopes, relative to those on Earth, is their ability to explore the lowest radio frequencies, which correspond to the first luminous structures to form in the Universe. At UCLA, Co-I Furlanetto's group developed a theoretical framework for the formation and evolution of these early populations, which they submitted for publication in Fall 2017 (Mebane, Mirocha & Furlanetto, 2018). Their flexible, parameterized models allow efficient exploration of a wide range of physical prescriptions for this heretofore unobserved population. In Mirocha et al. 2018 (also submitted in the Fall), they further showed that these first generations of stars can exhibit unique signatures in the 21-cm background. Furlanetto's group is now exploring how these models impact spatial fluctuations in that background through semi-numeric and analytic models.

1.2.3 Trade Study of Low Radio Frequency Lunar Arrays

As part of the key project "Exploration Enables Astrophysics," Co-Is Bowman, MacDowall, and Hallinan commenced a trade study of a lunar array prototype. Astronomical observatories on the lunar surface and in cis-lunar space have the potential to be amongst the most sensitive probes of the early Universe and habitability on of Earth-like exoplanets. The requirements for these telescopes will push both technology boundaries and our knowledge of environmental effects at target destinations for human exploration. We initiated our efforts in Year 1 by investigating the compatibility of high-level science objectives across several astrophysical areas of study. We structured our investigation around the question "Can a single array perform Cosmic Dawn, heliophysics, and exoplanet science?" We found significant overlap in instrument requirements for angular resolution, spectral coverage, and sensitivity, particularly for the study of exoplanet habitability and 21-cm cosmology. Based on these findings, we initiated a trade study for a near-term pathfinder array able to achieve scientifically relevant advances in heliophysics, exoplanet space weather science, and demonstrate core technologies for a large array to target full-scale 21-cm science. By the end of the first six months of NESS, we completed a literature review of previous studies, collected relevant environmental information, and established a notional array for trade-off investigation and optimization.

1.3 Heliophysics

As part of the key Heliophysics and Space Physics project of NESS, we are working with the key Astrophysics project to design a lunar radio array pathfinder. The goal of this trade study is to develop a near-term pathfinder array that would address as many different scientific targets as possible. The ultimate goal of this effort is to develop hardware to be landed on the lunar surface by the commercial lander services that are now becoming available. For example, we have been in contact with the lander and rover provider Astrobotic Technology Inc., to determine how to take advantage of the services that they provide.

Co-I MacDowall at GSFC has submitted a proposal to the NASA Heliophysics Technology and Instrument Development for Science (H-TIDeS) opportunity. The primary goal of this proposal is to increase the Technical Readiness Level (TRL) of a low-frequency radio observatory intended for location on the lunar surface. The motivation for this observatory is that it will use multiple antennas and aperture synthesis to image solar and other radio bursts at frequencies below the terrestrial ionospheric cutoff (~10 MHz). To date, such bursts have only been observed below 10 MHz with one or more spacecraft, permitting triangulation of the source locations as a function of frequency, but without imaging capability. We demonstrate that imaging will provide additional information about the bursts that will clarify the physics of the emission process. Imaging the radio bursts will also provide data relating to the environments of near-Sun missions like the Parker Solar Probe and Solar Orbiter. The images will also improve the application of the radio events to space weather prediction by refining the effective trajectories of the radio emitters. The mission hardware design will also contribute to future lunar radio observatories focused on various astrophysical sources – cosmology, exoplanet magnetospheres, etc. Funding obtained from a successful H-TIDeS proposal will be leveraged with the funding and activities of the NESS team.

Co-I Kasper and graduate student Alex Hegedus mainly

Figure 2: Close up view of the student-built COTS rover at the University of Colorado Boulder. The forward facing stationary camera is mounted at the front and the top camera is mounted on two servos for manipulation. The various electronics controlling the rover are housed underneath the white and black protective shields. The painted rocks are exploration targets for this teleoperated rover.

worked on two tasks in support of the key Heliophysics and Space Physics Project: simulation of radio array performance on the lunar surface, and simulation of diffuse emission from energetic electrons in the Earth's radiation belts. Low frequency radio array simulation code developed by Hegedus was extended to accommodate antennas placed in fixed locations on the lunar surface. The code can accept maps of diffuse emission on the sky and then simulate the antenna response as the Moon rotates and moves around the Earth and Sun, and reconstruct the images. Maps of the surface of the Moon developed with Lunar Reconnaissance Orbiter (LRO) data were used to identify several representative locations for Sun observing lunar radio arrays, both near the equator and at the poles, and several simulated solar observations were generated. Initial results were presented at the NASA Exploration Science Forum last summer, and in the next year we look forward to using the code to help with the pathfinder trade studies.

1.4 Surface Telerobotics

NASA plans to construct the "Deep Space Gateway" (DSG) in cis-lunar space early in the next decade. The proximity to the lunar surface allows for direct communication between the DSG and surface assets, which enables low-latency telerobotic exploration. One constraint associated with low-latency surface telerobotics is the bandwidth available between the orbiting command station and the ground assets. The bandwidth available will vary during operation. As a result, it is critical to quantify the operational video conditions required for effective exploration. CU undergraduates B. Mellinkoff and M. Spydell, under the direction of PI Burns, designed an experiment to quantify the threshold frame rate required for effective exploration. The experiment simulated geological exploration via low-latency surface telerobotics using a modified commercial-off-the-shelf rover in a lunar analog environment. The results from this experiment indicate that humans should operate above a threshold frame rate of 5 frames per second. In a separate, but similar experiment, we introduced a 2.6 second delay in the video system. This delay recreated the latency conditions present when operating rovers on the lunar farside from an Earth-based command station. This time delay was compared to low-latency conditions for teleoperation at the DSG (≤0.4 seconds). The results from this experiment show a 150% increase in exploration time when the latency is increased to 2.6 seconds. This indicates that such a delay significantly complicates real-

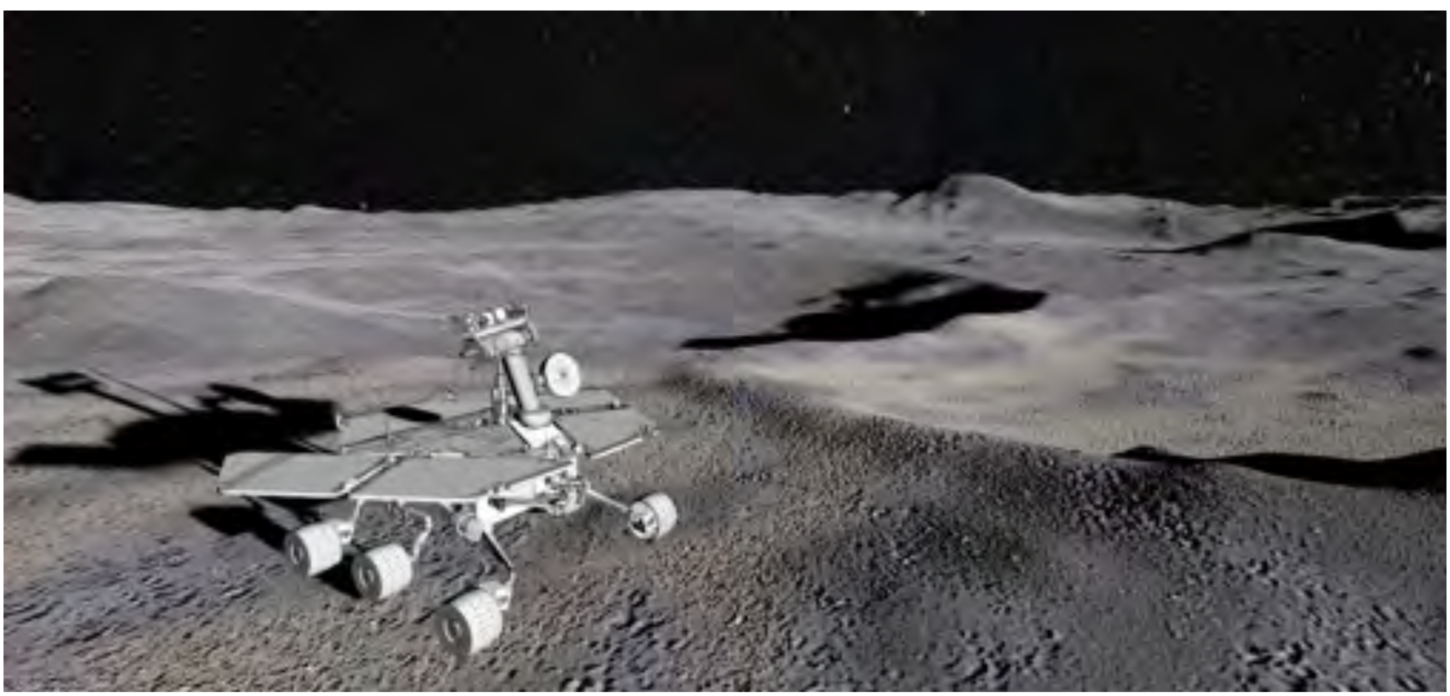


Figure 3: Virtual rover and lunar surface as seen from a virtual reality head-mounted display. This experimental framework allows for 3rd and 1st person rover teleoperation for user studies, user training, and rapid prototyping of user interfaces and rover designs — all without the need of physical hardware.

time exploration strategies. These results were reported as posters by Mellinkoff and by Spydell during the 2017 Exploration Science Forum and in a peer-reviewed IEEE Aerospace publication (Mellinkoff, Spydell, Bailey & Burns, 2018).

Collaborator D. Szafir, CU graduate student M. Walker, and Burns began to develop a virtual reality (VR) simulation testbed for prototyping lunar surface telerobotics. This experimental framework utilizes a VR head-mounted display to fully immerse users within a high-fidelity virtual lunar environment with realistic terrain and authentic rover design for real-time 3rd and 1st person teleoperation — all without the need of physical hardware. The simulation's robust physics and kinematics provide a platform for advancing algorithms that govern low-level robot autonomy and support interactive trade-offs between teleoperation and supervised control. This work has led to a new collaboration with Lockheed Martin to jointly explore the design of new interfaces that support ground control, and/or crew operation of surface robots from the Deep Space Gateway to significantly improve critical NASA lunar exploration missions. Recently, Co-I Fong provided a synthetically enhanced high-resolution lunar digital elevation model (DEM) that has been developed by NASA Ames for our NESS simulation, education, and public outreach activities. The DEM is based on publicly available images and laser altimetry of the Hermite A region that were acquired with the Lunar Reconnaissance Orbiter (LRO). The DEM covers a 1 km x 1 km area and includes artificial high-resolution detail (4 cm/pixel) including rocks and small craters.

References

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Nhan, Bradley & Burns (2017) ApJ, 836, 90

Tauscher, Rapetti, Burns & Switzer (2018), accepted in ApJ, arXiv:1711.03173

Mebane, Mirocha & Furlanetto (2018), submitted to MNRAS, arXiv:1710.02528

Mirocha et al. (2018), submitted to MNRAS, arXiv:1710.02530

Mellinkoff, Spydell, Bailey & Burns, 2018, in Proceedings of the IEEE Aerospace Conference, Big Sky, arXiv:1710.01254

2 Inter-team/International Collaborations

P.I. Burns and NESS Assistant Director Rapetti are developing an MOU with NESS International Collaborators Falcke and Klein-Wolt to work on adapting the 21-cm data analysis pipeline being developed at the University of Colorado (CU) Boulder to the Netherlands-China Low-Frequency Explorer (NCLE). The latter is a low-frequency radio antenna developed at Radboud University & ASTRON to be launched in the Chinese Chang'e 4 mission and orbit around the Earth-Moon L2 point in 2018. The plan is that the Dutch collaborators will supply the relevant instrument information to build training sets for the uncalibrated systematics of the beam and receiver as well as the expected characteristics of the data set to the CU Boulder team. Our team will then incorporate this input into the construction of an analysis pipeline for this instrument. For this purpose, the CU team will also perform simulations of the ability to separate systematics from the astrophysical foregrounds that in this case will be the signal to be studied. In addition, we will specifically work together on developing analysis tools to properly remove the relatively strong radio frequency interference from Earth that is expected in the L2 environment. Currently, these techniques are planned to be based on machine learning algorithms such as neural networks, in addition to using experimental design to benefit from the differences in behavior as a function of time between signal and systematics.

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 and European collaborators.

Co-I Fong visited CU Boulder in December 2017, met with students and researchers there, provided feedback on current research activities. He also participated in a collaborative meeting between CU and Lockheed Martin members as well as Fiske Planetarium staff and a filmmaker to plan the production of a Planetarium show for the return of human exploration of the Moon.

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.

3 Public Engagement

The event International Observe the Moon Night event was held at the Fiske Planetarium and Sommers-Bausch Observatory (SBO) on the CU Boulder campus. This 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 conducted the following activities throughout the evening: the planetarium show “Back to the Moon for Good” at Fiske, telescope observations of the Moon at SBO, and the show “Dark Side of the Moon Laser Floyd” at Fiske. Members of NESS including Monsalve, Mellinkoff and Rapetti contributed to these activities by attending answering questions from the public.

In December 2017, PI Burns was interviewed on ‘The Inquiry’ BBC radio program about space and lunar exploration in the episode titled How Do We Rule The Universe? On the same month, Burns was also interviewed about this theme by the American Institute of Aeronautics and Astronautics, in an interview that is towill be published in 2018.

4 Student/Early Career Participation

Undergraduate Students

- Benjamin, Mellinkoff, University of Colorado Boulder, Surface telerobotics - Instrumentation.
- Matthew, Spydell, University of Colorado Boulder, Surface telerobotics - Instrumentation.
- Alex Sandoval, University of Colorado Boulder, Surface telerobotics - Instrumentation.

Graduate Students

- Keith Tauscher, University of Colorado Boulder, Physics/Astrophysics, Cosmic Dawn – Theory / Data.
- Bang Nhan, University of Colorado Boulder, Astrophysics, Cosmic Dawn - Experiment.
- Richard Mebane, University of California Los Angeles, Astrophysics, Cosmic Dawn -Theory.
- Marin Anderson, California Institute of Technology, Astrophysics, Cosmic Dawn – Theory / Data.
- Alex Hegedus, University of Michigan, Astrophysics, Heliophysics.
- Janelle Holmes, University of Michigan, Astrophysics, Heliophysics.
- David Bordenave, University of Virginia, Astrophysics, Cosmic Dawn - Experiment.
- Nivedita Mahesh, Arizona State University, Astrophysics, Cosmic Dawn - Experiment.
- Michael Walker, University of Colorado Boulder, Surface telerobotics - Virtual Reality Telerobotics. simulations.

Postdoctoral Fellows

- Jordan Mirocha, University of California Los Angeles, Astrophysics, Cosmic Dawn - Theory.
- Raul Monsalve, University of Colorado Boulder, Astrophysics, Cosmic Dawn – Experiment / Data.
- David Rapetti, University of Colorado Boulder / NASA Ames Research Center, Astrophysics, Cosmic Dawn – Theory/Data.

Junior Faculty Members

- Daniel Szafir, University of Colorado Boulder, Surface Telerobotics - Virtual reality.

- Gregg Hallinan, California Institute of Technology, Astrophysics, Cosmic Dawn – Theory / Data / Experiment.

5 Mission Involvement

- Justin Kasper, active missions within last decade: Parker Solar Probe SWEAP PI, 2018 launch; Wind mission Faraday Cup lead, 1994 launch; DSCOVR mission Faraday Cup lead, 2015 launch; LRO Co-I CRATER Project Scientist, 2009 launch

- Justin Kasper, missions under development: SunRISE PI, in Phase A concept study; Europa Clipper Co-I, in development NET 2022 launch

- Robert MacDowall, active missions: RBSP magnetometer, Wind/WAVES, STEREO WAVES, Parker Solar Probe

- Sun Radio Interferometer Space Experiment (SunRISE), Justin Kasper (PI), Robert MacDowall, Alex Hegedus

- NASA Resource Prospector, Terry Fong (Deputy Rover Lead)

- Netherlands-China Low-Frequency Explorer (NCLE), Heino Falcke (PI), Mark Klein Wolt

- Deep Space Gateway (DSG, Lockheed Martin), Scott Norris, Tim Cichan, Joshua Hopkins, Chris Norman

- Dark Ages Radio Explorer (DARE), Jack Burns (PI), David Rapetti, Keith Tauscher, Raul Monsalve, Jordan Mirocha, Richard Bradley, Bang Nhan, Steven Furlanetto, Robert MacDowall, Judd Bowman, Justin Kasper, William Purcell, Dayton Jones

- Dark Ages Polarimeter PathfindER (DAPPER), Jack Burns (PI), David Rapetti, Keith Tauscher, Raul Monsalve, Jordan Mirocha, Richard Bradley, Steven Furlanetto, Robert MacDowall, Judd Bowman, Justin Kasper, Dayton Jones

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 Projects: Production of Volatiles via Simulated Solar Wind Proton Interactions.

In the past few years, several major space missions have been completed (e.g., Deep Impact, LCROSS, Chandrayaan-1, Stardust, Hayabusa) which have had a large impact on our knowledge of radiation processing that occurs throughout the Solar System. As shown in **Figure 1**, radiation processing or more generally space weathering encompasses bombardment by numerous sources of energetic radiation (e.g., the solar wind, galactic cosmic rays, and magnetospheric ions and electrons) as well as bombardment from meteorites. Since there is no atmosphere or protective magnetosphere shield surrounding the Moon or asteroids, all of these particles will directly impact their surfaces. The solar wind interaction with regolith has been implicated as a possible source of important molecules (i.e. water and methane) that may be trapped and sequestered in the near surface and polar regions of the Moon. During this past year, a new solar-wind initiated reaction cycle has been developed from both experiment (in collaboration with VORTICES) and modeling to account for the diurnal variation of the optical signature of hydroxyl on lunar regolith. Specifically, the 2.8-μm feature can be accounted for by following the formation and loss mechanisms of solar wind produced chemically bound hydroxyl (-OH) groups on and within lunar regolith grains (**Figure 2**). It is known that implanted H in the form of OH may be affected by ultraviolet photo-dissociation and sputtering. In addition, water and molecular hydrogen formation at the surface or within the interface region occurs via recombinative desorption (RD) involving OH and M-H groups. RD can occur at

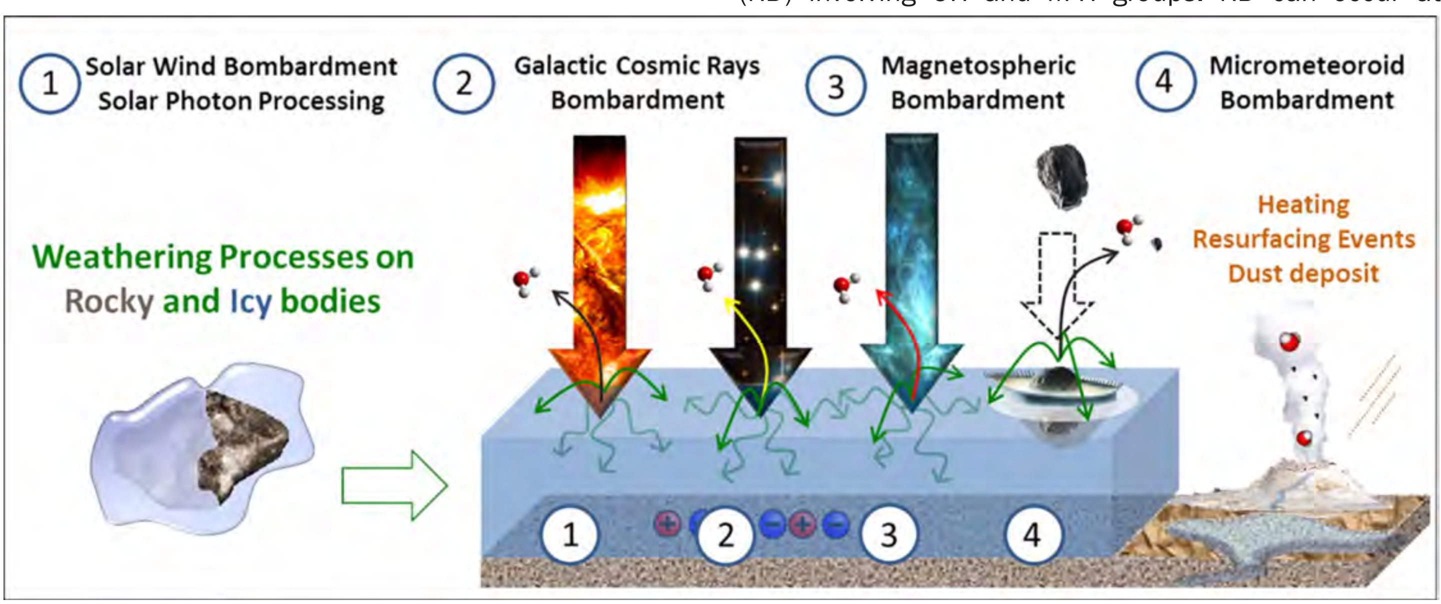


Figure 1: The primary mechanisms of transforming rocky and ice-covered surfaces in the inner and outer Solar System. These include bombardment with the solar wind, galactic cosmic rays, magnetospheric particles, and micrometeorite impact. Gardening and material turn-over also occurs. Figure from Bennett et al. Chem. Rev., 113, 12 9086 (2014).

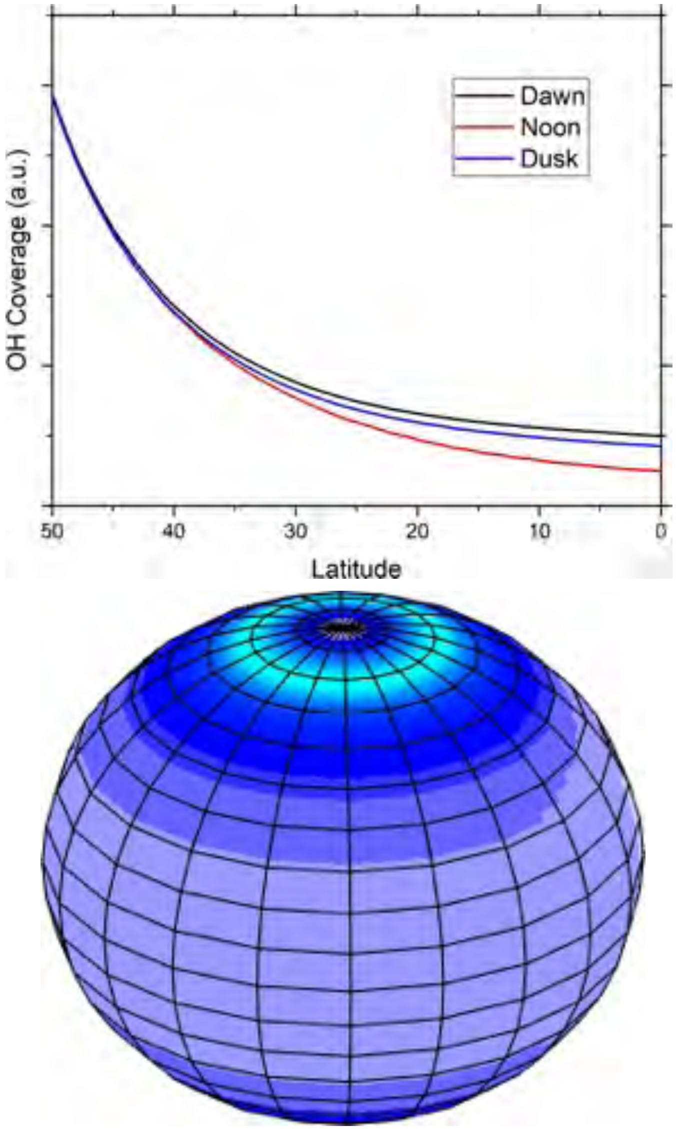


Figure 2: Simulated OH concentration profiles using the coupled kinetic model that invokes H+ implantation followed by OH destruction and water or molecular hyudrogen formation and release via recombinative desorption (top). Diurnal variation of the chemically bound hydroxyl formed via solar wind bombardment within the lunar regolith as a function of latitude as predicted by the kinetic model. (bottom) The lowest concentration is at the equator followed by a build-up near the poles.

temperatures below the maximum excursion temperature on the sun-lit face, depending upon the amount of hydroxylated Ti-, Al-, Mg- and Fe- oxides. Hydroxyls formed via solar wind are constantly removed and replenished by these known processes resulting in formation and release H_2O(g) or H_2(g). Though the H_2 escapes, H_2O(g) undergoes photodissociation and molecular/ dissociative re-adsorption on the lunar surface over limited distances and over a typical lunation period. Overall, the cyclic solar wind "hydration" process depends on substrate

> The optical signature of water on the Moon is modeled using available and recently obtained data on the non-thermal and thermal rates of water and molecular hydrogen formation and desorption from hydroxyl-terminated regolith and surrogates.

temperature, chemical composition, and can be generally applied to other airless bodies exposed to solar wind.

Epitaxial Growth of Lunar Substrate Analogs: Atomic and molecular-level characterization is necessary for the elucidation of fundamental mechanistic details relevant to proton implantation via solar wind and recombinative desorption. Our team has conducted preliminary growth and characterization of substrates that should serve as well controlled surrogates of lunar regolith surfaces and space weathered rims. Here, initial SiO_2 thin-films are grown in-situ on clean Ru(0001) terminated thin films (~200 nm thick) over C-axis sapphire in ultrahigh vacuum (UHV). The sample holder and low-energy electron diffraction (LEED) image of the Ru(0001) thin-film base for SiO_2 and $Al_xSi_{(1-x)}O_2$ (with $x < 1$) films is shown in **Figure 3.**

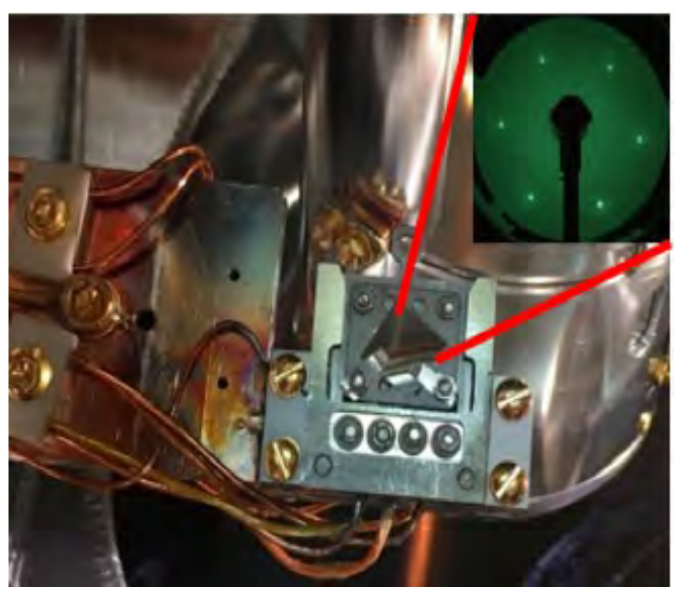


Figure 3: Sample holder and LEED pattern (upper right) of single crystal Ru(0001) thin-film sample for growth of lunar surface surrogates.

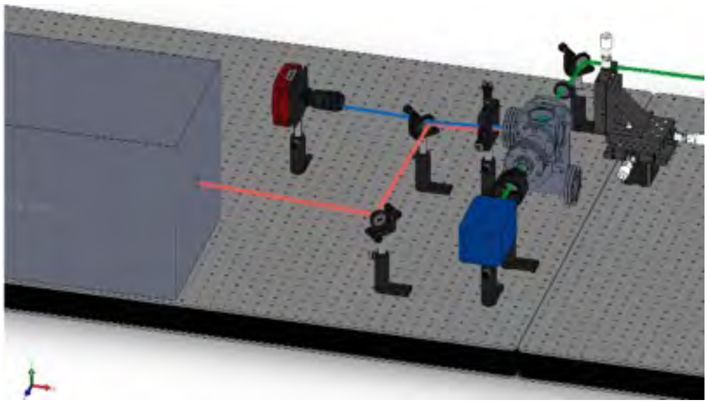


Figure 4: Schematic of laser induced micro-particle accelerator to simulate hypervelocity impacts.

Laser-based Micrometeorite Bombardment Source: We have started a program to directly address chemical evolution of volatiles on airless bodies during and following micrometeorite impact events. We have built and are now testing a Laser Induced Micro-particle Accelerator (LIMA, **Figure 4**) for impact micrometeorite studies. Our starting point is similar to the approach first reported by Lee et al. (Nat. Commun. 2012, 3, Article number 116). This technique uses a short laser pulse to propel a single grain, or multiple grains at once, achieving a maximum velocity of 1 to 10 km/s. The setup consists of a propelling laser assembly (a combination of a laser and a camera) and a launching pad (a borosilicate microscope coverslip coated with gold and topped with a thin polymeric layer). Once the micro-meteorite is launched towards the target, its velocity can be determined by looking at the scattered light of sequential pulses from a second laser. The resulting image indicates the position of the moving impactor at known times. The team, which includes collaborators at the University of Stuttgart, the University of Heidelberg and the European Space Agency, have completed micrometeorite impact studies of Allende chondrite and NWA 6966 eucrite targets using a 2 MV Van De Graff accelerator. A detailed illustration of micrometeoroid bombardment effects is shown in **Figure 5.** Here, mono-sized, spherical Cu particles bombard a single olivine crystal. The large Cu-particle (diameter: 20.5 μm; height: 4.2 μm) is implanted into an olivine crystal upon impact and experiences partial melting and/or deformation. Most interesting is the obvious lateral damage around the particle, which severely altered the optical properties of the target material around the impactor. The damaged area also shows a slightly modified topography as visible in the 3D-height image. The mechanical deformation was correlated with optical reflection measurements over the 700 -1200 cm-1 range with a general reddening trend, typical for space weathering.

Diffusion Studies of Lunar and NEA Samples: Volatile interactions with the surface of near-Earth Asteroids (NEAs) and the lunar surface regolith are important for the development of in-situ resource utilization (ISRU) technologies. Previous studies have quantified volatile interaction with regolith at atmospheric (viscous) conditions. Studies have focused on the permeability of packed-beds where the Knudsen number (K_n, the ratio of the mean free path to the pore diameter of the packed bed of particles) is in the viscous (continuum and slip) regime. Whereas the K_n number approaches and exceeds unity, placing the lunar environment in the transition (10-1<K_n<10) zone. Available modeling techniques describe the transport of gases at high K_n numbers, but depend on experimentally determined coefficients. To measure the

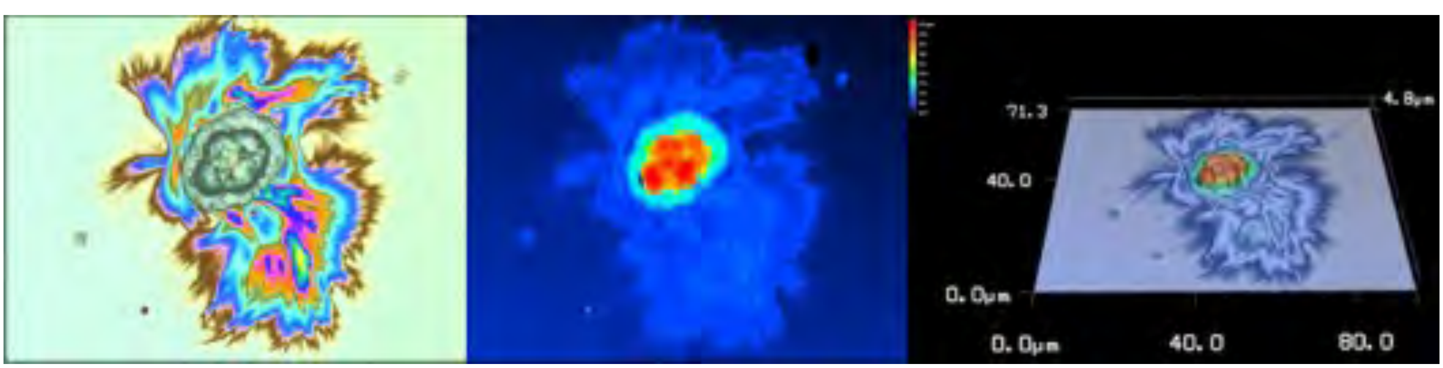


Figure 5: Combination of optical and laser contrast images of bombarded samples. Height image; tilted 3D view. A spherical Cu-particle embedded in an olivine with San-Carlos-like composition. Note the shape and extent of the lateral damage induced upon impact around the particle which also reflects in an uplifted surface area of a few nanometers. (Figure: K. Fiege, et al., submitted to J. Geophys. Res. and Guglielmino (Ph.D. thesis 2017).

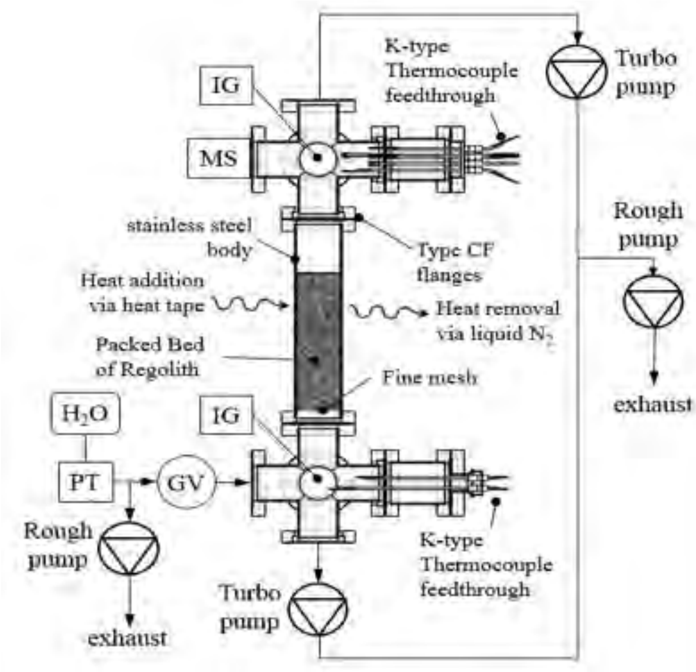


Figure 6: Instrumentation schematic of the packed bed vacuum chamber. PT refers to pressure transducer, GV to gate valve, IG to ion gauge, and MS to mass spectrometer.

diffusion rates and residence time of volatiles in regolith, a packed-bed chamber/experimental station shown in **Figure 6** has been designed, and fabrication has begun.

Development of Polymer-Graphene Nanocomposites as Lightweight Materials for Spacesuits: Human radiation risks and mitigation approaches for long-duration deep-space missions are only partially understood, and are the subject of a variety of ongoing and long-term NASA and International Partner studies. Although radiation shielding is surely required for humans in deep space, equally essential are: i) The ability to constantly monitor real-time radiation exposure for each crewmember by way of one or several active dosimeters. ii) New materials for spacesuits, habitats, and vehicles with experimentally-tested responses to radiation, thermal and mechanical stress, dust, and mechanical fatigue.

Design drivers of novel spacesuits for human exploration should therefore include multifunctional, lightweight materials with optimal mobility/flexibility, robust radiation protection, high durability, along with appropriate thermal and electrical conductivities. This latter functionality is being advocated by the investigators of the SSERVI DREAM2 node team, as analogously to the skin conductivity requirements of spacecraft immersed in space plasmas. The REVEALS team has worked on the development of hydrocarbon composites that contain well-dispersed

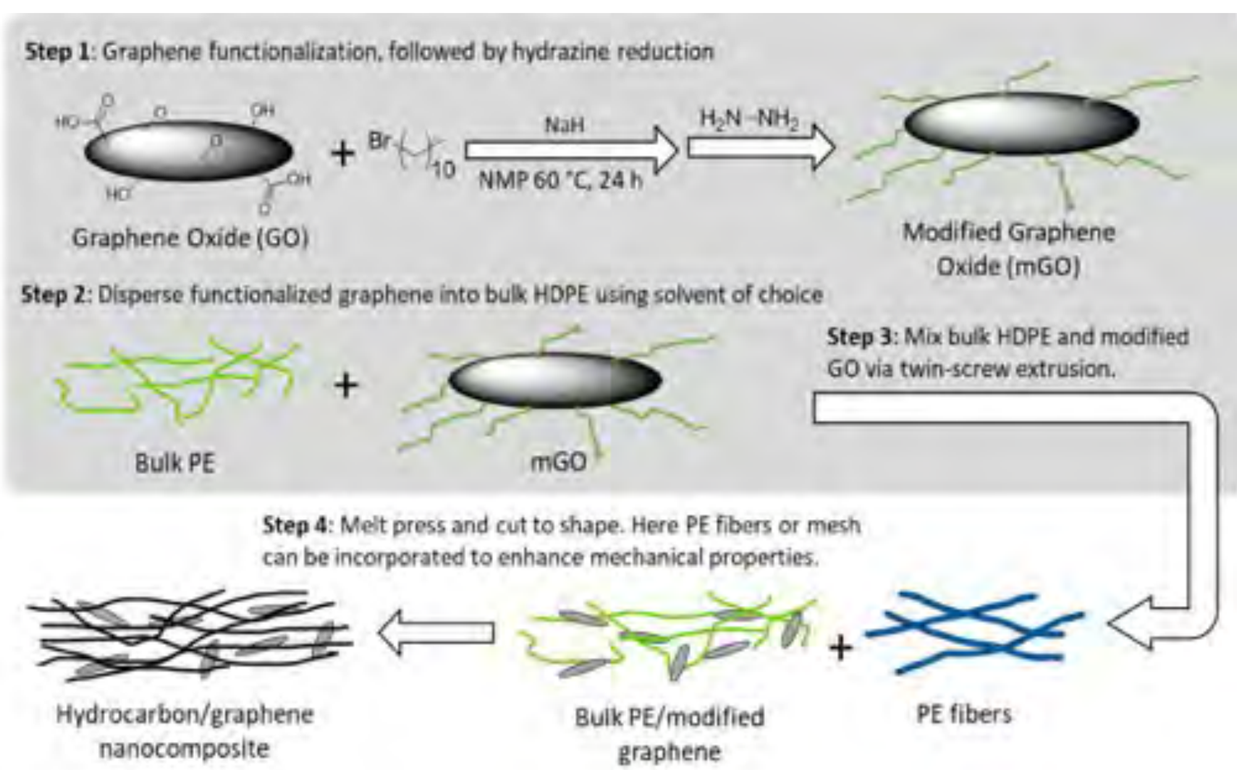


Figure 7: Process for forming and testing polyethylene fiber reinforced graphene: polymer nanocomposites as spacesuit patches with electrical conductivity, thermal conductivity, and radiation hardness.

graphene after melt processing. The abundance of hydrogen in hydrocarbons such as polyethylene (PE) allows it to mitigate the effects of ionizing radiation. Furthermore, its chemical makeup makes it less likely to undergo degradation upon radiation exposure compared to materials containing larger heteroatoms. The challenge in incorporating graphene into hydrocarbon composites is obtaining a well-dispersed distribution of the nanoparticles throughout the composite. The laboratory is currently investigating two approaches to alleviate graphene aggregation: i) Functionalize graphene oxide (GO) to make it compatible with organic solvents and increase the miscibility with hydrocarbon polymers in the solid state (**Figure 7**) ii) Mix GO and a hydrophilic polymer in solution. After casting the composite, the polymer and the GO are reduced using hydrazine vapors to realize a hydrocarbon-graphene nanocomposite.

Development and Testing of Miniaturized Active Sensors for Real-Time Dosimetry

Development of Graphene Electronics: Graphene has been proposed as a novel material that may be used to develop sensitive radiation detectors. A determinative factor for the performance of graphene electronics and sensors is the inherent noise level that limits input sensitivity. Team members carried out a systematic study of the low-frequency electrical noise in sidewall epitaxial graphene nanoribbons as a function of bias voltage (V_{bias}),

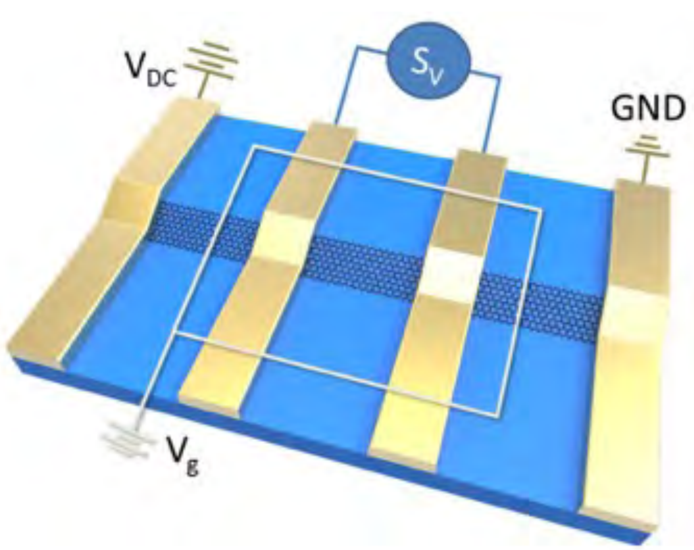


Figure 8: Nanoribbon graphene FET device. (O. Vail et al., manuscript in preparation)

top-gate voltage (V_g), and temperature (T). They showed that at low bias, the voltage noise (S_V) is just above the Johnson-Nyquist level, while at high bias, S_V is dominated by a $1/f^{\gamma}$ dependence, with the value of γ consistently between 0.9 and 1.1. The V_g-dependence of S_V also reveals that the dominant noise source is long-range scattering presumably at the ribbon and gate dielectric interface. By comparing the electrical noise of epitaxial graphene nanoribbons with other carbon systems, its potential in future nanoelectronics is asserted.

Topological insulators, particularly 2D topological insulators, have also been identified as potentially valuable materials for use in personal radiation monitors [Orlando et al. 2018, Cell]. The team is exploring ZrTe5 and HfTe5 as candidate 2D topological insulators. Our spectroscopic studies, using a scanning tunneling microscope (STM), will help to determine whether these materials are “weak” or “strong” topological insulators, i.e., whether their electronic properties are dominated by 3D electronic band structure, or the 2D electronic structure of weakly-interacting layers. We used the STM to acquire topographic data and with simultaneous conductance spectra (STS; interpreted as density of electron states) over a range of electron energies and found a surface defect (a Te dimer vacancy). We expect this to be a common vacancy when the sample is exposed to ionizing radiation, so, for use in radiation monitors, we seek an understanding of how they affect local electronic properties and transport properties. Processing and interpretation of these complex data sets is ongoing.

Integration of New Materials and Active Dosimetry into EVA and Surface Exploration Concepts: The Team has begun the process of inventorying materials and mechanical properties for both the current NASA EVA EMU and the next-generation spacesuit for planetary surface excursions. The result of this inventory will be a database of materials and their applications from which a suite of tests will be defined for 3-D flexure/folding characteristics, material attachment methods, edge-treatments, and layering techniques.

In addition to developing low-power, light weight radiation detectors, since these are real time monitoring devices,

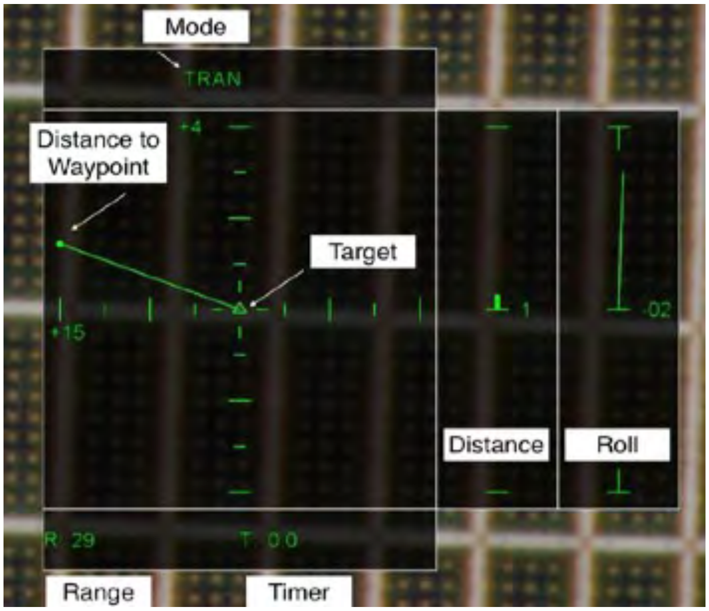


Figure 9. Proposed in-helmet display for EVA navigation and real-time radiation exposure monitoring.

we are also working toward developing general real time data assessment and decision making protocols that can be utilized during EVA operations. The team also began the process of studying scientific data and compiling a log of literature dedicated to space radiation safety, and risk management in human space missions. The database provides a platform of current projects from which REVEALS can compare findings and establish research parameters.

2 Inter-team/International Collaborations

IMPACT and DREAM2 Collaborations: Charged dust grain interactions

Experiments to directly examine the effects of charged dust grains on lung cell membranes have been designed in collaboration with IMPACT and DREAM2 teams. Specifically, we will measure the role of charge and the local potential change at the membrane surface on the permeability and stability of lung surfactants. New nanoparticle surface analysis tools are also being developed to determine what types of carcinogens may exist on regolith dust grains due to radiation processes, space weathering and electrostatic discharges. We also intend to integrate these particle studies with longer term toxicity studies. W. Farrell is also a member of the REVEALS advisory board.

VORTICES Collaborations: Understanding the fate and sources of lunar water

A modeling effort on the diurnal variation of the 2.8 micron optical signature of “water” has been completed. The effort was a collaboration with VORTICES Co-Is, K. Hibbitts and D. Dyar. The model demonstrates that the diurnal variation of water can be understood by taking into account the recombinative desorption (RD) of water from hydroxyl terminated metal-oxide surfaces such as thus expected to be present within the regolith. The pre-factors and energetics of RD from anorthite and the lunar regolith JSC-1A have been measured with VORTICES support. The results indicate that the activation energies are below 100 kJ/mol and are within the range which allows this second-order process to be important in controlling the terminal OH densities and hence the observable 2.8 micron feature reported in the observational data. A. Rivkin is also a member of the REVEALS advisory board.

CLASS Collaborations: Asteroid water release

The REVEALS team has measured the temperature programmed release of molecular water from lizardite and antigorite samples that have been supplied by CLASS. This is part of a joint effort to understand the thermal processing of asteroid surface materials. D. Britt is also a member of the REVEALS advisory board.

International Collaborations

Germany/ESA

The collaboration with ESA (N. Altobelli) and the Germany Cosmic Dust Analyzer team (K. Fiege, R. Srama and M. Trieloff) has resulted in two recently submitted joint papers: “Space weathering induced via micro-particle impacts: Part 1: Modeling of impact velocities and flux of interplanetary and interstellar dust in the main asteroid belt and the near-Earth environment” and “Space weathering induced via micro-particle impacts: Part 2: Dust impact simulation and meteorite target analysis.”

Sapienza University

REVEALS is collaborating with Sapienza University of Rome on assessing the quality of a UV-C nanocomposite

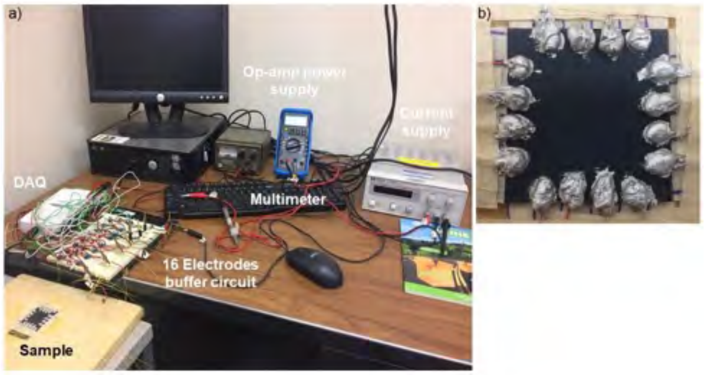


Figure 10: a) Experimental setup for electrical resistance tomography tests on b) samples produced at Sapienza University, and tested at UC Davis.

sensor applied to relevant composite samples (carbon fibers with a space-rated epoxy resin, prepared with resin transfer molding). The sensor is composed of graphene and DNA dispersed in a polymeric matrix (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate, or PEDOT:PSS). Changes of electrical conductivity are correlated to damage in the sensor and its host structure, and are analyzed through electrical resistance tomography—a technique applied to composite structures by the REVEALS Co-I at UC Davis (**Figure 10**).

3 Public Engagement

UCF/Florida Space Institute Women in Technology International (WITI)

Dr. Beltran was invited as a keynote speaker at the WITI Tampa Bay 5th Annual Geek Glam, October, 2017. The title of the talk was: "No Limits!" WITI is a premiere global organization empowering women in business and technology. It provides a forum for women to network with each other, forge connections, and share resources. Attendance on site was over 200 people. The talk was broadcasted via YouTube across all WITI's International partners.

International Observe the Moon Night

The event, organized by the UCF physics department, Robinson Observatory and student organizations including the Astronomy Society, was held as part of the worldwide celebration of lunar science and exploration. The UCF gathering, led by NASA's Lunar Reconnaissance Orbiter Education and Communications team, was held on October 29th, 2017. Dr. Beltran collaborated with CLASS in the activities.

Morris Brandon Elementary School - Atlanta Public Schools

Dr. Orlando distributed the SSERVI lunar eclipse glasses to the Morris Brandon elementary school students and presented two general talks on "Being in the path of a total lunar eclipse."

Life in the Cosmos: Past, Present, and Future – Georgia Tech Public Symposium

Dr. Paty was an invited speaker at a public Symposium on Astrobiology and Society in Fall 2017 with sessions dedicated respectively to "The Origin and Evolution of Life on Earth and The Search for Life Beyond our Home Planet." Her talk, "Searching for Europa's Hidden Ocean" focused on the diverse instruments working collaboratively to determine the habitability of Europa's ocean, and the 'evolution' of diversity and cooperation in the field of planetary science.

4 Student / Early Career Participation.

Undergraduate Students

1. Aaron, Guizar, UC Davis, recruited to work in 2018 to define a materials testing protocol for strength, durability, abrasion, and dust-embedment in the La Saponara and Robinson labs, at an effort rate of 5hrs/week each
2. Adriana, Henriquez, UC Davis, recruited to work on mechanical properties testing for Theme 2 (to start in 2018)
3. Brooke, Raabe, UC Davis, recruited to work in 2018 to define a materials testing protocol for radiation exposure response at the UC Davis Crocker Nuclear Lab, at an effort rate of 5hrs/week each
4. Jonathan, Thomas, UC Davis, recruited to work on mechanical properties testing for Theme 2 (to start in 2018)
5. Nicholas, Hamilton, Georgia Institute of Technology, Physics (recruited for work to start in 2018)
6. Shreya, Rastogi, UC Davis, recruited to work on

mechanical properties testing for Theme 2 (to start in 2018)

7. Steven, Licciardello, Georgia Institute of Technology, Physics (recruited for work to start in 2018)

8. Hannah Lyons, Univ. of Florida/University of Central Florida, summer intern with Dr. Beltran

Graduate Students

1. Ardalan, Sofi, UC Davis, recruited in Fall 2017, will work on numerical modeling in 2018

2. Darh, Bijoa, University of Central Florida, Physics – epitaxial growth of lunar surrogate surfaces

3. Elliot, Frey, Georgia Institute of Technology, Chemistry (recruited for work to start in Jan. 2018)

4. Hsin-Ju, Wu, Georgia Institute of Technology, Physics– developing 2D materials for passive radiation detectors

5. Marialaura, Clausi, Sapienza University of Rome (Italy). Ph.D. student advised by Dr. Laurenzi and Dr. Santonicola, spent a period of 6 months in 2017 at UC Davis; she carried out manufacturing, testing and analysis of sensors for structural health monitoring.

6. Matthew, Gabel, UC Davis, recruited in Fall 2017, will work on manufacturing and testing in 2018

Post-doctoral Fellows

1. Demian Marchione, Georgia Institute of Technology – developing the Laser Induced Micro-meteorite Accelerator

2. Zach, Seibers, Georgia Institute of Technology – developing novel polymer composites for spacesuits

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, PEP, Science Co-I

Amanda Hendrix

Planetary Science Institute in Tucson, AZ

Toolbox for Research and Exploration (TREX)

CAN 2 Team

1. TREX Project Report

Since selection as a SSERVI team in March 2017 (funded in August), the TREX team is off to an excellent start, having made significant progress in several areas in this partial first year. TREX (trex.psi.edu) is based at the Planetary Science Institute. Roughly two-thirds of TREX scientists are with PSI, distributed at locations across the country and Europe, with co-investigators and collaborators at Goddard Space Flight Center (GSFC), Columbia University, Carnegie Mellon, Lunar and Planetary Institute (LPI), Univ. Colorado, Univ. Winnipeg, Univ. Illinois, the German Aerospace Center (DLR) and Smithsonian Institute: TREX thus represents a truly virtual team. TREX 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 will focus on characteristics of the fine grains that cover the surfaces of these target bodies—their spectral characteristics and the potential resources (such as H2O) they may harbor.

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.

1.1 The TREX Fine-Particle Spectral Library

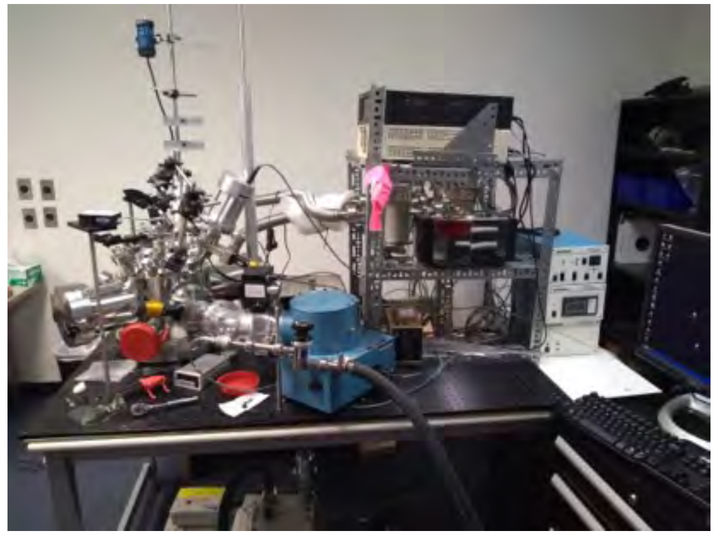
The TREX spectral library focuses on fine-grained (<10 µm) planetary materials measured over ultraviolet, visible/near-infrared, and mid-infrared (UV-VNIR-MIR) under environmental conditions that mimic the surfaces of the airless targets (in vacuum, when possible, and at various temperatures) (see table below). This library will be invaluable in interpreting spacecraft data (e.g. for Moon and small bodies tasks outlined below) and will be made available to the larger community as well. Furthermore, the spectral library will be ingested into software used in autonomous sample selection in the TREX fieldwork theme (Sec. 1.3). The lab measurements will include a range of pure terrestrial minerals (including ~6 samples previously measured in other SSERVI labs, for cross-correlations), lunar samples and meteorites. A goal of performing measurements in a suite of labs is to harness both unique and overlapping capabilities to derive a robust set of cross-calibrated laboratory spectra.

1.1.1 Sample Acquisition and Preparation

In 2017, we worked to begin acquiring and preparing samples for measurement. Theme lead Melissa Lane leads the effort in choosing samples, arranging for purchase, and coordinating with co-investigator Darby Dyar in the preparation of the samples and shipment to the various TREX labs. Dyar sent the SSERVI-shared <25 um San Carlos forsterite olivine sample for particle size analysis; results showed that the sample was 90% finer than 7.42 µm in diameter. This result suggests that the SSERVI suite of prepared <25 µm samples may require no more processing to reach the ~10-µm diameter size for the TREX spectral analyses (good news).

1.1.2 Laboratory Facilities

In 2017, we also worked to prepare the TREX labs for measurement of samples. Co-investigator Ed Cloutis is working on some environment chambers and hopes to widen the UV capabilities, under ambient pressure, to as short as 150 nm. Co-investigator Roger Clark has made great progress in setting up the PSI spectroscopy lab (see photo below). Lab technician Neil Pearson was hired at PSI to run the instruments and will do most of the measurements at PSI for TREX. Clark is working to create a set of reflectance standards to share among the TREX labs. Details are being finalized on the purchase of the lab equipment for the UV measurements at LASP (Univ. Colorado); the LASP measurements will focus on mineral-ice mixtures. Lane is planning a trip to Berlin in the spring of 2018 to make infrared measurements over a variety of temperatures in the DLR lab with co-investigator Jorn Helbert.



The Spectroscopy Lab at PSI (Tucson)

1.2 Lunar and Small Bodies Studies

The Moon is a primary focus of TREX studies, as the only Solar System body humans have visited, and a likely future human destination. TREX lunar investigations combine the lab measurements acquired under lunar conditions (vacuum and a range of temperatures) with lunar spacecraft data and modeling techniques to characterize particle size, mineralogy, thermal attributes, space weathering effects, and correlations with geologic features. The overarching goals of the lunar studies are to expand our understanding of the Moon scientifically and as a target for future human and robotic exploration, and to address ISRU and future instrument development needs.

In 2017, Hendrix and TREX deputy PI Faith Vilas worked with Lunar Reconnaissance Orbiter (LRO) Lyman-Alpha Mapping Project (LAMP) colleagues and DREAM2 investigators Farrell and Hurley in interpreting LRO LAMP data of far-UV spectral slopes (indicative of daytime hydration). LAMP data, when considered with LRO Diviner temperatures, support the observation of desorption of water from sites of varying activation energy (also temperature dependent). TREX team members, including Theme 1 lead Maria Banks, were active in community Moon meetings such as LEAG and the “Back to the Moon” workshop held in October.

In the Fall, Co-investigator Ryan Clegg-Watkins submitted a paper to the Earth and Space 2018 Conference on the topic of boulder distributions on the Moon. Clegg-Watkins also attended a SOCET GXP training, where she learned how to produce Digital Terrain Models (DTMs) that will come in handy for various TREX tasks. Co-investigator Deborah Domingue submitted a paper on “Characterization of Lunar Surface within Tsiolkovsky Crater: Photometric and Albedo Properties,” and Co-I Norbert Schorghofer began working with undergraduate student Christopher Nguyen on Diviner data processing (one step toward a map of grain size). The Lunar photometry/mineralogy group continued work on 1) Analysis of South Pole Aitken Basin (SPA) thorium, in conjunction with co-investigator Tom Prettyman and Aaron Boyd at ASU; 2) Geologic features that may inform the source of the thorium anomalies.

The TREX Small Bodies Theme delves into several topics, many of which are synergistic with the other TREX Themes. The main topics include photometry, spectral modeling, laboratory simulations of space weathering processes relevant to asteroids, the assembly of an asteroid regolith database, the dichotomy between nuclear and reflectance spectroscopy, and the dynamical evolution of asteroids and the implications for the retention of volatiles.

In 2017, Theme lead Deborah Domingue, a Hayabusa 2

Lab*	Measurement	Wavelength	P,T
DLR PSL	Reflect.	0.18 - 20 um	0.7 mbar; ambient T
	Emission	3 – 20 um	Purged air; 30-200C
	Reflect.	0.7 – 300 um	0.7 mbar; ambient T
	Emission	0.7 – 300 um	0.7 mbar; 50-300C
Mount Holyoke	Raman	3 - 33 um	Ambient
	Mossbau.	14.4 KeV	Ambient
PSI	Reflect.	0.11 – 0.22 um	<mbar; 77K
	Reflect.	0.18 – 0.88 um	77 – 490K; <mbar to 1.5 bar
	Reflect.	0.35 to 2.5 um	77 – 490K; <mbar to 1.5 bar
	Reflect. (future)	1.5 to 50+ um	77 – 490K; <mbar to 1.5 bar
Univ. Winnipeg	Reflect.	0.16 – 0.4 um	Ambient
	Reflect.	0.35 – 2.5 um	Ambient
	Reflect. (future)	1.6 – 20 um	<mbar; ambient T
LASP	Reflect.	0.12 to 0.6 um	<mbar P; 90K for ices
Univ. Illinois	Refl.; Irradiation	0.35 – 2.5 um	<mbar P; 77-900K
NASA-JSC	Impact sims	n/a	n/a

TREX laboratories

team member, worked on topics relating to Itokawa and its opposition surge as observed by the AMICA instrument. Co-investigator Nobert Schorghofer began calculations on his model of ice loss from asteroids. For lab studies related to space weathering (solar wind & impact simulations) of small bodies, the group worked to prioritize samples; co-investigators Karen Stockstill-Cahill and Domingue are in plans for small bodies spectroscopy study. Hendrix and Vilas are studying the UV-visible spectral shapes of low-albedo class asteroids to understand relationships with composition and weathering effects; results were presented and discussed at the Exploration Science Forum in July.

1.3 Field Applications

TREX field work focuses on improving science yield by delegating mission planning, data collection, analysis, and decision-making to an automated robotic explorer. This Theme group, led by Eldar Noe Dobrea met in August to begin planning field trips and instrumentation for the rover (see photo above). The meeting helped the group define plans and establish a timeline for work; they discussed the rover capabilities (provided by co-investigator David Wettergreen at Carnegie Mellon), the instrumentation, the field sites, and the rover's role in spectral identification using Tetracorder software and decision-making software.

Co-investigator Shawn Wright got a great start on TREX field work by participating with the RIS^{4}E team on their field trip in June. Wright also went on a 3-day GSA field trip to sample and do advance scouting of the Palouse loess in southeastern Washington, one of the sites of TREX field work. Wright collected six samples of the finest loess from six different locations, took field pictures of sample location sites, and collected GPS points of several possible locations for the TREX rover in 2019-2020.

Co-investigator Prettyman completed field testing of a portable gamma ray detector at GSFC, in advance of TREX field work, and measured gamma ray spectra for samples from a prospective field test location in New Mexico. Noe Dobrea developed C code to control the

The rover Zoe, to be used for TREX field exercises

Flame spectrometer using Linux in anticipation of rover work. Co-I Wettergreen started working (with students) on rover Zoe to determine what needs to be done to prepare for field work.

1.4 Other work

The TREX team held a spectroscopy software workshop Nov 1-3 at PSI-Denver, hosted by Co-I Roger Clark. Team members and colleagues learned about the use of the software SpecPR, for use in interpretation and modeling of spectroscopic datasets.

An additional activity during 2017 was getting the TREX website (trex.psi.edu) up and running; the website now serves to inform the public and planetary community of TREX activities and results, and also as a conduit for sharing information and files among the team members.

Hendrix and Vilas organized and chaired a panel discussion at the Fall AGU meeting on "Planetary Bodies in the Ultraviolet," which was well attended and a good discussion was held. A summary article is being prepared. Hendrix and Vilas are also coordinating a SSERVI-sponsored workshop, to be held in April 2018, on "Carbon in the Solar System."

2 TREX Inter-team/International Collaborations

The TREX team has begun inter-team collaborations with the RIS^{4}E, DREAM2, VORTICES, REVEALS, CLASS and SEEED teams. Discussions are ongoing with the RIS^{4}E team regarding field work collaborations, and a TREX Co-I participated on the RIS^{4}E field trip in June 2017; additional collaborative studies with RIS^{4}E may come in the way of lab studies in future years, where samples measured in TREX labs may be measured in RIS^{4}E facilities for cross-calibration and comparison. Furthermore, the five SSERVI PIs in Boulder (Hendrix, Horanyi, Burns, Bottke, Parker) gathered for conversation on several occasions in 2017 and are discussing potential student projects and/or seminars among the Boulder group.

Hendrix is collaborating with Bill Farrell and Dana Hurley (DREAM2) in interpreting and understanding LRO LAMP data of dayside hydration on the lunar surface; Thom Orlando (REVEALS) has also offered his insights and we expect this collaboration to continue. **Hendrix and Vilas (also a CLASS team member) are collaborating with CLASS Co-I Humberto Campins on studying 3200 Phaethon using UV observations from the Hubble Space Telescope (HST), a project sparked by discussions at the NASA Exploration Science Forum.**

TREX Co-I Karen Stockstill-Cahill is collaborating with Rachel Klima and Andrew Rivkin from VORTICES to study the spectral signature of adsorbed water for nominally anhydrous minerals in ordinary chondrites. The team will collect VIS-NIR spectra under ambient conditions to test for spectral signatures of adsorbed water present under terrestrial ambient conditions. Under vacuum conditions, the team will collect UV, VIS, and SWIR of samples before slowly heating samples to ~100°C to drive off adsorbed water. Collection of UV-NIR spectra will be repeated again post-heating, while still under vacuum. Comparison of the spectra before and after heating will allow the team to ascertain the effects of adsorbed water on the spectra of ordinary chondrites.

TREX Co-I Tom Prettyman is collaborating with SEEED PI Carle Pieters to investigate and explore the connections between remotely determined elemental and mineral compositions of surfaces. The differences between the suite of instruments used to determine surface composition presents some challenges as well as opportunities to improve surface characterization. In this collaboration we are exploring the joint analysis of elemental and mineral data to provide a more complete picture of the physical and chemical mineralogies of small body surfaces, providing constraints on regolith, crustal, and interior processes.

We have also been collaborating with Dr. Sue Lederer at NASA's Johnson Space Center (JSC) and Dr. Akbar Whizin (Planetary Resources), who have performed impact experiments at JSC on various minerals (primarily phyllosilicates), similar to what TREX will do as part of small bodies space weathering simulations; they have offered samples to TREX for characterization in our labs (before and after impact samples). This collaboration will expand the number of samples we can study under impact situations.

3 Public Engagement

TREX team members participated in several EPO activities during our first year.

In August, for the solar eclipse, Amanda Hendrix gave a public talk "Learning about our Moon during the Eclipse" at a Dubois (WY) K-12 school (see photo below left); she handed out SSERVI eclipse glasses and LRO/NASA/Moon swag. Some of the students were involved in CATE projects (see photo above).

In September, TREX Co-I Lynnae Quick gave a presentation at Howard University about identifying the amount and location of volatiles near volcanic constructs at equatorial latitudes on the lunar surface (while simultaneously recruiting undergrads to help on TREX tasks).

In October, Amanda Hendrix gave a talk "The Moon: Our Closest Neighbor" at the Colorado School of Mines, hosted by IMAPCT Co-I Angel Abbud-Madrid.

At the December American Geophysical Union (AGU) meeting in New Orleans, Amanda Hendrix gave an Flash talk at the NASA booth in the exhibit hall: "Preparing for new astronaut footprints: NASA's TREX team."

TREX scientists have many ideas for public engagement and look forward to more opportunities in 2018.

4 Student / Early Career Participation

In our first year, TREX had graduate students working with Co-I Dr. David Wettergreen in the Robotics Institute at Carnegie Mellon and with Dr. Jean Paul Allain at the University of Illinois. Also, Co-I Deborah Domingue has enlisted the enthusiastic help from Maryland high school students in interviewing TREX team members for the personnel pages on the TREX website (trex.psi.edu).

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. Camilo Jaramillo, 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

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 CoPI

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.

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 2017, SSERVI has been working with representatives from Japanese and Mexican Space Agencies on development of proposals for membership. In addition, SSERVI participated in and/or accomplished the following activities:

Italy

This year the Italian Space Agency (ASI) submitted a proposal to SSERVI to upgrade the existing partnership from Affiliate to Associate. The Istituto Nazionale di Fisica Nucleare (INFN)—Italy's National Nuclear Physics Institute—became an Affiliate Member of SSERVI in 2014. With the addition of the Italian space agency in 2017, the partnership was upgraded to an Associate-level partnership. The agreement was signed in May at the Italian Embassy in Washington, DC with representatives from ASI and NASA HQ in attendance.

NASA Planetary Science Division Director Dr. Jim Green (center) and Dr. Enrico Flamini, Scientific Coordinator of the Italian Space Agency (ASI) signed the SSERVI Associate partnership agreement on June 14th, 2017 at the Italian Embassy in Washington DC. Credit: Schmidt/NASA SSERVI

Pan-European Consortium (Germany, United Kingdom, Netherlands, Italy, and France)

European Lunar Symposium

The 5th European Lunar Symposium was held May 2-3, 2017, at the University of Münster, Germany. New Views of the Moon 2 workshop took place immediately following the ELS at the same venue on May 4-5th.

This meeting built upon the success of previous European Lunar Symposiums (ELS) held in Berlin (2012), London (2014), Frascati (2015) and Amsterdam (2016). The fifth ELS was held under the umbrella of the European SSERVI teams, supported by the local team at Münster 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 123 presentations made over two days (60 orals + 63 posters) along with a special talk by ESA Astronaut, Matthias Maurer. Over 150 participants, representing the global community of lunar scientists and explorers, made this a highly successful event.

The 5th European Lunar Symposium was held at the University of Münster, Germany, May 2-3, 2017. There were a total of 123 presentations made over two days along with a special talk by ESA Astronaut, Matthias Maurer. ELS organizers Harry Hiesinger and Mahesh Anand did an outstanding job of bringing together over 150 participants, representing the global community of lunar scientists and explorers, which made this a highly successful event. Credit: ELS Organizers.

ESA

SSERVI's Solar System Treks Project (SSTP) conducted a lunar traverse planning workshop with our ESA partners at their ESTEC facility and provided data to their MoonDesk software project. They continue to work with our Italian partners in lunar reflection studies. SSTP is working with the International Phobos/Deimos Working Group and with JAXA in the design and implementation of the new Phobos Trek portal.

Korea

In Korea, SSERVI staff gave presentations on using Moon Trek for mission planning, data dissemination, and higher education; we briefed them on working with the Planetary Data System and the International Planetary Data Alliance; provided an overview of conducting mission EPO; as well as gave a remote invited presentation at the Korea-Japan Bilateral Planetary Program's Planetary Geology Workshop.

UK

SSERVI Central gave a remote presentation at our UK partner's international Observe the Moon Night event.

Australia

We are working with our Australian partners, actively facilitating the expansion of the Australian Desert Fireball Network beyond the Australian Outback, to become a global network. Working with SSERVI's Saudi Arabian partner, DFN cameras are now being established on the Arabian Peninsula. As we work to formalize a partnership with the Mexican Space Agency, expansion of the DFN into the Sonoran Desert is a key component of the proposal. We have conducted preliminary discussions about expanding the network into the Atacama Desert of Chile, working with the University of Antofagasta.

Saudi Arabia

Our Saudi Arabian partner designated Dr. Thamer Alrefay from the King Abdulaziz City for Science and Technology (KACST) as the new PI for our existing partnership this year. Immediately the potential for collaboration with the DFN was recognized and Dr. Alrefay's secured funding to deploy three DFN cameras in the Saudi Arabian deserts in 2018.

Development of new Partnerships

Mexico

SSERVI worked with Dr. Mario Santander from the Mexican Space Agency (AEM) to identify opportunities for development of an international partnership. Meetings were held at the Pinacate BioReserve near Puerto Penasco, Sonora, Mexico in April and in Mexico City, Mexico in September. SSERVI also met with the President of AEM to review the benefits of a SSERVI partnership with AEM to outline the potential collaboration topics for their proposal. Included in the outline is the opportunity for SSERVI researchers to gain access to the Pinacate volcanic fields for analog studies while SSERVI could help with an exhibit at the Pinacate Visitor Center. Our Apollo Astronauts all spent time in the Pinacates to train for field work on the Moon at this location, which was discussed as a focal point in a new exhibit at the visitor center. In addition, Dr. Day was a keynote speaker at their Mexico

Brian Day presenting to the Mexico Hacia Mars Workshop in Mexico City

> SSERVI Central partnered with UNAM University and Universum Science Museum on a remote Solar Eclipse program in Mexico, and gave a keynote talk at Mexico's first Mars Exploration Congress in support of our efforts to establish an international partnership with the Mexican Space Agency.

Hacia Mars workshop where he engaged in discussion about the possibilities for Mexico to participate the global exploration efforts.

JAXA

SSERVI met with JAXA management and researchers during a trip to Tokyo for the Japan GeoScience Union meeting in May. Representatives of ISAS shared ideas of potential partnership for their research and educational organizations. Representatives from the science and exploration organization attended and presented at the Exploration Science Forum while SSERVI representatives attended their SELENE symposium. Both furthering the development of collaboration focuses for a JAXA partnership proposal.

India

SSERVI has partnered with Berkeley Haas School of Business for the Open Innovation Hackathon, and Open Innovation Forum on the Scalable Smart Villages Project. This is the continued effort centered around science and technical education involving robotic challenges and developing small pocket satellites for educating and inspiring the next generation of scientists and engineers.

SSERVI representatives attended several key meetings in India with the Chief Minister of India and over 40 village leaders in attendance. Indian officials are interested in firms that offer promising solutions to upgrade over 650,000+ villages across India with relevant and affordable technical solutions. SSERVI offered subject matter experts to help educate the next generation on developing small satellite projects, and encouraged the first Robotic Competition event in India (RoboRave India Sept 2016 and November 4-5, 2017). SSERVI Central Office staff served as a keynote speaker at an event in Mori, India on Sept 1st-2nd (Mori was the first Smart Village in a pilot program for children to build small satellite projects) where he was presented with a Small Satellite Project built by the students of Mori Riverside School.

By promoting NASA inspired university level mining competitions SSERVI encourages the development of innovative robotic excavation concepts by student teams which may result in clever ideas and solutions which could be applied to actual excavation devices and/or payloads on an ISRU missions. The unique physical properties of basaltic regolith, reduced 3/8th of Earth gravity and other factors make off-world excavation a difficult technical challenge. Advances in Lunar and Martian mining have the potential to significantly contribute to our nation's space vision and benefit's NASA space exploration operations.

International Partner Reports

Australia

1. Team Project Report

On 25 September 2017, the Australian Government announced its intention to establish an Australian space agency. This announcement was guided by input for the review of Australia's space industry capability. The agency will provide international representation, support to critical partnerships, coordination of a national strategy and activities and support for industry growth.

SSERVI Australia continued its advocacy role in highlighting the recognised, substantive and growing planetary science community, working with policy makers, academic and industry leaders to solidify its future capability. We are involved at every level to ensure that planetary science, space, and exploration science are key components of the future agency.

2. Collaborations with SSERVI Teams and International Partners

The Desert Fireball Network is being expanded with new international partners to form a Global Fireball Observatory. Partners get camera hardware that allows them to setup their own independent networks. Partners drive the research and engagement opportunities generated by their network, but because all data collection and reduction is common, the whole can be united to form a network-of-networks: a global planetary facility that should observe >5 meteorites per month. Over 40 cameras have already been and shipped to partners in the US, UK, Canada, Morocco, and Saudi Arabia. SSERVI Central is a key partner in this collaborative effort, identifying new partners and sites for cameras.

In collaboration with NASA, the Desert Fireball Network and its Australian SSERVI Partners mounted an observation campaign for the OSIRIS-REx spacecraft Earth Gravity Assist manoeuvre over Australia on the night of Sept 22 /23, 2017. Our team were stationed across Australia and New Zealand in strategic locations to optimise viewing angles of OSIRIS-REx to achieve three separate goals for tracking the spacecraft: providing a baseline so NASA can compare its telemetry from the spacecraft with the team's ground observations, testing the team's equipment and orbital analysis calculations, and engaging Australian astronomers and the broader community.

R.Sayers presenting with Brian Day at 2017 Citizen Science Association conference, Twin Cities MN

>100 papers in high impact journals. Highlights include:

Research published in Science Advances (Phil Bland and Bryan Travis) suggesting that many of the original planetary building blocks in our solar system may have started life not as rocky asteroids, but as gigantic balls of warm mud.

Study published in Nature Geoscience (Craig O'Neill and Southwest Research Institute researchers) uncovering the ways in which giant meteorite impacts may have helped to kick-start our planet's global tectonic processes and magnetic field. The study explores the effect of meteorite bombardment in geodynamic simulations of the early Earth.

Review paper published in forthcoming issue of Annual Reviews of Earth and Planetary Science (Marc Norman and Bill Bottke) on the Late Heavy Bombardment.

Research published in Geology (Aaron Cavosie and Nicholas Timms) exploring the geology of impact melt from an as-yet undiscovered crater in Southeast Asia, and the history of asteroid Itokawa through study of dust particles collected by the Hayabusa space probe (Fred Jourdan).

Numerical modeling Lunar research published in Geophysical Research Letters (Karina Miljković, Myriam Lemelin, Paul Lucey) showed the peak-ring forms from the material that is part of the central uplift outwardly thrust over the inwardly collapsing transient crater rim.

American Chamber of Commerce Innovation Mission visited SSERVI Central at NASA Ames for a presentation on the SSERVI collaboration with the Desert Fireball Network and Fireballs in the Sky.

Lockheed Martin Space Systems Company and Curtin University have signed an agreement confirming a joint Research and Development partnership to evaluate, assess and potentially adapt the Desert Fireball Network meteorite tracking capability and further develop Australia's niche capabilities.

3. Public Engagement

Fireballs in the Sky continues to be the flagship ongoing outreach initiative for SSERVI Australia, with its citizen science app upgraded with 34,769 downloads in 90 countries and 3,416 reports. The program was presented at the 2017 Citizen Science Conference in Minnesota, and the American Geophysical Union with SSERVI Central.

SSERVI Australia Engagement Lead Renae Sayers visited SSERVI partners at NASA Goddard Space Flight Centre, NASA Ames, and hosted a webinar for NASA JPL to expand collaborations, grow our media profile, and meet common goals in science outreach.

Alongside the NASA DFN OSIRIS-REx Observation campaign, the team engaged astronomy communities and the media across Australia to track the spacecraft.

4. Student/ Early Career Participation

Curtin University PhD graduate, Timmons Erickson received a Postdoctoral Research Fellowship at Lunar and Planetary Institute in Houston. After his time at Curtin, Timmons has a publication record of 18 articles in top quality peer-reviewed journals, and h-index of 9, and a total of 189 citations.

Curtin University PhD candidate Nicole Neville won the VSSEC NASA space prize for geosciences for her Honours research and was awarded a three month LPI internship at the Johnson Space Centre in Houston Texas, where she commenced her research: Coordinated analysis of primordial components within primitive meteorites: Implications for the pre-solar environment and the formation of the protoplanetary disk.

Curtin University Undergraduate student Morgan Cox received the Eugene Shoemaker Impact Cratering Award which facilitated fieldwork to the Kimberley in Western Australia. The samples collected from the ancient Spider impact crater will be part of the upcoming Honours project,

Renae Sayers with Brian Day presenting Fireballs at Clyde Arbuckle Elementary School, San Jose CA

Curtin University PhD candidate Nicole Neville at Lunar Sample Laboratory Facility during her LPI internship

Morgan Cox (Eugene Shoemaker Impact Cratering Award) holding a recovered sample of shatter cones from Wolf Creek Crater, Western Australia

investigating shocked microstructures in tiny crystals from rocks found in the center of the crater. Morgan also has a first author paper in review, confirming a brand new impact crater in Western Australia.

University of New South Wales PhD candidate Tara Djokic, uncovered fossils in ancient hot spring deposits in the Pilbara Craton of Western Australia, pushing back the earliest known evidence for microbial life on land by 580 million years. Her first author research was published in Nature Communications (Earliest signs of life on land preserved in ca. 3.5 Ga hot spring deposits).

Curtin University graduate, Lucy Forman completed her PhD: Impactors and the Impacted: Analytical Techniques to Identify and Understand the Impact Evolution of Extraterrstrial Materials, with commendation from the Vice Chancellor. Now has a position as a postdoctoral research associate in the School of Earth and Planetary Sciences, Curtin University, primarily working on Martian meteorites.

Curtin University graduate, Luke Daly, completed his PhD: Understanding Our Protoplanetary Disk by Chemical Analysis of Components in Meteorites. Now has a position as a Postdoctoral Research Associate in the School of Geographical and Earth Sciences at University of Glasgow, UK.

5. Mission Involvement

OSIRIS-Rex [Phil Bland, Trevor Ireland]; InSight [Katarina Miljjkovic]; Mars Science Laboratory [Penny King]; Akatsuki (Frank Mills), BepiColombo (Phil Bland), ExoMars (Martin Towner), Harabusa 2 (Trevor Ireland)

6. Grant Success totaling AU$3,309,895

Australian Research Council

Future Fellowship

- Unravelling the geology of Mars, awarded to Gretchen Benedix, $1,000,000.

Discovery Early Career Researcher Award

- Impact processes and evolution of the Martian crust, awarded to Katarina Miljkovic, $342,949.

Discovery Projects

- Structure of crust on Mars (Katarina Miljkovic, $148,259)
- A terrestrial hot spring setting for the origin of life? (Martin Van Kranendonk, $590,000)
- Lunar crustal structure from high-res gravity, topography, and seismic data (Will Featherstone, $393,100)

Royal Society Te Apārangi Marsden Fund, New Zealand

- Some Liked it Hot: Searching for Early Life in Terrestrial Hot Springs (Martin Van Kranendonk, AI, NZD$900,000)

7. Workshops

Shock metamorphism in terrestrial and extra-terrestrial rocks: this multidisciplinary four-day workshop brought together 32 Australian and international researchers from state-of-the-art laboratory methodologies in terrestrial and extra-terrestrial rocks, mineral and meteorite sample analyses. Researchers conducted numerical modelling and laboratory experiments on shock-wave progression in geologic and planetary analogue materials. The meeting was be followed by a three-day field trip to the Wolfe Creek crater, located near Halls Creek in Western Australia.

A two-day joint SSERVI AU and Macquarie Planetary

Shock Workshop SSERVI group 2017

Research Centre workshop, '2017 Planetary Frontiers', involved 88 participants from around Australia with two international keynote speakers, and was extremely successful. In addition to tremendous science, it provided a forum for the community to discuss strategy for how to respond to opportunities presented by the Australian Space Agency announcement, and major funding in 2018 (proposal for an Australian Research Council Centre of Excellence in Planetary Science).

Canada

1.Canadian Lunar Research Network (CLRN) Team Project Report

The Canadian Lunar Research Network (CLRN) is comprised of approximately a dozen universities from across Canada. The lead institution is the University of Western Ontario (Western). Below we detail activities for 2017.

1.1. Science Activities

Lunar science activities have been concentrated at the lead institution (Western). Dr. Phil Stooke has been using LRO images to re-map Apollo traverses and to find spacecraft impact locations. In 2017 he reported on the locations of Apollo 12 and 14 Lunar Module ascent stage impact sites, the location of the impact of Chang'E 1, the first Chinese orbiter, and SMART-1, an ESA lunar orbiter (Stooke, 2017). The Apollo 15 and 17 LM impact sites have been found since then. The systematic Apollo EVA re-mapping is being reported at the Lunar and Planetary Science Conference (LPSC) in 2018 (Stooke, 2018, LPSC abs #1007).

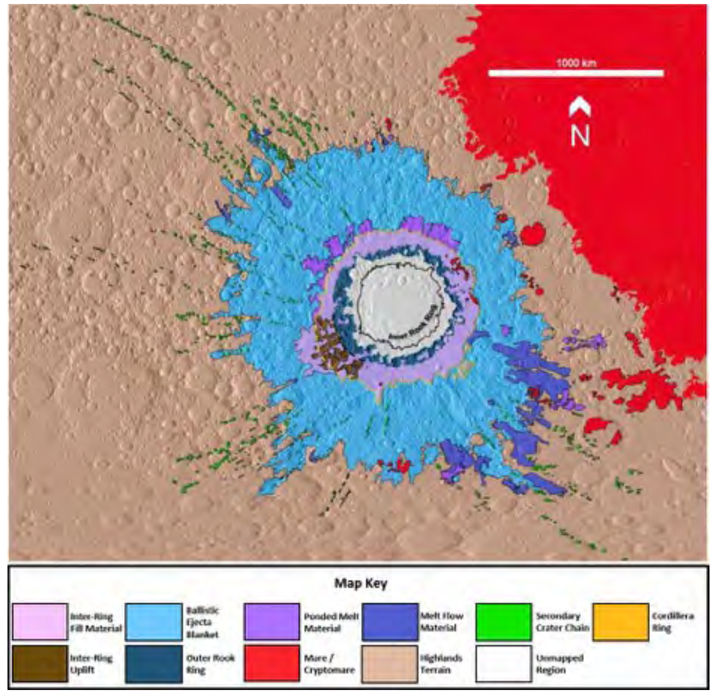


Fig. 1. New morphologic map of ejecta facies of the Hevelius Formation and other major units within and around Orientale Basin. For reference, an approximation of the Inner Rook ring is shown, represented by the black line within the unmapped region at the Basin center. Base image: NASA LRO-LOLA 1024PPD derived hillshade dataset. Base Image Credit: NASA / GSFC / Arizona State University. Figure modified from Morse et al. (2018).

Within the last year Zachary Morse (PhD candidate), together with Drs. Osinski and Tornabene, completed a new morphologic mapping and analysis of Orientale basin and its associated ejecta deposits. This new mapping using high-resolution LRO-WAC and NAC imagery is the most accurate representation of the location and distribution of the Orientale ejecta facies yet produced (**Fig. 1**). From this mapping effort they were able to determine several patterns in the overall emplacement of the ejecta which indicate that the Orientale impact direction was toward the southeast, and this impact occurred at an angle of 25° to 45°. This mapping also showed clear evidence that a large portion of the melt-rich ejecta around Orientale was emplaced as a secondary wave, after the initial ballistic ejecta emplacement. For additional detail on this work see Morse et al. (2018). This work has now been extended to the analysis of Tsiolkovsky Crater and the associated ejecta deposits. Analysis of this mapping has revealed similar patterns in the ejecta emplacement including a bilateral symmetry to all ejecta facies as well as a distinct "forbidden zone" devoid of secondary impact craters to the northwest of the impact structure. This work has been submitted to the 2018 LPSC (Morse et al., 2018, LPSC abs #2196).

PhD Candidate Patrick Hill, together with Drs. Osinski, Banerjee, Herd (U. Alberta), Korotev (Washington U. Saint Louis), and Nasir (Sultan Qaboos U.), have completed a classification of three lunar meteorites (Dhofar 1673, 1983, and 1984) that are potentially paired based on the petrology and geochemistry of the samples. This work utilized bulk chemistry, mineral chemistry, petrography, and isotope chemistry to discuss the relationship of these three meteorites and was submitted to Meteoritics & Planetary Science. Hill and Osinski are extending this work to the investigation of the emplacement of impact melt rock in lunar impactites. Several authors have stated that volatile phases play an essential role in the formation of impact melt rock bearing breccias, particularly "suevites";

however, given the absence of volatile material on the lunar surface there should not be "lunar suevites". Preliminary results of this work were presented at the 80th Annual Meeting of the Meteoritical Society. Work on this project is ongoing, with more impactites from different terrestrial being compared to the lunar samples and the suevite samples found at the Ries impact structure.

Dr. Silber (PDF; now at Brown University), with Drs. Osinski and Grieve, used numerical modeling to investigate the combined effects of impact velocity and acoustic fluidization on lunar craters in the simple-to-complex transition regime (Silber et al. 2018). This study suggests that the transition from simple to complex structures is highly sensitive to the choice of the time decay and viscosity constants in the Block-Model of acoustic fluidization. Scaling suggests that the simple-to-complex transition occurs at a larger crater size, if higher impact velocities are considered, and is consistent with the observation that the simple-to-complex transition occurs at larger sizes on Mercury than Mars. Osinski, together with Drs. Silber, Grieve, Johnson (U. British Columbia) and Tornabene, have extended this to a study of fresh transitional craters on the Moon. They demonstrated that number of terraces increases with increasing crater size and in general, mare craters possess more terraces than highland craters of the same diameter. There are also clear differences in the d/D ratio of mare versus highland craters, with transitional craters in mare targets being noticeably shallower than similarly sized highland craters. They have proposed that layering in mare targets is the major driver for these differences. This work has been submitted for publication and will be presented at LPSC 2018 (Osinski et al., 2018, LPSC abs #1734).

Dr. Zanetti (PDF) is a co-investigator on a NASA Lunar Data Analysis Program proposal to study the formation and distribution of self-secondary ejecta fragments and their influence in the ejecta emplacement process of Copernican craters on the Moon. This proposal is an extension of his work published in February 2017 (Zanetti et al. 2017). He is also involved in studies mapping and calculating the volume of impact melt produced by simple and transition diameter craters on the Moon. This impact melt study is meant to provide observational evidence for the constraining the relationship of projectile impact velocity to melt production volume (Silber et al., 2018, LPSC abs #1401). He is also studying the volumes of lunar volcanic domes using tools he co-developed for improved methods of volume estimation (Baum et al., 2018, LPSC abs #2442). He is collaborating on a project comparing the compositional properties and glass content of lunar impact melt flows to their circular polarization ratio radar roughness.

In other work, Drs. Flemming and Osinski collaborated with Dr. Hui (Nanjing U., Notre Dame U.) in a study of hydrogen isotopes of lunar highlands samples that suggest a heterogeneous lunar interior (Hui et al., 2017). Dr. Osinski also collaborated with Dr. Zhang (Macau U. of Science and Technology,) to investigate the diversity of basaltic lunar volcanism associated with buried impact structures (Zhang et al. 2018).

1.2. Exploration Activities

In collaboration with MPB Communications, Dr. Cloutis (U. Winnipeg) completed an ESA SysNova challenge project looking at a 12U cubesat to map volatiles in permanently shadowed regions of the Moon. This concept study was selected by ESA for the next level of effort. Results will be presented at the 2018 LPSC (Cloutis et al., 2018, LPSC abs #2189). Dr. Cloutis has also been working with MPB on a project (funded since 2016) to develop a lunar surface simulation chamber for CSA (Kruzelecky et al., 2018).

At Western, Dr. Osinski won a contract from the Canadian Space Agency (CSA) to conduct a Science Maturation Study for the Precursor to Human and Scientific Rover (PHASR) Lunar Demonstrator Mission, currently being considered by ESA, CSA and JAXA. This mission involves lunar sample return via the evolvable Deep Space Habitat (eDSH). As part of this contract, the Western team is refining science objectives and requirements, investigating science instrument payloads needed to address objectives, conducting traverse planning, studying requirements for sample handling and curation, and data analysis.

1.3. Sudbury Impact Cratering Field School

From September 23rd to 30th 2017, the CLRN, in

Fig. 2. Students exploring the Sudbury impact structure.

collaboration with the Centre for Planetary Science and Exploration at Western and the Inner Solar System Impact Processes team (PI: Kring), ran the third successful field school at the Sudbury impact structure (**Fig. 2**). Thirty students attended: 14 students from the US and supported by SSERVI, 2 students from Belgium, 1 student from the University of Alberta, and 13 students from Western. This intensive 7-day short course and field training program focused on understanding impact cratering as a planetary geological process. The course introduced students to the processes and products of impact cratering on Earth and throughout the Solar System and featured a mix of lectures, field excursions and a field research project.

2. Collaborations with SSERVI Teams and International Partners

Dr. Cloutis is a collaborator on a SSERVI proposal that was approved in 2017: 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, and they also co-organized the Impact Cratering Short Course and Field School that was held at the Sudbury impact structure in September 2017 (see above). 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). The main work focused on modelling of bolide impacts to estimate ground damage, in particular the probability that windows are damaged as a function of bolide yield and impact frequency. This is collaborative work with the ATAP NASA Ames team and has resulted in a series of model estimates of ground-level overpressure from real bolides. Dr. Brown has also conducted refinement of airwave signal measurements for bolides to more accurately estimate yield (Gi and Brown, 2017).

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 our group is field testing several DFN cameras in Canada for eventual deployment across the country to augment the planned global fireball observatory.

3. Public Engagement

CLRN has continued working alongside the Centre for Planetary Science and Exploration's outreach program to promote planetary science education in Southern Ontario. Several of the activities delivered to elementary and high school students cover the topics of impact cratering, lunar meteorites, Moon-Earth orbital dynamics, and rover and human exploration of the lunar surface.

Members of CLRN along with CPSX and members of the Royal Astronomical Society of Canada (RASC) hosted an event in celebration of International Observe the Moon Night on October 28th 2017. This event was held at the Hume Cronyn Memorial Observatory on the campus of Western University and featured several outreach activities for the younger attendees, lunar observation using several high-powered optical telescopes, and three public talks by members of CPSX and CLRN. Dr. Stooke presented his work on locating of potential crash sites for lunar orbital satellites which impacted the lunar surface after the termination of their mission. Hill presented on the distribution of natural satellites throughout and the Solar System before highlighting the proposed hypotheses for the formation of our Moon. Morse discussed his mapping efforts around Orientale basin along with the methodology and process of mapping lunar surface features using remote sensing datasets. This event was covered by local media including a radio panel discussion focused on lunar exploration and a television interview with CTV London. The events for International Observe the Moon night at Western were well attended with over 60 members of the public visiting throughout the night. Hill's research, on the formation of the Moon, was also covered by the Western University student newspaper and the local radio-podcast Gradcast.

4. Student / Early Career Participation

Undergraduate Students

1. Racel Sopocco, University of Western Ontario, mapping of lunar craters.
2. Kayle Hansen, University of Western Ontario, mapping of lunar craters.
3. Chang Yu Sung, University of Western Ontario, VLF radiation from meteors
4. Denis Heynen, University of Western Ontario, LLF radiation from meteors (Sep 2016- present)
5. Sean Huggins, University of Western Ontario, EMCCD matched filter detection for meteors
6. Michael Molliconi, University of Western Ontario, specular radar – optical simultaneous measurements

Graduate Students

7. Patrick Hill, University of Western Ontario, lunar meteorites, stable isotope studies of Apollo samples.
8. Zachary Morse, University of Western Ontario, impact cratering processes.
9. Chang Yu Sung, University of Western Ontario, search for VLF emission from fireballs
10. Mark Froncisz, University of Western Ontario, detecting interstellar meteoroids using radar
11. Denis Vida, University of Western Ontario, high precision optical meteor reduction techniques
12. Michael Mazur, University of Western Ontario, origin of low velocity meteoroids at Earth

Postdoctoral Fellows

13. Michael Zanetti, University of Western Ontario, impact cratering processes, lunar exploration technologies
14. Eric Pilles, University of Western Ontario, impact cratering processes, lunar exploration technologies

5. Mission Involvement

1. Chang'e 3 lander/rover, Cloutis, Collaborator, data analysis.
2. Lunar Reconnaissance Orbiter Camera (LROC), Michael Zanetti, Science Team Member, data analysis.

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France

Overall context:

With the official signing on May, 24th, 2016, at the US consulate in Toulouse, France, IRAP became a SSERVI partner after the acceptance 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 58th ('Surface Exploration and Sample Return: a New Era in Planetary Sciences') and LPSC 48th meetings held in Houston (March, 18th-24th, 2017) and met with the SSERVI partners and staff at the EC meeting held on March, 19th. Then IRAP attended the 5th European Lunar Symposium held in Muenster, Germany, on May, 2nd- 3rd, 2017, followed by the New Views of the Moon meeting on May, 4th -5th and met with many SSERVI colleagues. IRAP also regularly interacted with SSERVI officers and staff in order to prepare and organize the next ELS meeting to be held in Toulouse, France, on May, 13th-16th, 2018.

P. Pinet and S. Chevrel participated in a brainstorming workshop of the EuroMoon team held at the International Space Science Institute (ISSI) in Bern focused on lunar surface composition and processes, and preparing for the future exploration of the Moon (10/02-10/05/2017). The objectives are 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 also attended in Bern the first workshop of the ISSI team on the topic 'An international reference for seismological data sets and internal structure models of the Moon' (23/10 – 10/ 27/ 2017). 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.

Selected Science and Future Project Highlights

Lunar Orbital Imaging Spectroscopy and Geology:

Given the wealth of the dataset acquired by the Moon Mineralogy Mapper imaging spectrometer (M^3) onboard the Chandrayaan mission, advanced hyperspectral processing (MGM modelling) 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 processes. 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 M^3 spectra with the objective of documenting the petrology at Copernicus and Aristarchus craters through characterization of plagioclase and mafic crystal field absorptions, from exposed outcrops (e.g., central peaks, inner walls and rims) (Chevrel et al., 2017a; 2017b; Pinet et al., 2017).

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. The current approach considers for the first time the stratification of scattering properties and the spherical geometry (Gillet et al., 2017; Gillet, Toulouse University Ph.Dissertation, dec. 2017).

To quantify attenuation and distinguish between elastic (scattering) and inelastic (absorption) mechanisms, the time of arrival of the maximum of energy tmax and the coda quality factor Qc are measured. The former is controlled by both scattering and absorption, while the latter is an excellent proxy for absorption. Using an advanced attenuation model, the depth of shallow moonquakes is determined by inversion n based on the observed variation of tmax with epicentral distance. On average, they are found to originate from a depth of about 50 km ± 20 km, which suggests that these earthquakes are caused by the failure of deep faults in the brittle part of the Moon. But shallow moonquakes are the most energetic events on the Moon, with magnitudes as large as 5, and are also characterized by a strong stress drop. In future work, the problem of the seismic stress drop will be reexamined with the aid of this new attenuation model.

Future Lunar Missions and Instruments

SELMA:

IRAP is contributing to the SELMA (Surface, Environment, and Lunar Magnetic Anomalies) mission proposal submitted in response to ESA's Cosmic Vision AO for the M5 mission Opportunity. SELMA is a mission to study how the Moon environment and surface interact. SELMA addresses four overarching science questions: (1) What is the origin of water on the Moon? (2) How do the "volatile cycles" on the Moon work? (3) How do the lunar mini-magnetospheres work? (4) What is the influence of dust on the lunar environment and surface? SELMA uses a unique combination of remote sensing via UV, IR, and energetic neutral atoms and local measurements of plasma, fields, waves, exospheric gasses, and dust. It will also conduct an impact experiment to investigate volatile content in the soil of the permanently shadowed area of Shackleton crater. The spacecraft will carry an impact probe to sound the Reiner-Gamma mini-magnetosphere and its interaction with the lunar regolith from the SELMA orbit down to the surface. SELMA is a flexible and short (15 months) mission including the following elements: SELMA orbiter, SELMA Impact Probe for Magnetic Anomalies (SIP-MA), passive Impactor, and Relaying CubeSat (RCS). SELMA is placed on quasi-frozen polar orbit 30 km x 200 km with the pericenter over the South Pole. Approximately 9 months after the launch SELMA releases SIP-MA to sound the Reiner-Gamma magnetic anomaly with a very high time resolution of <0.5 s to investigate the small-scale structure of the respective mini-magnetosphere. At the end of the mission the passive impactor impacts the permanently shadowed region of the Shackleton crater >10 seconds before SELMA and the SELMA orbiter flies through the resulted plume to perform high resolution mass spectroscopy of the released volatiles.

DORN:

Since the early stages of 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 gas transport through the lunar regolith and of volatiles and dust in the lunar exosphere, the monitoring of 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") is being developed at IRAP, which is aimed at measuring both radon and polonium atoms around the lander, and the subsurface flux of radon at the landing site.

LIBS:

Since 2012, Laser-induced Breakdown Spectroscopy (LIBS) 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.

Small bodies:

ROSETTA:

With Rosetta's end-of-mission in late 2016, IRAP is currently phasing out its work for this space mission. In 2017, a number of studies related to the molecular species of the comet 67P by Rosina (Hoang et al. 2017), and studies of the interior of the comet by the CONSERT radar (Ciarletti et al. 2017) were finalized and published.

We are now preparing for the next generations of instruments that will assess the interior of small bodies in the Solar System by using monostatic and bistatic radars (Herique et al., 2017).

IRAP is also involved in the development of new space cameras based on the CMOS technology. These cameras will be equipped on the next NASA Mars 2020 Rover with the SuperCam instrument on-board. These detectors are very versatile and will be used

in many configurations. With an agreement with the Google X-prize competitor Team Indus, a set of CMOS detectors will be launched to the Moon in 2018 (https://presse.cnes.fr/fr/cooperation-spatiale-entre-la-france-et-linde-signature-daccords-pour-les-lanceurs-futurs-et-pour). Another mission will also take advantage of this development: IRAP is starting 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 early 2019 (Levasseur-Regourd et al. 2014).

Dawn:

This year, the Dawn spacecraft has completed an initial "extended mission," returning to an altitude well above the surface of Ceres. This maneuver allowed the Gamma-Ray and Neutron Detector (GRaND) instrument to obtain a much better measure of background noise and to understand how this background noise may have changed over time. Thanks to this new information, the instrument data obtained during the Low-Altitude Orbit Mapping (LAMO) have been reprocessed in order to obtain much better estimates of the water and Fe content on the surface of the asteroid. A publication in Science (Prettyman et al., 2017) presents these maps of the distribution of water and iron. The results show a strong enrichment in H towards the poles, certainly related to the presence of ice in the sub-surface. Moreover, the H and Fe contents in the equatorial zone (without ice) are close to 'chondritic' values, even if in detail there seems to be a slight depletion in Fe. This latter observation can be interpreted in terms of internal differentiation (Fe transport downwards), or it may be the result of dilution by a 'neutral' element such as C. In parallel to these broad instrument-related activities, the Toulouse team has worked on a numerical model of the physical, chemical, thermal and geological history of Ceres--work presented at the LPSC in 2017. In addition, we have contributed to other work in press concerning the internal structure of Ceres, the similarity of Ceres and meteorites, and a theoretical study of the geochemical evolution of the interior of the asteroid; the latter works will be part of a special volume of the journal Meteoritics and Planetary Science dedicated to Ceres.

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Germany

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 CoI-contributions to PI-experiments.

German solar system exploration and research activities are related to the following missions. Mars Express, Rosetta share the same ESA bus design and have similar remote sensing payload.

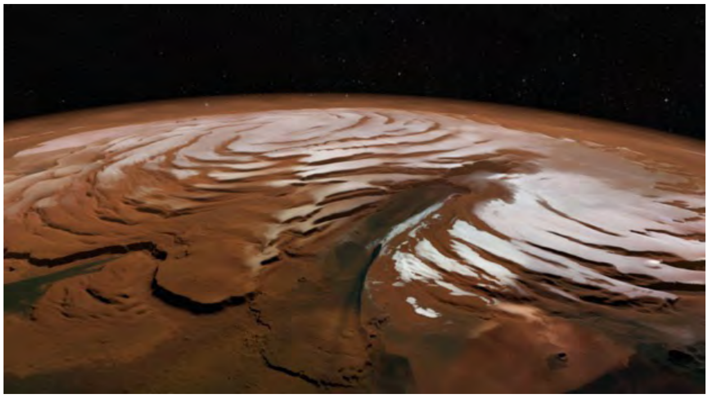
Rosetta is an ESA cornerstone mission to P/67Guryumov Gerasimenko with the camera OSIRIS as major German orbiter contribution, a significant contribution to the Italian spectrometer (VIRTIS) and the Rosetta Philae Lander with a set of German instruments (MUPUS, ROLIS, SESAME, COSIMA) is also a major German contribution. The mission consisted of the Rosetta orbiter and the Philae lander. The probes were launched on 2 March 2004, travelled 6.4 billion km in 10 years and, with the help of a few planet swing-bys, arrived at Comet 67P/Churyumov-Gerasimenko on 6 August 2014. DLR 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 –

Outgassing 67P/Churyumov-Gerasimenko. ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPMDASP/IDA67P/ NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.

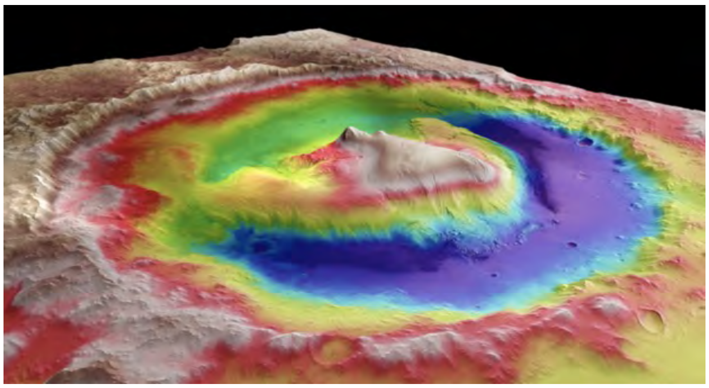
a feat never before accomplished – was designed and controlled. On 27 July 2016, after almost two years of cometary exploration, the communications unit on board the Rosetta orbiter (which it used to communicate with the Philae lander) was switched off. On 30 September 2016, the operational part of the mission came to an official end, within the orbiters controlled descent to the surface of 67P/Churyumov-Gerasimenko.

Mars Express orbits Mars with the High Resolution Stereo Camera (HRSC) as major German contribution. HRSC provides three- dimensional color mapping of the Martian surface and with resolution of 10-20 m/pixel as well as monitoring of surface atmospheric clouds and dust. In addition HRSC maps the Martian moons Phobos and Deimos and supports public outreach in many ways. Germany is also contributing to the ESA **ExoMars** Rover Mission by providing a High Resolution Camera in cooperation with the panorama camera of UK and also contributes to the NASA **Mars 2020** MastCam-Z instrument by supporting stereo processing.

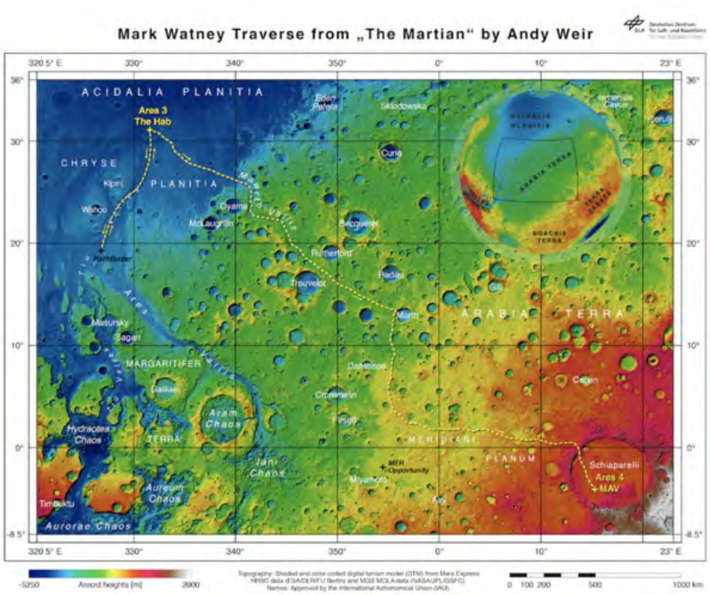
Dawn is a NASA Discovery Mission launched in 2007 to explore the two major asteroids Vesta and Ceres. The



The Martian North Pole as seen by the High Resolution Stereo Camera (HRSC) on the ESA Mission Mars Express. ESA/DLR/FU Berlin.



Digital Terrain Model of Gale Crater by the High Resolution Stereo Camera (HRSC) on the ESA Mission Mars Express. ESA/DLR/FU Berlin.



Digital Terrain Model of the Martian Quadrangle MC11East by the High Resolution Stereo Camera (HRSC) on the ESA Mission Mars Express. ESA/DLR/FU Berlin. Public Outreach example: the movie 'The Martian' tells the story of Mark Watney's journey from Acidalia Planitia to Schiaparelli crater which is marked on the HRSC derived topographic map.

framing camera (FC), the stereo observation definition of the mission, the stereo data evaluation and the cartographic definition and processing are the major German contributions to Dawn.

NASA's **InSight** mission will be the first geophysical station on Mars. The major German contribution is the heat flow probe (HP3) and the leveling system for the French seismometer.

For **Messenger** and **Lunar Reconnaissance Orbiter** Germany is mainly contributing to the estimation of the surface topography and age determination.

The JAXA mission **Hayabusa2** is on a sample return mission to asteroid (162173) Ryugu and on board carries the **MASCOT** lander, which was built by DLR in collaboration with the French National Center for Space Studies (CNES). The aim of the mission is to find out more about the origins and evolution of our Solar System. Asteroids account for some of the most primordial celestial bodies. Researching asteroids allows us to take a glimpse into our cosmic past. But that is not the only reason: Ryugu belongs to the class of asteroids referred to as near-Earth asteroids. The 10 kg MASCOT carries 4 instruments, is designed to live for 2 days and nights on the asteroid and will provide in-situ data as well as ground truth for the orbiter instruments. Hayabusa 2 will arrive at Ryugu in April 2018 and Mascot will land in October 2018. After sampling the surface Hayabusa 2 will return the samples to Earth in 2020.

Bepicolombo is an ESA cornerstone mission to Mercury to be launched in 2018. Major German contributions are the laser altimeter (BELA) and the infrared spectrometer (MERTIS).

JUICE is an ESA L-mission to Ganymede to be launched in 2024 to explore the Galilean Satellites. Major German contributions are the laser altimeter (GALA) and the camera (JANUS) an Italian/German cooperation and the microwave experiment.

The French mission **Corot** detected about 30 confirmed exoplanets with a software contribution provided by Germany and the ESA S- and M-missions **CHEOPS** and PLATO will search for exoplanets with focus on rocky planets with telescope and camera contributions from Germany. In addition, Germany is contributing to ESA in context with the lunar Prospect activities and also studying additional lunar lander possibilities. In 2016/2017 we also carried out a field campaigns for three month to Antarctica to study dry valleys as Mars analogous and for testing ExoMars lander instrumentation.

In context with the above missions the scientific objectives are investigating the origin and evolution to solar system objects with respect to their surface geology, interior, atmospheres and habitability.

Italy

1. Italy Team Project report

The SSERVI Italian node was established in September, 2014, when the Istituto Nazionale di Fisica Nucleare (INFN) of the Italian Republic became an Affiliate partner, with the main research topic of retroreflectors for planetary exploration. The Italian partnership was elevated to Associate level, when the National Aeronautic and Space Administration (NASA) and Italian Space Agency (ASI) signed a dedicated Implementing Arrangement, during the Workshop held on June 14th 2017, at the Italian Embassy in Washington DC. The workshop was also an interesting opportunity to discuss respective national programs and plans in the field of small bodies, with particular reference to asteroids and Mars moon Phobos, but also for small satellite missions and planetary laser ranging.

Dr. Jim Green, NASA Planetary Science Division Director and dr. Enrico Flamini, ASI Chief Scientist, signing the Implementing Arrangement for ASI Association

Group picture of the MiniWorkshop participants at Italian Embassy

The Italian Node Association has been based on the "Italian Proposal for the participation to the NASA SSERVI International Partners Program -Associate membership Application", issued by ASI on 16th June 2016 and reviewed and accepted by NASA in the following months. The Proposal summarize the main research areas where the Italian scientific community, composed by research institutes like INFN and INAF and national Universities, is active.

In particular, concerning Lunar Science:

- Lunar geology and crater chronology
- Spectral characterization of minerals in compact rocks and dust
- Analysis of the regolith and Terrestrial Analogues (operations simulation)
- Radio-astronomy
- Satellite/lunar laser ranging (SLR/LLR) and retroreflector arrays
- Astrobiology and life science
- Robotics
- In-situ resources utilization (ISRU)
- Surface Mobility
- Trajectory optimization and Non-Keplerian Orbits

For NEO Science, the Italian scientific community is currently active in:

- Near-Earth Object dynamics, physical characterization and impact monitoring
- Mission design in proximity of irregular bodies

The Museo Civico di Rovereto is intended to provide specific support for outreach activities related to Moon observation and exploration, and for specific training events.

The following sections provide a summary of the main research conducted and results obtained.

Logo of the Italian SSERVI team

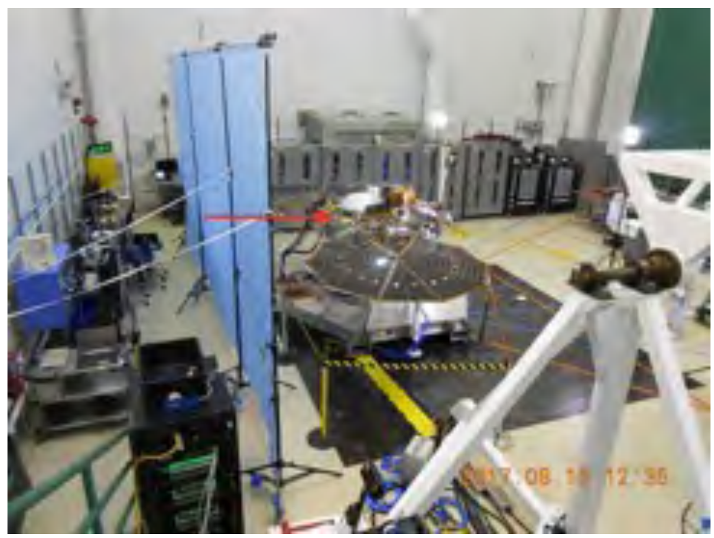
1. INFN Team Activities

Since the very first days of INFN's affiliation with SSERVI, the most important activity carried on by the SCF_Lab of INFN-LNF has been the R&D on laser retroreflectors for solar system exploration and research, working in very close collaboration with ASI's Matera Laser Ranging Observatory (MLRO) at ASI-CGS space geodesy center. This activity culminated in the space flight qualification of the micro-reflector payload INRRI-EDM/2016 onboard ExoMars EDM Schiaparelli 2016 (Advances in Space Research 59 (2017) 645-655). In 2017, the SCF_Lab qualified for space flight LaRRI for the InSight Mars lander (described in the following) and built MoOnLIGHT, a single, large retroreflector for lunar laser ranging from MLRO for precision tests of general relativity. LaRRI is the microreflector array space qualified for the InSight Mars lander (Space Research Today, No. 200, December 2017), which is scheduled to fly to Mars in May 2017. InSight is a NASA Discovery Program mission, and, from 2018 to 2020, will investigate the interior of Mars, in order to shed light on the formation of the rocky planets in the inner solar system. Once on the surface of Mars, as the first-ever operational retroreflector on the Red Planet, LaRRI will serve as a passive, maintenance-free 'milestone' for laser interrogation by future orbiters, through laser altimetry, laser ranging, lidar atmospheric observations from orbit, laser flashes emitted by orbiters, and lasercomm.

2. INAF Team Activities

Moon: during 2017, in the frame of the UE "Horizon 2020" call for Space activities, the INAF OAPD and INAF IAPS were part of the winning proposal on PLANetary MAPping (PLANMAP), PI Matteo Massironi University of Padova. PLANMAP is designed to generate pipelines and enhanced products with three aims: 1) support observational strategies of planetary surfaces by orbiting spacecraft; 2) produce high-resolution products to characterize potential landing sites and sites of interest of future robotic and human missions, and 3) use 3D

LaRRI (the base of the dome has a diameter of 54 mm; each CCR has a front face diameter of 1/2 inch)



Red arrow pinpoints the position of the microreflector on board InSight probe geological reconstructions and virtual environments for training astronauts and planetary scientists. The bodies that will be studied within the proposal are: Mercury, Mars and the Moon.

The INAF-IAPS team (M.C. De Sanctis, S. De Angelis, M. Formisano, IAPS, INAF Rome and J.R. Brucato INAF-Astrophysical Observatory of Arcetri Florence), together with colleague of University of Milan (Michèle Mavagna) is part of the PROSPECT project, for Moon exploration within the ESA framework. The Project foresees different missions for the exploration of the Moon, and for exploration of the Lunar poles in particular. They actively participated in the definition of mission requirements, that included the examination of the lunar volatiles at the Poles, and supported the team with simulations of the lunar ice sublimation during the extraction and delivery to the instruments. Laboratory activities are ongoing for the investigation of ice sublimation from sample analogues collected from the drill.

In the same year, INAF-OAC Naples (F. Esposito, C. Molfese, F. Cozzolino,) scientifically collaborated with IKI (Moscow) for dust detection and characterization experiments for lunar exploration.

The INAF-IAPS in collaboration with University of Parma (Cristian Carli; Maria Sgavetti e Giovanna Serventi) have been involved in the last years in scientific activity related to spectral analysis of mineral mixture and rocks, suitable as lunar analogues. Moreover, they are collaborating with colleagues of IRAP (CNRS Toulose) in spectral imaging measurements and analyses of lunar analogues.

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2. Pinet PC, Glenadel-Justaut D, Daydou Y, Ceuleneer G, Gou S, Launeau P, Chevrel SD, Carli C:2016. MGM deconvolution of complex mafic mineralogy rock slab spectra from visible-near infrared imaging spectroscopy: implications for the characterization of the terrestrial ocean crust and of the lunar crust. Whispers, LosAngeles, USA (August 2016). Abs#

Phobos: on November 26, 2016, the ESA ExoMars Trace Gas Orbiter performed a close approach to Phobos at a distance of about 7600 km. The geometry of the observation allowed the new stereo camera on board CaSSIS to capture a stereo pair centered on the boundary of the two spectral units in the direction of the sub-mars point. The group at the Astronomical Observatory of Padova (OAPD, INAF) started a study to focus on these data in order to refine the distribution and spatial extent of the two units, and to provide detailed colored maps. CaSSIS is a stereo camera based on the push-frame concept, with one panchromatic and 3 broad-band filters deposited on top of the window shielding the detector. It can acquire stereo pairs for each filter at the same time allowing scientists to generate a Digital Terrain Model (DTM) for each band. The new software developed at OAPD to generate DTMs from the CaSSIS data will allow researchers to exploit additional information coming from the spectral data in order to improve the performance of the image matching, but it should also provide more 3D information on the regions observed at different wavelengths. The first images of Phobos, obtained using all the filters, are the best candidates to be used for multispectral 3D analysis.

In the period 2015-2017, INAF-OAC Naples (F. Esposito,) participated as a member of the ESA Study Team, to define the scientific requirements of a Sample Return mission from Phobos in the frame of the project “Phobos Sample Returm” under study by ESA. In this framework, they also worked, in cooperation with IKI (Moscow), on a dust sensor proposal for monitoring of the abundance and electrical charge of dust grains possibly present close to the Phobos and Deimos orbits.

NEA: the INAF IAPS (M.C. De Sanctis, S. De Angelis) supported the exploration of NEA performing spectral analysis of meteorites coming from NEA, using the spectroscopy facilities at IAPS (spectrometer in the range of 0.2-2.5 microns; Spectral imager in the range of 0.2-5 microns, with a 38 micron pixel size) to characterize different meteorites and micrometeorites.

Curation Facility: (J.R. Brucato and A- Meneghin INAF-

Astrophysical Observatory of Arcetri, Florence) EURO-CARES (European Curation of Astromaterials Returned from Space) www.euro-cares.eu is a multinational three-year project running from January 2015 to December 2017, and funded by the European Commission H2020 program. The project involved 6 different countries and 14 different institutions. The objective was to roadmap a European Sample Curation Facility (ESCF) that would be suitable for the curation of material returned from the Moon, Mars and asteroids. While there have been previous studies specific to particular missions, countries, or target bodies, this was the first project to bring together scientists and engineers from across Europe to plan a single facility that would fit the needs of European sample return missions over the next decades. The team planned the pathway of returned samples from the landing site, transport to the facility, early and preliminary examination, and long-term storage.

3. IRSPS Team Activities

The research group is mainly focused on geological analyses of remote sensing planetary data and on terrestrial planetary analogues used for scientific and technologic research in preparation for human exploration missions.

Lava Tubes

Identification of lava tubes on the Moon, Mars and Earth may support human exploration of planetary bodies. Lava tube entrances, in particular skylights and pit chains will be analyzed. Terrestrial skylight features and related lava tubes are under study in the Middle Atlas of Morocco in support of this analysis. In this area, lava tubes developed in Quaternary basaltic lava of small Flood Basalts. These are good analogues for the widespread lava plateaus on the Moon, Mars and Venus. The analysis will include mapping of the lava tubes by geoelectric tomography and high-frequency seismic surveys. Surveys of the lava tubes and related skylight will be operated by speleological crews. This analysis will be useful in understanding the nature of lava tube in Flood Basalts. The information will be also used in (i) planning the use of lava tubes as shelters during Solar flares, (ii) understanding how integrate lava tube shelters in a permanent base, (iii) integrating the exploration of lava tubes to enlarge the explorable range of areas around permanent bases.

Moon Exploration

We are also identifying possible locations for the installation of permanent bases and analyzing operational strategies. Several requirements are under consideration, such as accessibility and lithology suitable for ISRU. A first task is to define requirements for a Moon Base. This will be done by operational analysis based also on tests in analogue terrains. Then a careful geological and geomorphological analysis will be performed in order to identify suitable locations based on resources availability, illumination, flat areas, trafficability, etc.

Planetary Analogue Terrains

We will test systems and subsystems for robotic and human planetary exploration with the analysis of Earth analogues. IRSPS has an intensive program of analogues for planetary bodies, including the Moon and Mars. The Institute manages several field sites for science and technological tests in Morocco, Ethiopia, Italy, and elsewhere. In Morocco the Ibn Battuta Center successfully tested instruments for Mars exploration. It carried out a three-year test of the Dreams instrument that was on-board ExoMars 2016. It has also tested the radar-altimeter for the ExoMars mission and future automated EDL controls. Other experiments have been organized for radar sounders, drillings, electric subsurface tomography, etc. Scientific analogue studies have also been implemented. IRSPS is Partner and the Ibn Battuta Center is a Facility of the Europlanet Research Infrastructure financed by the EU Commission. IRSPS finances and hosts a dozen scientists to work on field sites for analogues research and tests.

Landing Site Analysis

We are also mapping landing sites and researching engineering constraints. IRSPS is analyzing, for the European Space Agency and Thales Alenia Space, the landing sites of the ExoMars missions for the definition of their compliancy to engineering constraints and other issues. In addition, we are analyzing mobility and trafficability for the ExoMars 2020rover.

4. Politecnico di Milano Team Activities

Moon

The Politecnico di Milano PoliMI team developed and experimentally validated the numerical model (Energy Exchange Model) for the PROSEED tool. This allowed the team to analyze the thermal energy exchange during icy regolith drilling and sampling in the lunar environment, and to tune the drill design and operations profile to minimize volatile sublimation. During the study, the thermal properties of the highlands dry and wet simulant were numerically and experimentally characterized, fundamental to any significant ground test or icy soil drilling. A numerical-experimental study was performed on lunar regolith simulant, characterized in vacuum and low temperature, dry and wet, to specify requirements and drive procedures to build a ground facility for low temperature/vacuum icy soils drilling, sampling and distribution testing, in support of PROSEED activities. Preliminary tests allowed the air trapped in the soil during vacuum creation to be quantified-- a critical datum to correctly reproduce analogue thermal properties for simulant in the test chamber; this property strongly affects the sublimation rate of potential volatiles injected in the soil.

PoliMI built and calibrated an experimental facility to validate with HIL vision-based algorithms for generating hazard avoidance maps and relative on-board navigation during landing phases. The facility is equipped with a 240x240 cm Moon diorama, a single camera, a robotic arm to simulate the landing vehicle, and a set of led lights calibrated to reproduce the vacuum Sun illumination on the lunar surface. The facility is also available for relative GNC and HDA in proximity of different objects like asteroids and comets with a dedicated mockup of the surface.

PoliMI developed in the past the plant design and the chemical dynamics simulator for an ISRU effort to produce water (Oxygen and Hydrogen) from lunar regolith, based on carbothermal reaction: a breadboard was built to demonstrate feasibility and efficiency of the process. Politecnico di Milano is currently updating the design and running further experimental tests to increase the reaction efficiency and demonstrate sustainability of the production cycle. The team also run a study to assess the Selective Laser Melting process applicable to 3D printing of lunar regolith. The study successfully demonstrated the printing feasibility from raw highlands simulants: the products were tested to characterize mechanical features, confirming the suitability for the 3D printed bricks for on-Moon construction. The study is still on going to further increase the product design complexity, and to design a printer suitable for the reduced gravity and vacuum conditions on the lunar surface.

Politecnico di Milano is also a prime contractor of the mission study LUMIO (Lunar Meteoroid Impacts Observer), awarded by ESA as winner of the SysNova competition. The mission consists of a 12U cubesat at Earth-Moon L2 to continuously monitor the lunar farside to detect flashes produced by meteoroid impacts, to complement information gathered through ground-based assets. The mission is currently undergoing a CDF review by ESA. Contacts have been established within this project with R. Suggs and D. Moser at NASA MSFC. The consortium includes also one partner from USA (University of Arizona).

Mars:

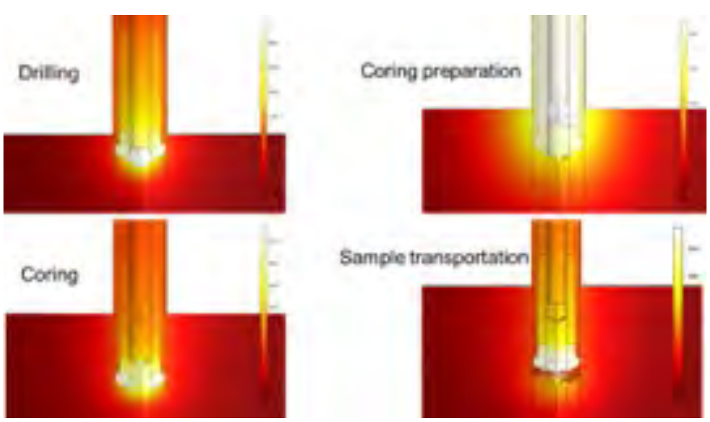
Politecnico di Milano has worked on a new concept to reach Mars based on ballistic capture. This allows reducing the total mission cost, widening the launch windows, and increasing the overall mission safety. Contacts have been established with J. Green. Moreover, the team is developing a robust guidance for the Entry descent and landing in Mars atmosphere and running feasibility studies on ISRU from Martian atmosphere to produce thrusters propellants.

NEA-Asteroids/small bodies

Politecnico di Milano had the scientific responsibility of the SD2 drill on Philae, the Rosetta lander. The team performed an extensive campaign to characterize the instrument and developed all the mission plans, integrated with those of the other instruments on-board Philae. The drill operated successfully during the First Science Sequence on comet 67/P. In the same mission, the team modeled the solar panels of Philae, the Rosetta lander. The team characterized the solar cells and solar panels and provided the hardware simulation tools to be integrated in the ground reference model of Philae.

In addition, Politecnico di Milano played a relevant role in the AIDA European part, the AIM mission phase A/B1 to define the spacecraft mission analysis to get to binary asteroids and to define the trajectory profile around a binary to maximize spacecraft science, according to the instruments requirements (lightening conditions, ground contacts visibility, etc). Moreover, Politecnico di Milano designed the DLR Mascot lander release trajectories to minimize the vehicle velocity after bouncing at the secondary surface contact, below the escape velocity and to maximize the lander retention by the secondary asteroid's gravity field. In this frame, Politecnico di Milano developed an N-body code to simulate the N-body (particles in the order of 105) aggregation in the formation processes of irregular bodies (asteroids/comets) under gravity effects to more precisely reproduce the gravity field at the body proximity, fundamental to a precision mission analysis designed for spacecraft hovering around irregular bodies. A tool for the classification of orbit families in the perturbed 3-body modelling environment for formation flying in binary systems is under development.

Moreover, Politecnico di Milano, in cooperation with former Selex-Galileo, developed simulation models for the breadboard of a sampling tool mechanism for low gravity bodies, based on the discrete elements method (DEM) formulation. The contribution to the study has been on soil simulation model, sampling tool simulation model, DEM simulation and comparison with experimental tests.



Energy Exchange Model EEM simulation results: temperature distribution during drilling in marble.

PoliMI Optical GNC lunar facility

1. V. Franzese, P. Di Lizia, and F. Topputo, Autonomous Optical Navigation for LUMIO Mission, 2018 Space Flight Mechanics Meeting, AIAA SciTech Forum, Paper AIAA 2018-1977

2. V.Pesce, M.Lavagna, R.Bevilacqua, Stereovision-Based Pose and Inertia Estimation of Unknown and Uncooperative Space Objects, Advances in Space Research ASR-D-16-00323R2

3. V.Pesce, L.Losi, M.Lavagna, vision-based state estimation of an uncooperative space object, Paper no.IAC-17,C1,3,7,International Astronautical Congress, Adelaide, September 2017

4. M.Ciarambino, L.Losi, M.Lavagna, A new ground facility for experimental testing of vision-based autonomous planetary landing, paper no.IAC-17,B6,3,5, International Astronautical Congress, Adelaide, September 2017

5. L.Losi, M.Lavagna, Vision based navigation for autonomous planetary landing, paper no.IAC-17,A3,2C,1,x40949 International Astronautical Congress, Adelaide, September 2017

6. F. Ferrari, A.Tasora, M.Lavagna, P.Masarati, N-body gravitational and contact dynamics for asteroid aggregation Journal Multibody System Dynamics, 2017, Vol.39(1), pp.3-20

7. E.Blazquez, F.Ferrari, M.Lavagna, Numerical Simulation of N-Body Asteroid aggregation with GPU-parallel hierarchical tree code algorithm, 27th AAS/AIAA Space Flight Mechanics Meeting, San Antonio, Texas, 5-9 February 2017

8. L.Bucci, M.Lavagna, F.Renk, Relative dynamics analysis and rendezvous techniques for lunar Near Rectilinear Halo Orbits, IAC-17,C1,9, 25-29 september 2017,Adelaide -Australia

9. A.Colagrossi, M.Lavagna, Assembly and Operations for a Cislunar Orbit Space Station, IAC 17,C1,9, 25-29 september 2017,Adelaide -Australia

10. M.Lavagna, L.Andreasi, NU-LHT-2M lunar simulant outgassing characterization, European Planetary Science Conference– 18-23 September 2017, Riga, Latvia

11. M.Lavagna, subsurface lunar icy samples collection: the tool-soil energy exchange model to drive penetrators design, European Planetary Science Conference– 18-23 September 2017, Riga, Latvia

5. University of Bologna Team Activities

NEA: at University of Bologna (UNIBO), the Radio science and Planetary Exploration Lab was involved in 2016-2017 in the Asteroid Impact Mission (AIM), at that time a candidate ESA mission to the binary Near-Earth Asteroid (65803) Didymos. AIM was ESA's contribution to the proposed joint mission AIDA (Asteroid Impact & Deflection Assessment), which also included NASA's spacecraft DART (Double Asteroid Redirection Test). AIM was intended to characterize for the first time a binary asteroid system, providing an understanding of its formation, and of the origin of the Solar System.

UNIBO's involvement in AIM was twofold: on the one side we led an ESA-funded study mainly targeted at performing numerical simulations of a radio science experiment (RSE) [1] with AIM, focused at its precise orbit determination within the Didymos system, providing an assessment of the accuracies achievable in the estimation of the scientific parameters of interest, like the heliocentric orbit of the system, the masses and the extended gravity fields of Didymos and Didymoon, and their rotational states. On the other side, since the original AIM spacecraft concept was designed to carry on-board two CubeSat Opportunity Payloads (COPINS), the University of Bologna studied, jointly with the University of Vigo (ES) and Micos Engineering GmbH (CH), a mission concept called DustCube [2]. Based on a 3U CubeSat platform, DustCube is intended to enhance the capability of the AIM spacecraft to unveil the properties of the natural dust environment of the Didymos binary system, by measuring concentrations, sizes and speeds of natural dust in the vicinity of Didymoon. Also, it was proved DustCube's capability to quantify and characterize the plume ejected during DART's impact by using a light scattering Nephelometer for remote (RNH) and in-situ (INH) measurements.

The original AIM spacecraft concept is now being reshaped to become lighter and more affordable [3] and is now called Hera. Hera leverages technology and payload pre-developments of the previous AIM, and focuses on key measurements to validate impact models such as the detailed characterization of the impact crater.

1. Zannoni M., et al., "Radio Science Investigations with the Asteroid Impact Mission", Advances in Space Research, In Press, Accepted Manuscript, DOI: 10.1016/j.asr.2017.12.003

2. Lasagni Manghi R. et al., "Preliminary orbital analysis for a CubeSat mission to the Didymos binary asteroid system", Advances in Space Research, In Press, Accepted Manuscript, DOI: 10.1016/j.asr.2017.12.014

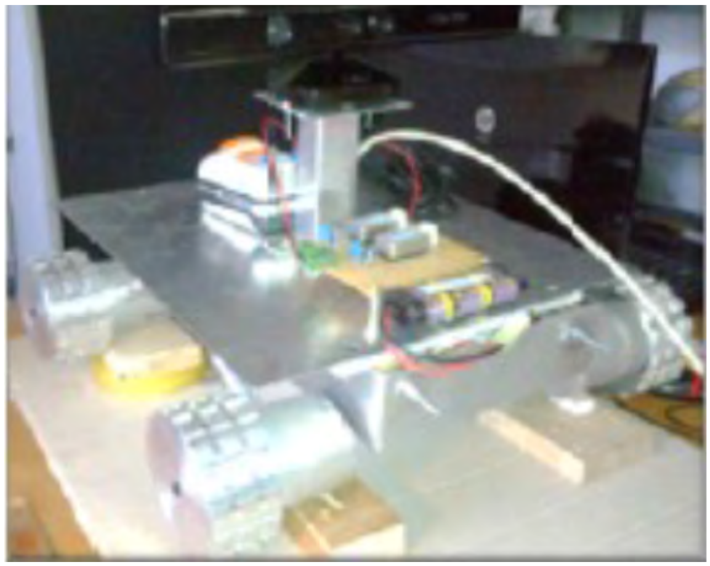
3. Michel, P., et al. "European component of the AIDA mission to a binary asteroid: Characterization and interpretation of the impact of the DART mission". Adv. Space Res. (2017), doi: 10.1016/j.asr.2017.12.020

6. “Sapienza” University of Rome Team Activities

Moon

Sapienza University of Rome built an experimental facility simulating the lunar environment, in order to test hardware-in-the loop guidance algorithms for lunar landing and surface robotic exploration. The facility has been constructed thanks to collaboration among professors and students at the School of Aerospace Engineering. The facility consists of a simulated surface and a tri-axis moving frame (a Cartesian robot) equipped with infrared distance sensors, accelerometers, and a video camera. In particular, a site on the Moon located in the Mare Serenitatis has been selected for a simulated surface. The soil is the result of sifted basalt powder in order to obtain grains of 0.2 mm of diameter, while the craters are obtained through molds and chalk according to the shape and structure of real lunar craters. The surface is scaled in dimensions with respect to the real site by a factor 1:2000. The reason for a scalable surface scenario is the use of cameras in the navigation of landing space vehicles for different phases of the descending trajectory. On the other hand, a scalable dusty surface allows for the simulation of the dusty environment that a legged or wheeled mobile robot meets when travelling in a harsh terrain on Moon or on Mars. An application of the simulation facility is based on a sort of Terrain Relative Navigation (TRN) method. The principle of this method lies on the localization of the space vehicle through the observations of known characteristics on a map. TRN systems assist space vehicles during the landing phase to compute a precise and safe landing. The systems use active range sensors to collect the altitude values of the surface under the lander and compare it with a Digital Elevation Model (DEM) database. For this purpose, a DEM of the simulated lunar surface has been carried out using the IR sensors in order to create a database of the flying area.

A small lunar rover has been developed with autonomous GNC capabilities to test steering algorithms on the simulated lunar soil. The design of the rover has involved the following subsystems: structure; locomotion (wheels and motors); power; vision; on-board computer, and communications. The rover is four-wheel-drive and can be represented using the unicycle model. The navigation is based on the vision system. In particular, a structured light device is used instead of stereo cameras.



Lunar rover operating at Moon simulant facility

7. MoonMapping project

The ‘Moon Mapping’ initiative was established in 2014 between the Italian and Chinese Governments to promote cooperation and exchange between undergraduate students from both countries. The operational phase of the project started in early 2015 and ended in 2017.

The main aim was to train new scholars to be able to work on different kinds of remotely-sensed data collected over the lunar surface by the Chinese space missions Chang’E-1/2. The project coordination has been assigned to the Italian Space Agency for the Italian side and to the Center of Space Exploration, China Ministry of Education, for the Chinese side.

Six main research topics have been identified:

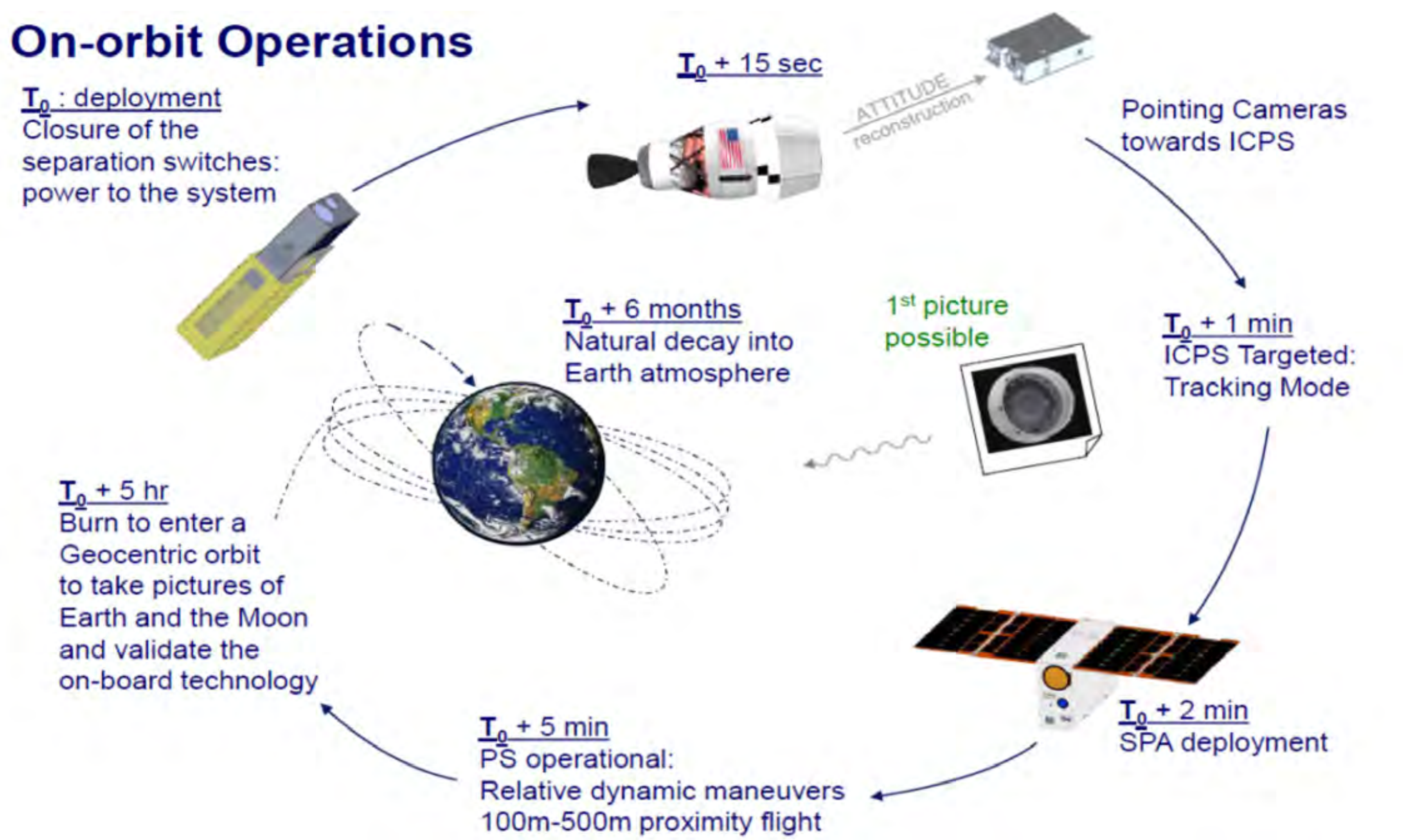
1. map of the solar wind ion
2. geomorphological map of the Moon
3. data pre-processing of Chang'E-1 mission
4. map of element distribution
5. establishment of 3D digital visualization system
6. compilation and publication of a tutorial on joint lunar mapping

8. Collaborations with SSERVI Teams and International Partners

The first joint activity was the organization and management of the session LSE2 "Site selections for lunar outposts and permanent bases" (Convener: S. Pirrotta, Co-Conveners: G. Schmidt , G. G. Ori) at the European Planetary Science Conference (EPSC2017), 17th – 22nd September 2017, Radisson Blu Hotel, Riga, Latvia.

9. Mission Involvement

The Italian Space Agency is working on the development of the 6U cubesat "Argomoon," selected in 2016 by NASA HQ Exploration Systems Mission Directorate (ESMD) as a Secondary Payload for the Exploration Mission 1 (currently planned for December 2019) 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, in particular of the ICP stage and cubesats' dispensers. 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. Two cameras with wide and narrow FoVs will allow the main functions of the imaging dedicated algorithm: target identification, proximity navigation, and low and high resolution picture capturing. The program is currently in phase C and the industrial prime contractor for ASI is Argotec company, located in Turin, Italy.



Argomoon mission summary

Being the first Italian mission in deep space, the satellite will also be used for education and outreach projects.

Moreover, the scientific Italian teams are involved in the following missions:

1. TeamIndus mission 2018, MoonLIGHT and INRRI. INFN will deliver the next generation big lunar retroreflector (MoonLIGHT), and a microreflector payload, like LaRRI, intended for lidar interrogations from lunar orbit. TeamIndus launch is scheduled for 2018.
2. Moon Express Mission 1, MoonLIGHT and INRRI. INFN will deliver another INRRI and MoonLIGHT, as per formal agreement signed at the European Lunar Symposium (els2015.arc.nasa.gov) held in Frascati in May 2015. Moon Express launch is scheduled for 2018.
3. AIM, phase A/B1 (M. Lavagna, Politecnico di Milano)
4. Lunar Drill Development (M. Lavagna, Politecnico di Milano)
5. GLXP-Landing Technology (M. Lavagna, Politecnico di Milano)

Netherlands

1. Netherlands Team Project Report

1.1. Exploration

Members of the Dutch SSERVI team (led by Heino Falcke) have developed and built the Netherlands-China Low-Frequency Explorer (NCLE), a low-frequency radio experiment for the Chinese Chang'e 4 mission that will go in a Lissajous orbit around the Earth-Moon L2 point in 2018. NCLE is a pathfinder mission for a future low-frequency space-based or moon-based radio interferometer; the principle science objective is the detection and tomography of the 21-cm Hydrogen emission line from the "Dark Ages." The instrument design concept involves 3 ~5 m long orthogonal monopole antenna elements, mounted perpendicular to the upper side of the satellite. During 2017 the instrument was built and tested.

1.2. Science

Lunar science in the Dutch SSERVI team currently concentrates on (a) experimental and numerical studies of the evolution of physical and chemical properties of the lunar crust, mantle and core, and (b) remote sensing studies of the lunar surface.

In 2017, numerical studies focused on the fate of ilmenite-bearing cumulates (IBC) formed from the solidification of the lunar magma ocean. Their high density is considered to trigger Rayleigh-Taylor instabilities which allow them to sink into the solidified cumulates below and drive a large-scale overturn in the lunar mantle. Knowledge of how the IBC participate in the overturn is important for studying the early lunar dynamo, chemistry of surface volcanism, and the existence of present-day partial melt at the lunar core-mantle boundary. PhD student Yue Zhao performed quantitative 2-D geodynamical simulations to measure the extent to which IBC participate in the overturn after their solidification, and tested the effect of a range of physical and chemical parameters. Her results show that IBC overturn most likely happened when the magma ocean had not yet fully solidified, with the residual melt decoupling the crust and IBC, resulting in 50-70% IBC sinking. Participation of the last dregs of remaining magma ocean melt is unlikely, leaving its high concentrations of radiogenic elements close to the surface. Simulations further indicate that foundered IBC can stay relatively stable at the core-mantle boundary until the present day, at temperatures consistent with the presence of a partially molten zone in the deep mantle as inferred from geophysical data. 30-50% of the primary IBC remain at shallow depths throughout lunar history, enabling their assimilation by rising magma to form high-Ti basalts (Zhao et al., under review at Earth and Planetary Science Letters).

Experimental studies focused on volatiles in the lunar interior. PhD student Yanhao Lin published the first fully experimental study of lunar magma ocean solidification in 2017, and specifically addressed the effect of lunar interior water on this process (Lin et al., 2017ab; Nature Geoscience and Earth and Planetary Science Letters). In his experiments (summarized in **Figure 1**), a deep layer containing both olivine and pyroxene is formed in the first ~50% of crystallization, β-quartz forms towards the end of crystallization, and the last per cent of magma remaining is extremely iron rich. In dry experiments, plagioclase appears after 68% vol. solidification and yields a floatation crust with a thickness of ~68 km, far above the observed average of 34–43 km based on lunar gravity. The volume of plagioclase formed during crystallization is significantly smaller in water-bearing experiments. His experiments

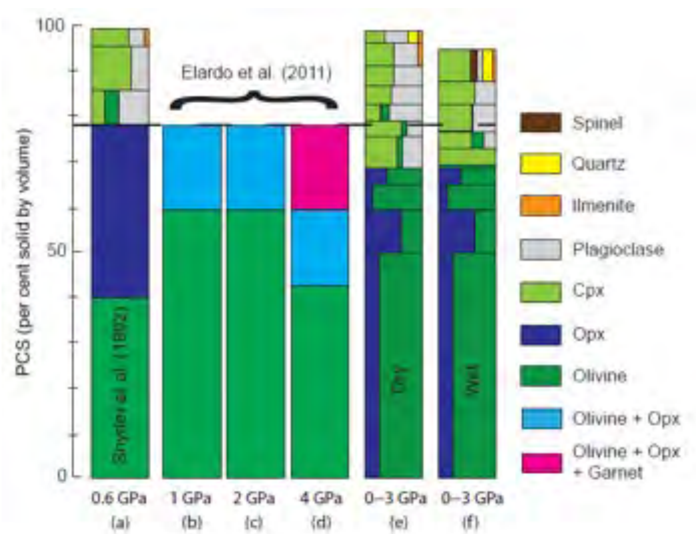


Fig. 1. Comparison between magma ocean crystallization sequences as a function of the percentage of the ocean that has solidified (PCS) from our study (panels e and f) and the literature (panels a-d) (from Lin et al. 2017a).

point to a systematic relationship between magma water content and the resulting crustal thickness (**Fig. 2**). Considering uncertainties in initial lunar magma ocean depth, he estimated that the Moon may have contained at least 270 to 1,650 ppm water at the time of magma ocean crystallization (**Fig. 2**), suggesting the Earth–Moon system was water-rich from the start.

PhD student Edgar Steenstra published several review papers in the online Lunar Encyclopedia concerning the interior evolution of the Moon. He also used experiments to show that elements that were previously considered to be depleted in the lunar mantle due to their volatility could have been sequestered into the lunar core. He showed this for the highly volatile elements selenium and tellurium (Steenstra et al., 2017; Scientific Reports) and has obtained data for potassium and sodium that show similar behavior. The implications of this work are that mantle depletions for volatile depletion in the Moon can be a result of both volatility and sequestration into the lunar core.

Finally, in the area of remote sensing studies, PhD student Melissa Martinot in collaboration with French SSERVI team members Flahaut and Quantin used Moon Mineralogy Mapper (M^3) reflectance data over the central peaks of a selection of 36 craters located in the feldspathic highlands to sample the lunar crust-mantle

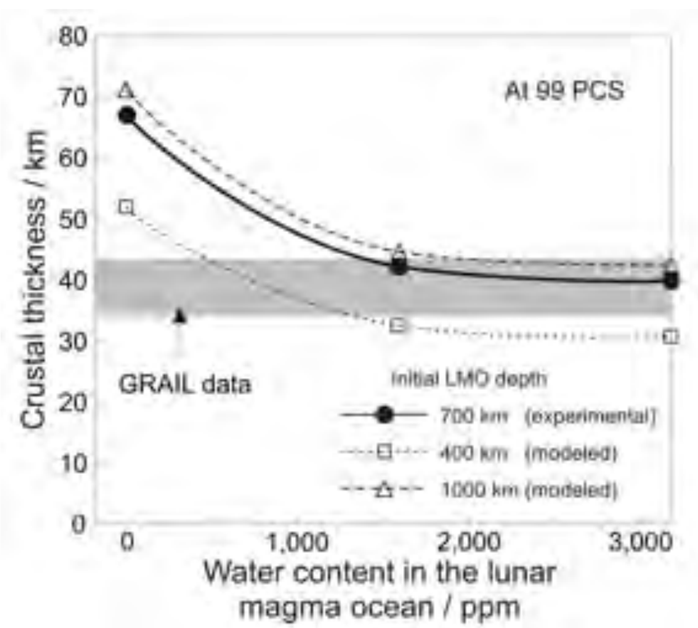


Fig. 2. Average thickness of the lunar crust as a function of initial magma ocean water content (From Lin et al. 2017a).

interface. Craterization equations, coupled with GRAIL crustal thickness models, predict that material from the lunar crust-mantle interface was potentially exposed in these craters' central peak. The survey characterized the mineralogy of the lunar crust-mantle interface and evaluated its vertical and lateral variations (Martinot et al. LPSC 2017).

2. Collaborations with SSERVI Teams and International Partners

Within Europe, there are active scientific collaborations between members of the Dutch, UK, German and French SSERVI teams. The Dutch team has increasingly strong collaborations with the University of Muenster (Prof. Stephan Klemme) in the area of experimental lunar science, and continue to liaise with UK colleagues at Open University (Dr. Mahesh Anand) about the lunar interior volatile cycles and degassing of materials from the Moon (a collaboration that was started within the frame of SSERVI). Lunar remote sensing studies are undertaken in collaboration with members of the French SSERVI team (Dr. Jessica Flahaut at Nancy, Prof. Cathy Quantin at the University of Lyon). The Dutch team continues discussions with US colleagues (Dr. David Draper, Dr. Chip Shearer) in the area of experimental lunar science in light of upcoming funding opportunities.

3. Public Engagement

Lunar and planetary science education options in the Netherlands were expanded by the development of a new introductory course on lunar and planetary science at Amsterdam, and a lunar and planetary science course for the University of the Third Age in Leiden. For the first time, undergraduate students were stimulated to submit some of their work on the design of future lunar and planetary missions to LPSC.

4. Student/Early Career Participation

Undergraduate Students

1. Mr. Milan Brussee, BSc student, Vrije Universiteit Amsterdam, high-pressure experiments on lunar core formation

2. Mr. Joeri Eising, BSc student, Vrije Universiteit Amsterdam, sulfur solubility in lunar magma

3. Mr. Bram Tomassen, BSc student, Vrije Universiteit Amsterdam, sulfur solubility in lunar magma

4. Ms. Frederique Webers, BSc student, Vrije Universiteit Amsterdam, sulfur solubility in lunar magma

5. Mr. Aart van der Waal, MSc student, Utrecht University, lunar core formation

6. Ms. Alix Seegers, MSc student, Vrije Universiteit Amsterdam, lunar core formation

7. Mr. Mitch Crockett, MSc student, Vrije Universiteit Amsterdam, lunar core formation

8. Mr. Nadav Agmon, MSc student, Vrije Universiteit Amsterdam, lunar heat production\

Graduate Students

9. Ms. Alix Seegers, Vrije Universiteit Amsterdam, lunar geochemistry

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

United Kingdom

SSERVI's UK team 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 just over 100 members representing 25 institutions from across the UK.

1. Recent Research Highlights

Barnes, J.J, Kring, D.A., Tartèse, R., Franchi, I.A.,

Anand, M and Russell, S.S. (2016). An asteroidal

origin for water in the Moon. Nature Comm., 7, #11684.

2. Barnes, J.J., Tartèse, R., Anand, M., McCubbin, F.,

Neal, C.R., Franchi, I.A. (2016). Early degassing of

lunar urKREEP by crust-breaching impact(s), EPSL,

447 pp. 84-94.

3. Eva, G., Coughlan, M., Joy, K., Smedley, A., Connolly, P., & Abrahams, D. (2016). A Potential Hidden Layer of Meteorites Below the Ice surface of Antartica. Nature Comm.

4. Bonnand, P., Parkinson, I.J., and Anand, M. (2016)

Mass dependent fractionation of stable chromium

isotopes in mare basalts: implications for the

formation and the differentiation of the Moon. GCA. 175, 208-221.

5. Robinson, K.L., Barnes, J.J., Nagashima, K., Thomen, A., Franchi, I.A., Huss, G.R., Anand, M., Taylor, G.J. (2016) Water in evolved lunar rocks: Evidence for multiple reservoirs. GCA. 188, 244–260.

2. Community Engagement

UK team members serving as panel members (Dr Simeon Barber and Dr Mahesh Anand) on ISECG Virtual Workshops on Exploring and Using Lunar Polar Volatiles

.

3. Involvements in Planning Future Lunar Missions

UK team members are involved in various advisory roles.

Moon 2020-2030 MeeDng at ESA ESTEC, NL

Discussion Meeting at the Royal Astronomical Society, London, UK - The use of Extraterrestrial Resources to Facilitate Space Science and Exploration.

Organizer: Ian Crawford, Martin Elvis and James Carpenter

Community Engagement

Meeting report is available at:

http://arxiv.org/abs/1605.07691

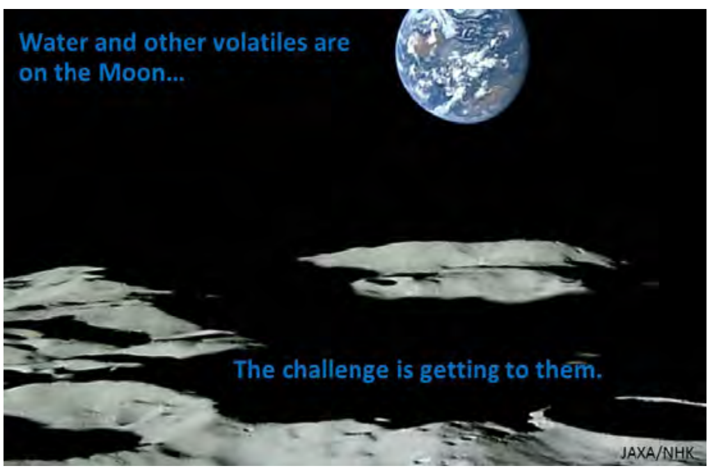
Videos of the talks are available at:

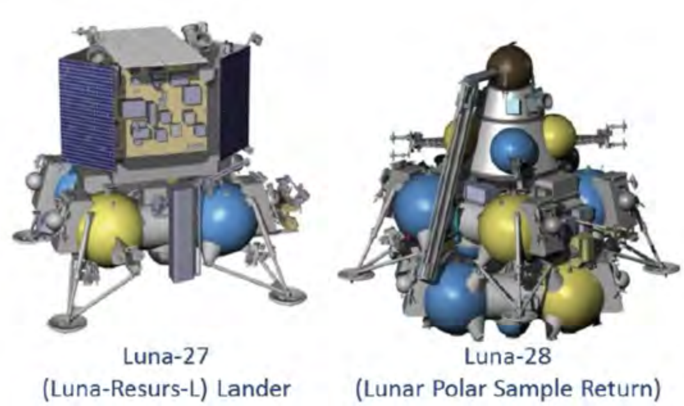
https://www.ras.org.uk/events-and-meetings/specialist-discussion-lectures

4. Education - MOONS MOOC

UK team members: Prof. David Rothery – Lead Educator, Dr Jessica Barnes – Facilitator.

A crowd-sourced lunar mission concept





Joint Russia-ESA Lunar ExploraDon Programme

UK-SSERVI-node members on the organising committee:

Ian Crawford, Katherine Joy

OBJECTIVES

The International Symposium on Moon 2020 – 2030: a New Era of Human and Robotic Exploration held at the European Space Agency's ESTEC centre in December 2015 brought European and international stakeholders together to lay the groundwork for a common scenario of increasingly integrated lunar exploration. The scenario includes an initial phase of robotic precursor missions followed by the return of human explorers to the surface of the Moon.

Ideas were sought for implementing approaches to human-robotic integration for better mission performance. In particular, the following questions were asked:

- How can we move beyond separate mission planning of automated and human missions to a combination of both?
- How do we evolve our thinking about planetary exploration to models that include collaborations among space agencies, academia, and private enterprise?
- How do we build a flexible and sustained strategy for lunar exploration that looks beyond a single mission and envisions multiple missions of increasing complexity?

Committees

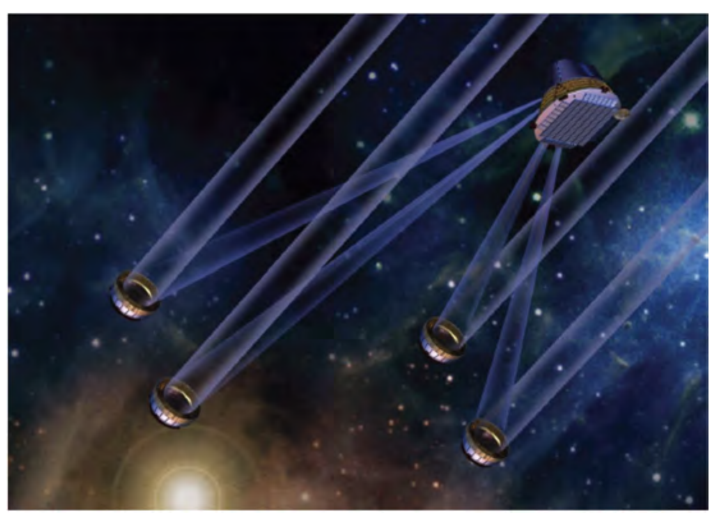
Programme Committee

Co-Chairs
- Bernhard Hufenbach (ESA)
- James Carpenter (ESA)

Members
- Ian Crawford (Birkbeck University of London, UK)
- Kip Hodges (Arizona State University, USA)
- Ralf Jaumann (DLR, Germany)
- Katherine Joy (University of Manchester, UK)
- Michelle Lavagna (Politecnico di Milano, Italy)
- Dan Lester (University of Texas, USA)
- Igor Mitrofanov (IKI, Russia)
- Clive Neal (University of Notre Dame, USA)
- Armin Wedler (DLR, Germany)

Organisation Committee Co-Chairs
- Markus Landgraf (ESA)
- Alessandro Bergamasco (ESA)

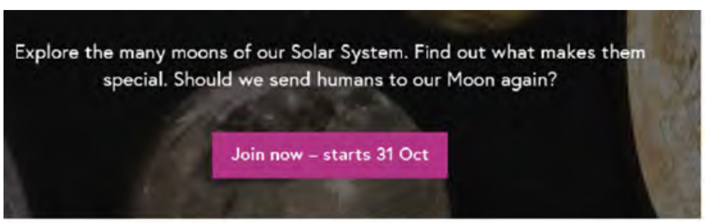
ESA Moon Challenge Jury
- Markus Landgraf (Mission Scenarios)
- Shahrzad Hosseini (Operations)
- André Schiele (Telerobotics)
- James Carpenter (Science)
- Nigel Savage (Education)

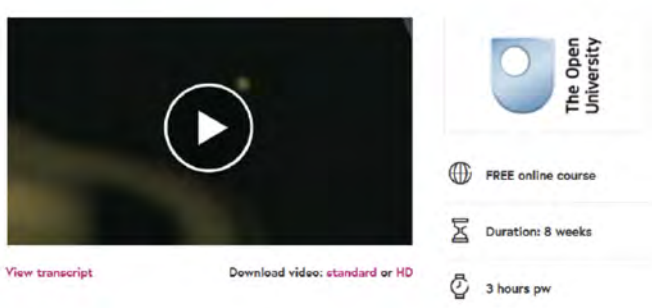


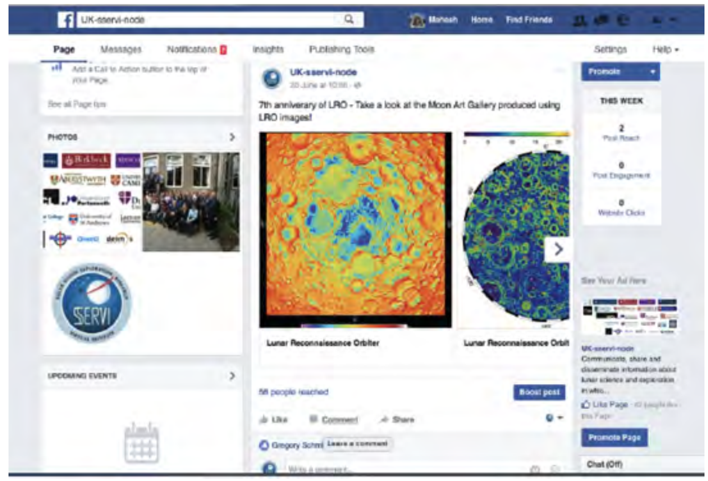
5. Public Resource - Virtual Microscope

UK team members: Prof. Simon Kelley, Dr Andy Tindle, Dr Mahesh Anand

http://www.virtualmicroscope.org/collections/apollo







6. Communication

https://www.facebook.com/uksservinode/

UK-SSERVI-NODE@JISCMAIL.AC.UK

Publications in 2017

The following list of 232 publications was compiled from all SSERVI teams for 2017, bringing the total for years 1-4 to 710.

1. Abedin, A., Spurný, P., Wiegert, P., Pokorný, P., Borovička, J., Brown, P., (2015). On the age and formation mechanism of the core of the Quadrantid meteoroid stream. Icarus 261, 100–117. doi: 10.1016/j.icarus.2015.08.016.

2. Abedin, A., Wiegert, P., Pokorn, P., 2016. The age and the parent of the daytime Arietids meteor shower. Icarus 281, 417–443. doi: 10.1016/j.icarus.2016.08.017.

3. Abedin, A., Wiegert, P., Janches, D., Pokorný, P., Brown, P., & Hormaechea, J. L. (2018). Formation and past evolution of the showers of 96P/Machholz complex. Icarus, 300, 360-385. doi:10.1016/j.icarus.2017.07.015.\

4. Adrian, D. R., King, D. T., Jaret, S. J., Ormö, J., Petruny, L. W., Hagerty, J. J., & Gaither, T. A. (2017). Sedimentological and petrographic analysis of drill core FC77-1 from the flank of the central uplift, Flynn Creek impact structure, Tennessee. Meteoritics & Planetary Science. doi: 10.1111/maps.12862.

5. Alí-Lagoa, V., Licandro, J., Gil-Hutton, R., Delbo, M., de León, J., Campins, H., ... & Hanuš, J. (2016). Differences between the Pallas collisional family and similarly sized B-type asteroids. Astronomy & Astrophysics, 591, A14. doi: 10.1051/0004-6361/201527660.

6. Banks, M. E., Xiao, Z., Braden, S. E., Barlow, N. G., Chapman, C. R., Fassett, C. I., & Marchi, S. S. (2017). Revised constraints on absolute age limits for Mercury's Kuiperian and Mansurian stratigraphic systems. Journal of Geophysical Research: Planets, 122(5), 1010-1020. doi:10.1002/2016JE005254.

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