YEAR THREE ANNUAL REPORT

2016

SOLAR SYSTEM EXPLORATION RESEARCH

VIRTUAL INSTITUTE

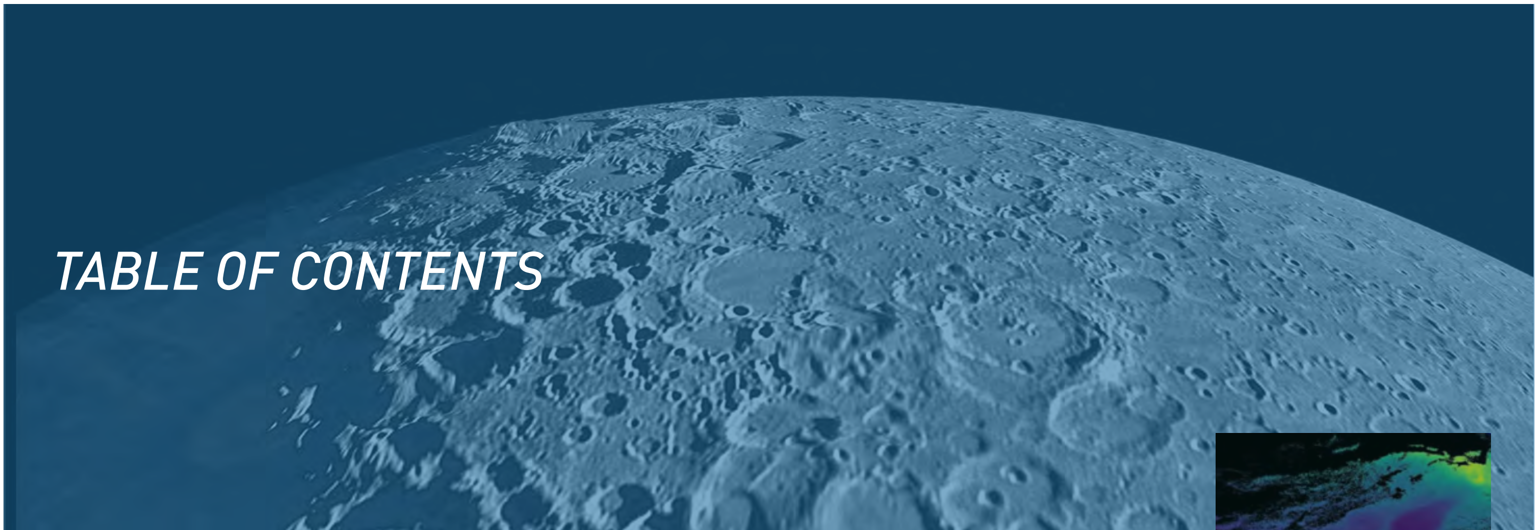
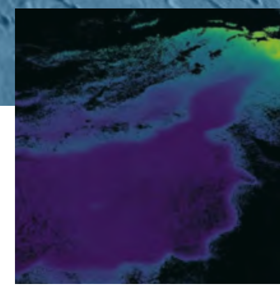
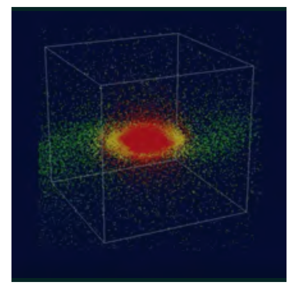
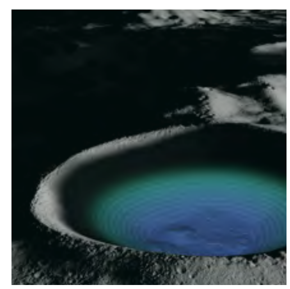
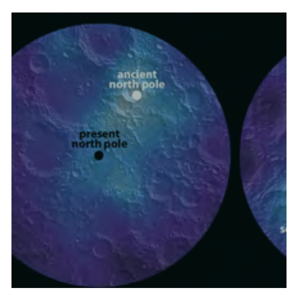


TABLE OF CONTENTS









FROM THE BRIDGE

Yvonne Pendleton
Director

Greg Schmidt
Deputy Director

NASA's Solar System Exploration Research Virtual Institute (SSERVI) is pleased to present the 2016 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. 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, California, provides the leadership, guidance and technical support that steers the virtual institute.

At the start of 2016, our institute had nine U.S. teams, each mid-way through their five-year funding cycle, plus nine international partnerships. However, by the end of the year we were well into the selection of four new domestic teams, selected through NASA's Cooperative Agreement Notice (CAN) process, and a new international partnership. Understanding that human and robotic exploration is most successful as an international endeavor, 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. We are proud to introduce our newest partnership with the Astrophysics and Planetology Research Institute (IRAP) in Toulouse, France. In 2016, Principal Investigator Dr. Patrick Pinet assembled a group of French researchers who will contribute scientific and technological expertise related to SSERVI research.

SSERVI's domestic teams compete for five-year funding opportunities through proposals to a NASA CAN every few years. Having overlapping proposal selection cycles 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. The strong community response to CAN-2 demonstrated the health of that effort. NASA Headquarters conducted the peer-review of 22 proposals early in 2017 and, based on recommendations from the SSERVI Central

Office and NASA SSERVI program officers, the NASA selecting officials determined the new teams in the spring of 2017. We are pleased to welcome the CAN-2 teams into the institute, and look forward to the collaborations that will develop with the current teams. The new teams are: The Network for Exploration and Space Science (NESS) team (Principal Investigator (PI) Prof. Jack Burns/U. Colorado); the Exploration Science Pathfinder Research for Enhancing Solar System Observations (ESPRESSO) team (PI Dr. Alex Parker/Southwest Research Institute); the Toolbox for Research and Exploration (TREX) team (PI Dr. Amanda Hendrix/ Planetary Science Institute); and the Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS) team (PI Prof. Thomas Orlando/ Georgia Institute of Technology).

In this report, you will find an overview of the 2016 leadership activities of the SSERVI Central Office, reports prepared by the U.S. teams from CAN-1, 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, as well as by subscribing to our Twitter feed and other social media sites.

SSERVI.NASA.GOV

@NASA_Lunar

@moonandbeyond

THE SSERVI CENTRAL OFFICE REPORT

Recognizing that science and human exploration are mutually enabling, NASA created 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 2016 research accomplishments, followed by a list of the 177 peer-reviewed papers published in 2016. Here we present the 2016 accomplishments by the SSERVI Central Office that focus on: 1) Supporting Our Teams 2) Community Building, and 3) Outreach that inspires the next generation, reaches underserved communities, and engages the general public.

Supporting Our Teams

The SSERVI Central Office supports our team research goals not only by assuring the timely distribution of their funds, but also through the general structure of the institute. Two advantages afforded by the virtual institute model adopted by SSERVI are that we provide long-term, stable funding 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 NASA virtual institutes would not occur in their absence, because there are no other NASA programs to which proposers could apply to address questions in this manner.

Advocacy and Relevance

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 through solicitation of new teams, community development, reporting to NASA Headquarters and beyond, public engagement, and providing the technical competence required to connect all of the represented teams, communities and agencies.

Reporting

The SSERVI Central Office regularly reports team accomplishments to both the Science Mission Directorate and the Human Exploration and Missions Operations Directorate at NASA Headquarters, and we provide direct visibility of team accomplishments through the establishment of a SSERVI Headquarters seminar series. Two to three times a year, 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 at the time. In 2016, Bill Farrell (PI of the DREAM2 team) and Dana Hurley (VORTICES team) presented headquarters seminars.

Site Visits

We make site visits (one to two teams are visited per year) to meet the rest of their team, including students, and to see their onsite facilities. In 2016, the SSERVI Central Office senior leadership visited the DREAM2 team (Bill Farrell, PI) at NASA Goddard Space Flight Center (GSFC) and the VORTICES team (Andy Rivkin, PI) at the Johns Hopkins University/Applied Physics Laboratory (JHU/APL). Recognizing that these visits provide additional opportunities for in-depth communication between the teams, we strongly encourage the principal investigators from each of the teams to join us in person. Our experience has shown that many cross-team collaborative ideas emanate from these visits. To further support cross-team interactions, the SSERVI Central Office has established a NASA post-doctoral fellowship position to be shared between two or more teams. In 2016, NASA post-doc fellow Dr. Katherine Kretke conducted research that further connected teams lead by principal investigators Bottke and Kring.

External 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. We are proud to highlight the SSERVI team members and PIs who were recently awarded the following:

- James Head was elected to the Russian Academy of Sciences
- Robin Canup was elected to the National Academy of Sciences
- Anthony Colaprete received the NASA Ames Research Center H. Julian Allen Award for outstanding scientific achievement
- Carle Pieters was named a Meteoritical Society Fellow
- Bill Bottke was named a Meteoritical Society Fellow
- M. Darby Dyar received the Geological Society of America Gilbert Award
- Paul D. Spudis received the NASA Columbia Medal
- Dan Durda received the American Astronomical Society/Division for Planetary Sciences Carl Sagan Medal
- Alberto Saal received a Guggenheim Fellowship

Virtual Events and Team Communication

The SSERVI technical staff 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, and mobile devices have been seamlessly integrated to produce virtual seminars and workshops. We are pleased to facilitate effective communication within and among teams and enable collaborative research and data sharing, through use of our social networks, shared databases, data visualization applications. More than 50 virtual events sponsored by the institute were supported by the SSERVI Central Office throughout 2016. These included several seminar series organized by SSERVI teams, including one on Phobos and Deimos jointly sponsored by the CLASS team (Dan Britt, PI) and the SEEED team (Carle Pieters, PI), 2 SSERVI Headquarters seminars, the Exploration Science Forum (ESF) which has a virtual as well as in-person component, and other meetings discussed in elsewhere in this report.

> 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.

Community Building

The SSERVI Central Office has the responsibility to grow and maintain a community of researchers beyond those directly associated with the institute at any one time. The wider community brought together through virtual and in-person events sponsored by the SSERVI Central Office and its teams include scientists and engineers who focus on lunar and other airless bodies, theoreticians, laboratory researchers, astronomical observers and field investigators. Recognizing that space exploration is a global enterprise, the SSERVI Central Office also focuses on the development and maintenance of its international partnership programs. In 2016, France became the tenth international partner to join SSERVI, and we look forward to the collaborations they will have with our domestic teams and other international partners. For more information on our global endeavors, see the Summary of International Activites section of this report.

Some of the measures we take to build and support the wider community include sponsoring the annual ESF and smaller in-person workshops, hosting community-wide virtual events, opening SSERVI-developed research facilities to the community, and through the Trek suite of online solar system visualization tools.

NASA Exploration Science Forum

The SSERVI Central Office organizes and sponsors the annual ESF, which brings together several hundred researchers to discuss topics ranging from modeling to mission science. The ESF is designed to be a forum where new ideas and innovation can be fostered through the mingling of both basic and applied researchers. To date, the ESF is the largest conference dedicated to promoting the intersection of science and exploration. The format of the ESF is a flexible event that produces special sessions, talks, panels, exhibitions, and discussions that reflect the direction of the Agency and the community.

At the ESF, SSERVI presents awards as a means of honoring key individuals in the community. The Eugene Shoemaker Distinguished Scientist Medal for lifetime scientific achievement, the Michael J. Wargo Award for outstanding achievement in Exploration Science, and the Susan Mahan Niebur award for early career achievement were presented in 2016. The SSERVI awards are open to the entire research community.

Eugene Shoemaker Distinguished Scientist Medal

The 2016 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. James Head, Professor of Geological Sciences at Brown University, for his significant scientific contributions to the field of lunar science throughout the course of his scientific career. Dr. Head worked with the NASA Apollo program, in which he analyzed potential landing sites, studied lunar samples and data, and provided training for the Apollo astronauts. Dr. Head is a member of SSERVI's SEEED team where he is studying the processes that form and modify the surfaces, crusts and lithospheres of planets, how these processes vary with time, and how such processes interact to produce the historical record preserved on the planets. He has served as an investigator with NASA and Russian Space Missions, such as the Soviet Venera 15/16 and Phobos missions, and the US Magellan (Venus), Galileo (Jupiter), Mars Surveyor, Russian Mars 1996, and Space Shuttle missions. The award includes a certificate and medal with the Shakespearian quote "And he will make the face of heaven so fine, that all the world will be in love with night."

The 2016 ESF at NASA Ames Research Center, Moffett Field, CA, featured scientific and exploration 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 ESF.

Michael J. Wargo Exploration Science Award

The Michael J. Wargo Exploration Science Award is an annual award given to a scientist or engineer who has significantly contributed to the integration of exploration and planetary science throughout their career. Dr. Michael Wargo (1951-2013) was Chief Exploration Scientist for NASA's Human Exploration and Operations Mission Directorate and was a strong advocate for the integration of science, engineering and technology. In 2016, the Michael J. Wargo Exploration Science Award was given to Dr. Dana Hurley, a planetary scientist at the Johns Hopkins University Applied Physics Laboratory (APL). She has studied the atmospheres of airless bodies, the magnetic fields of non-magnetized planets, the water cycles of desiccated moons, and helped to model processes acting to deliver water to cold traps on the Moon and Near Earth Objects– specifically the role of the solar wind as a source of water. Dr. Hurley has participated in the Lunar Reconnaissance Orbiter (LRO) mission and Lunar

Atmosphere and Dust Environment Explorer (LADEE) mission and is also a member of SSERVI's DREAM2 team.

Susan Mahan Niebur Early Career Award

The Susan Mahan Niebur Early Career Award is an annual award given to an early career scientist who has made significant contributions to the science or exploration communities. Susan Mahan Niebur (1978-2012) was a former Discovery Program Scientist at NASA who initiated the first ever Early Career Fellowship and the annual Early Career Workshop to help new planetary scientists break into the field. In 2016, the Niebur award was given to Dr. Noah Petro, a research space scientist at NASA GSFC in Greenbelt, MD. Dr. Petro was the Deputy Project Scientist for LRO and is a member of the RIS4E and FINESSE teams. He is also a member of the executive committee for the Lunar Exploration Analysis Group. Noah has shown excellence in his field and demonstrated meaningful contributions to the science and exploration communities.

More information on these awards and recipients, along with past awardees, can be found at: http://sservi.nasa.gov/awards.

Student Poster Competition and Lightning Round Talks

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

The 2016 ESF Student Poster Competition winners were:

• First place awarded to Yasvanth Poondla for the poster "Modeling the LCROSS Impact Plume-Photodissociation and Sublimation of Water."

• Second Place awarded to Anastasia Newheart for the poster "Apollo ALSEP/SIDE Observations of Stairstep Flux Profiles in the Terrestrial Magnetotail."

• Third Place awarded to Commack High School (Mike Delmonaco, Trevor Rosenlicht, Nicole LaReddola) for the poster "Resolving the Primary Mechanism Causing Floor-Fractured Craters Using GRAIL and LOLA Data."

• Honorable Mention awarded to Kickapoo High School (Mikala Garnier, Jonas Eschenfelder, Alysa Fintel) for the poster "Excavation Depths as Indications of Magnesium Spinel Formation via Impact Melting."

Support for Additional In-Person Meetings

In addition to the annual ESF and the numerous virtual events that SSERVI conducts in support of the science and exploration communities, the institute conducts scientific workshops which delve deeply into topics that cross SSERVI research areas.

A good example of this was demonstrated in 2016, with the Water on the Moon workshop held November 15-17, 2016, at JHU/APL. The purpose of the workshop was to advance our understanding on the topic of the locations and origins of the lunar water/OH that has been detected. The SSERVI Director worked closely with leaders from three SSERVI teams to organize the workshop which brought together 40 experts (invited from SSERVI teams as well as the broader scientific community) to share insights, questions and data. Hosted by the VORTICES team (Andy Rivkin, PI), and organized by VORTICES team member Dana Hurley, the workshop delved deeply into our current understanding based on published and pre-publication data, theoretical models and laboratory experimental results. Common themes emerged emphasizing the diversity of sources and the complexity of transport and retention processes. Discussions explored previously unappreciated links between the internal volatiles, surface volatiles and polar volatiles. Pre-publication data were shared which greatly aided the conversations. The outcomes from this workshop include an EOS workshop summary and a community-wide session dedicated to this topic at the 2017 ESF.

The SSERVI Central Office has also supported the European Lunar Symposium (ELS) since its beginnings, through service on the scientific organizing committee, by creating the website, facilitating on-line registration, and making presentations at the meeting. The ELS is held in a different locations in Europe each year, and consists 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."

In 2016, SSERVI also joined forces with the Mars Institute and the SETI Institute to co-sponsor the Third International Conference on the Exploration of Phobos and Deimos. Held at NASA Ames Research Center adjacent to the annual SSERVI ESF and organized by Pascal Lee of the SETI Institute, the program focused on the exploration of the moons of Mars with sessions on robotic and human exploration of these targets. The SSERVI Central Office created the website, facilitated registration, and handled the on-site logistics.

SSERVI COOPERATIVE AGREEMENT NOTICE-2

SSERVI released CAN-2 in 2016 that resulted in the selection of four new teams that will begin work in 2017, overlapping for approximately two years with the CAN-1 teams. Each CAN supports the teams selected for five years. The central office worked closely with NASA HQ to expand the breadth of SSERVI related research by drafting partnerships with other nontraditional planetary entities, specifically the Human Research Program (HRP) within NASA HEOMD and the Astrophysics Division (AD) within NASA SMD. These partners provided new areas of research to which teams could propose. The community responded to this CAN with 22 proposals from a wide spectrum of disciplines and teaming arrangements.

Virtual Events for the Community & Website Development

Nearly every conference, workshop and meeting that SSERVI hosts has a virtual component that becomes an archived resource available through the SSERVI website. In 2016, the SSERVI technical staff supported numerous events for our teams and the wider community. In addition, SSERVI is now recognized for our proficiency in this area, and our technical staff is requested throughout the year to assist with non-SSERVI events for other parts of NASA and to support activities that, while not sponsored by SSERVI, indirectly support the broader community. Additional events that indirectly supported the community included seminars, workshops, and meetings such as: the Asteroid Redirect Mission (ARM) Industry Day, IAC Winter School Seminar Series, International Space Exploration Coordination Group (ISECG) Lunar Polar Volatiles Workshop, the 14th and 15th Small Bodies Assessment Group Meetings, and the Asteroid Generated Tsunami Workshop.

> Collaboration technologies designed, developed, integrated, and administered by SSERVI continued to enhance the effectiveness of dispersed interdisciplinary research and training by providing the Institute's scientific community with a technological platform to engage in inter- and intra-team collaborations, seminars, workshops, and meetings.

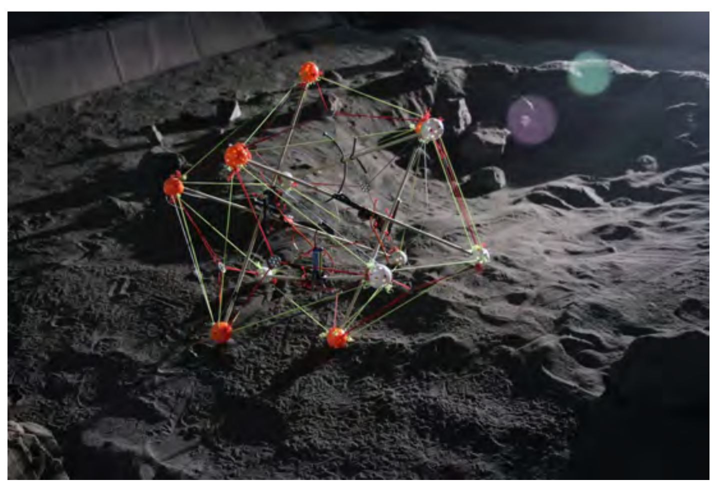
The SSERVI Central Office also regularly develops websites and web applications to support our communities. The SSERVI website, sservi.nasa.gov, is regularly updated with the latest science highlights and announcements, including press releases and news stories that highlight research results from SSERVI teams. Several of these websites are listed on the following page.

SSERVI Central's collaborative technologists were behind the scenes supporting virtual meetings for NASA ARM.

Website	Description	URL
SSERVI	SSERVI research highlights, related science, events/activities, and resources to the community.	sservi.nasa.gov
NASA Exploration Science Forum	ESF website where users find information on logistics, registration, abstract submissions, and on-demand playback of all presentations.	nesf2017.arc.nasa.gov
SSERVI Awards	The SSERVI Awards website highlights past winners of the distinguished Shoemaker Medal, Niebur, and Wargo Awards, and allows the community to nominate candidates for these annual awards.	sservi.nasa.gov/awards
SSERVI Books	The SSERVI Books website was created to highlight the Institute's literary efforts, including "Getting a Feel for Lunar Craters" and "Getting a Feel for Eclipses."	sservi.nasa.gov/books
European Lunar Symposium	ELS website provides users with logistics, registration, and abstract information related to the annual event.	els2017.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
Exploration Science Portal	The Exploration Science Portal exists to help bring scientific knowledge from SSERVI and its community to bear on questions of human exploration. Questions of interest are recorded and SSERVI either provides an immediate answer or brings experts to help.	sservi.nasa.gov/ask
Global Exploration Roadmap	The website where Global Exploration Roadmap (GER) activities are made available.	sservi.nasa.gov/ger
Ames Collaboration Team	SSERVI has provided the Ames Collaboration Team with an event scheduler application which records all events to a database while also automatically scheduling the events to a central calendar.	For Internal Use Only
URL Shortener	SSERVI continued to support a tailor-made URL shortener with analytics that have been used across the agency.	For Internal Use Only

Facilities Open to the Community

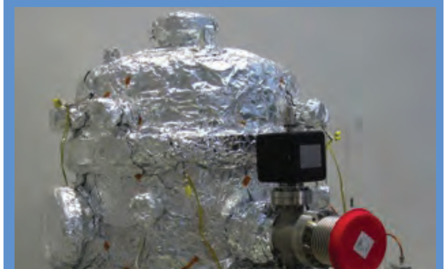
Some of the SSERVI teams build facilities to conduct their research. We encourage them to open those facilities to the wider research community when possible. The SSERVI Central Office maintains the Regolith Testbed Facility which is also open to the community. A list of SSERVI sponsored facilities that are available to other researchers follows. Interested parties should engage the facility POC to discuss scheduling time at the facility, along with any potential associated costs.



The SSERVI Regolith Testbed located at NASA Ames Research Center, shown here being used for lunar regolith mobility studies.

Dust Accelerator Laboratory (DAL) (U. of Colorado)

A 3 MV linear electrostatic dust accelerator which 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)

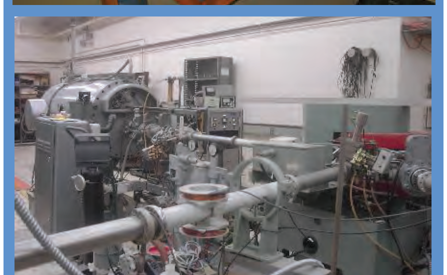
Spectroscopic data can be obtained for compositional information relevant to planetary surfaces. High precision, high spectral resolution, bidirectional reflectance spectra of Earth and planetary materials can be obtained using RELAB. Contact: http://www.planetary.brown.edu/relab/

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 (NASA's Ames and Kennedy Space Centers)

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

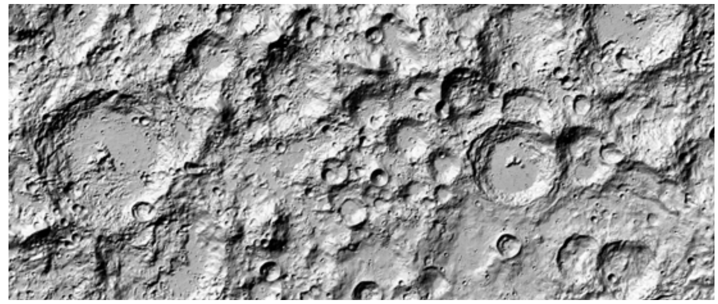
Solar System Treks

The SSERVI Central Office provides management oversight of NASA's Solar System Trek, a lunar and planetary mapping and modeling program formerly known as the Lunar Mapping and Modeling Project (LMMP). The project is managed at the program office level through the SSERVI Central Office by Brian Day. The development team is based at the Jet Propulsion Laboratory (JPL) with Emily Law serving as develpment and engineering lead. Solar System Treks has moved beyond the Moon to include multiple target bodies and has become a scientific resource and a wide audience within the planetary science community.

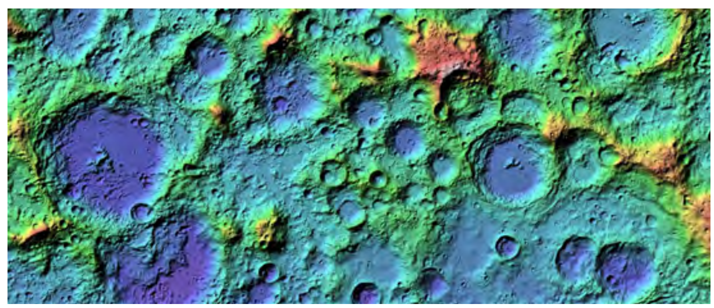
2016 was an exciting year for the Trek suite of online solar system visualization tools. The project released Moon Trek, the successor to LMMP, with enhanced visualization and navigation capabilities, as well as an updated client architecture. The team worked with domestic and international SSERVI researchers using LMMP and Moon Trek on lunar retroreflector placement and Lunar Orbiter Laser Altimeter (LOLA) applications studies. New collaborations with the Korea Aerospace Research Institute (KARI) and the European Space Agency were initiated to facilitate their uses of Moon Trek in mission planning.

Significant development was done on the Mars Trek portal during the course of the year. New enhancements were begun to support Human Landing Site Selection, including generating, posting, and sharing new CTX (Mars Reconnaissance Orbiter Context Camera) mosaics of Mars Exploration Zones. 2016 marked the 40th anniversary of the Viking 1 landing; to commemorate this, new Viking bookmarks and data sets were added to Mars Trek, detailing the Viking missions and regions where they landed. Meanwhile, from Gale Crater, interactive visualizations of Mars Science Lander data were added to Mars Trek through a collaboration with JPL's Experience Curiosity. This year, National Geographic focused on Mars with a high-profile TV docudrama and supporting online materials. The project supported this effort by providing Mars data sets to National Geographic for their development of Mars production and education materials. The project became a charter member of, and participated on the steering committee for, the nascent MarsGIS Working Group. Also

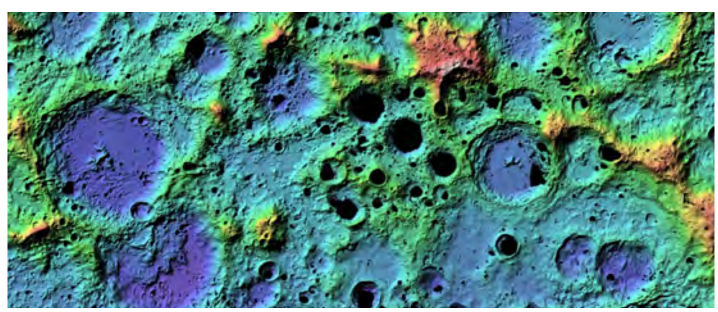
These maps were generated using the new Moon Trek Portal (https://moontrek.jpl.nasa.gov) from SSERVI's Solar System Treks, developed at NASA JPL. The maps are centered on the lunar South Pole and span a width of 855 km.



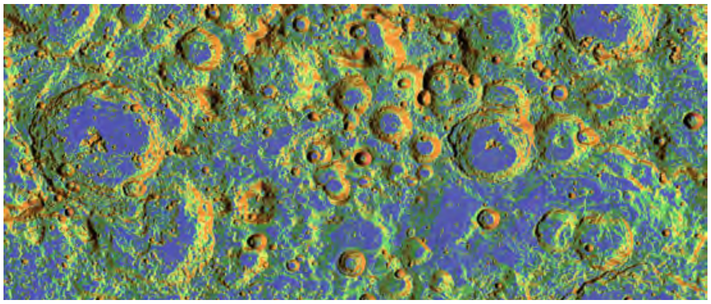
The South Pole LOLA map uses LRO's LOLA laser altimeter to pierce the long and shifting shadows of the polar region to reveal surface details that are obscured from the camera systems aboard LRO.



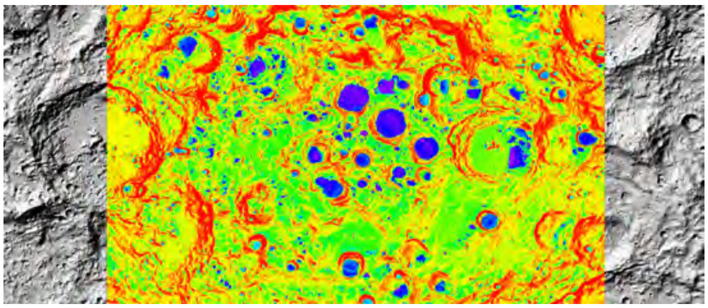
The South Pole Color Hillshade map uses color encoding of elevation levels in the LOLA data in order to emphasize surface topography.



This view shows Permanently Shadowed Regions (PSRs), areas that are strong candidates for sequestration of volatile compounds including water ice. The South Pole Color Hillshade with PSRs features an overlay showing the permanently shadowed regions on top of the color hillshade topography.



In planning surface operations, mapping slopes is critical to defining traverses. The South Pole Slope map depicts slopes from 0 degrees (blue) to 90 degrees (red).



Extreme temperatures are a critical consideration in understanding potential volatile resources at the lunar poles, and in mission planning. The center of this map shows maximum temperatures derived from LRO's DIVINER instrument from 25K (purple) to 200 K (red).

on the steering committee were Langley Research Center's Evolvable Mars Campaign GIS project, Mars Trek, JMars (Arizona State Univ.), and USGS. The goals of the group include Exploration Zone depiction and analysis, data coordination, standardization, and data augmentation.

In the field of Virtual Reality (VR), the team produced joystick and gesture controlled prototype VR clients that were demonstrated at the ESF and at the annual American Geophysical Union meeting in San Francisco. Additional work included development and demonstration of a new prototype portal for Comet Churyumov–Gerasimenko that integrated and made use of ephemeris data for the comet and SPICE data for the Rosetta spacecraft.

At the request of the Planetary Science Division (PSD), the project's management at the SSERVI Central Office and JPL developed a task plan for a Phobos portal with site selection for the Martian Moons eXploration (MMX) mission as a major driver. After the plan was approved by the Director of the PSD, the team began a survey of existing and anticipated data products, and initiated collaboration with the International Phobos/Deimos Landing Site Working Group. Continuing interaction with the various communities the project serves is essential for making sure they know about the portals' capabilities and the team understands the communities' needs. To that end, the project's work was presented at several workshops and conferences, as well as numerous school and public events.

Outreach

The SSERVI Central Office and our teams conduct extensive outreach throughout the year. SSERVI's Trek portals have been designated as a key infrastructure project in the NASA Science Mission Directorate's STEM Activation Initiative, and has represented the PSD in the NASA exhibition booth at various venues. In addition to the outreach activities of SSERVI teams, the SSERVI Central Office also conducted outreach to inspire the next generation, reach underserved communities and provide general public engagement opportunities.

Inspiring the Next Generation

SSERVI inspires the Next Generation in many ways. In addition to the training and student exchange programs conducted within and across the teams, the SSERVI Central Office supports the next generation by sponsoring a conference for graduate students, Lunar Grad Con, supporting the Next Generation of Lunar Scientists and Engineers for postdoctoral and early career individuals, and by giving all students visibility at the ESF through the

Number of Events	Category	Number of People Engaged
19	Public Events	2,800
24	K-12 Classrooms & Universities	2,270
1	Science Festivals (e.g. Space Festival)	3,000
3	Professional Conferences (e.g. AGU, ALA, etc)	7,000
5	Challenges Competitions (e.g. RoboTex, RoboRave Intl.)	9,500
1	National/State parks	2,500
Total: 53		**27,000**

SSERVI Central Office 2016 Public Engagement Summary student poster competition and lightning round talks.

Lunar Grad Conference

Lunar Grad Con is held each year adjacent to the ESF 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 only 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: http://sservi.nasa.gov/articles/lungradcon-2010 .

Next Generation Lunar Scientists and Engineers

Early career and post-doctoral fellows have joined together to form the Next Gen Lunar Scientists and Engineers (NGLSE). SSERVI supports their activities and welcomes their meetings which are often held adjacent to the ESF. The focus of NGLSE is to design, encourage, promote, and procure funding for experience-building and networking activities among group members. The group responds to the needs of the lunar community for input or service, in the form of convening workshops and meetings. The NGLSE group also supports education and public outreach (E/PO) activities for students and the general public.

Robotics Competitions

The SSERVI Central Office participated in RoboRAVE and RoboTech, an international robotics competition for K-12 students in Albuquerque, NM, that supports STEM, robotic exploration, and planetary science. Over 18 countries participated with over 1800 student competitors, and more than 3000 participants (parents, coaches and teachers) in attendance. The unique properties of basaltic regolith, reduced 3/8th gravity and other factors make off-world excavation a difficult technical challenge. Advances in Martian mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations. Judging large international competitions like RoboRAVE and college level Regolith Mining Competitions promotes SSERVI's mission to inspire our next generation of scientists and engineers to develop skills that can lead to technical careers. SSERVI also established a relationship with the Corporate Innovation Center at the Haas School of Business at Berkeley centered around Science and Technical Education involving Robotic Challenges and small Pocket Satellite development for educating and inspiring the next generation scientists and engineers. The SSERVI Central Office staff introduced Robotic Education Challenges that resulted in the first RoboRAVE India (http://roboraveindia.org) in November, 2016.

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 In-Situ Resource Utiliztion (ISRU) missions.

Reaching Out to Underserved Communities

Journey Through the Universe

As it has for several years now, the SSERVI Central Office participated in the Journey Through the Universe program. During the week of March 4-11, 2016, 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. Thanks to combined efforts, the Journey Program was able to reach approximately 8,000 students in both the Hilo-Waiākea district and Honoka'a Schools, and several hundred more in various community events.

SSERVI Central Office staff engaged students from the Hilo-Waiākea school district of Hawaii.

Smart Villages

Smart Villages is a community-based initiative aimed at harnessing the benefits of information technology for rural communities. In 2016, SSERVI's Deputy Director was invited to give a virtual address to the Chief Minister of India, Mr. Nara Chandrababu Naidu, in support of the Scalable Smart Village Project managed by Solomon Darwin, the Director of Corporate Innovation at the Haas School of Business at the University of California at Berkeley. Mr. Naidu is interested in firms that offer promising solutions for upgrading over 650,000+ villages across India with relevant and affordable technical solutions. The presidents and leaders from 40 villages surrounding Mori, India, attended the virtual meeting. SSERVI offered introductions to subject matter experts to help educate the next generation, to develop small satellite projects, and to inspire and develop technical skills for India's next generation of engineers and space scientists.

Books for the Blind

One of the truly unique products to emanate from a combined effort between the SSERVI Central Office, the SEEED team (Carle Pieters, PI), and the CLASS team (Dan Britt, PI) is a series of books for the sight impaired. Cass Runyon of the SEEED team has coordinated content provided by SSERVI team members on the various topics of the books. In 2016, 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. SSERVI provides design, graphics, and print production for our books for the blind. For more information on these books see:
https://sservi.nasa.gov/books/

Two of the SSERVI-sponsored books for the sight impaired.

Reaching Out to Engage the General Public

Citizen Science

As a member of NASA's Citizen Science Forum, organized by NASA's Office of the Chief Scientist, SSERVI maintains an active commitment to citizen science. In 2016, the SSERVI Central Office worked closely with our Australian partner at Curtin University, helping to expand world-wide usage of their "Fireballs in the Sky" citizen science app, showcased in presentations at the American Geophysical Union, the Telescope Science Symposium, and on science.nasa.gov. Learn more at http://fireballsinthesky.com.au/ .

The Solar System Treks project supported the 2016 NASA Space Apps Challenge, resulting in 14 projects being created using the Trek data our project provided.

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 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 seventh annual InOMN was held on October 8, 2016. The InOMN Coordinating Committee is led by the NASA LRO's Education and Communications Team, with representatives from SSERVI, the Lunar and Planetary Institute, the Planetary Science Institute, the Astronomical Society of the Pacific, and CosmoQuest. We look forward to seeing you at one of the upcoming events for this year's InOMN on October 28, 2017. Visit http://observethemoonnight.org/ to learn more.

Small Worlds Space Art Exhibition

The "Small Worlds and Beyond" Space Art Exhibition was open to the public during the ESF in 2016, and was focused on the exploration of Near-Earth Objects, Phobos, Deimos, and Mars. It was co-sponsored by the International Association of Astronomical Artists (IAAA), the Mars Institute and SSERVI. NASA Ames Research Center contributed an original signed Chesley Bonestell painting (1976) entitled "Pittsburgh at L-2" was displayed during

Pascal Lee (SETI), Greg Schmidt (SSERVI), and April Gage (NASA ARC) pose in front of "Pittsburgh at L-2" painting by Chesley Bonestell (1976).

the Phobos/Diemos workshop and the ESF. Depicted in the painting is a machine with international markings docked at an asteroid to conduct mining operations.

Acknowledgments

The SSERVI Central Office thanks our NASA Headquarters officials: Jim Green, Sarah Noble, Max Bernstein and Kristen Erickson from the Science Mission Directorate and Jason Crusan, Ben Bussey, Victoria Friedensen and Bette Siegel from the Human Exploration and Operations Mission Directorate. We thank David Morrison and Yara Al-Rajeh for their contributions as well as our teams for their dedicated and excellent work. We acknowledge the outstanding support we receive from Ames resource and procurement personnel: Ben Varnell, Michael Baumgarten, Barrie Caldwell and Beatrice Morales, as well as FILMSS contract manager, Marco Boldt. SSERVI thanks the broader community, including our international partners, who interact with the institute in many capacities throughout the year that help pave the path forward.

SSERVI Central Office Staff (including part-time individuals)
Senior Leadership
Yvonne Pendleton, Director Greg Schmidt, Deputy Director and Director of International Partnerships Brad Bailey, Associate Director for Science Kristina Gibbs, Associate Director for Management
Executive Assistant
Yvonne Ibarra
Virtual Collaboration and Information Technologies
Ricky Guest Ashcon Nejad Maria Leus
Public Engagement and Citizen Science
Brian Day Joe Minafra
Communications
Teague Soderman Jennifer Baer

The composition of the SSERVI Central Office Staff combines the talents of technical and creative individuals, enabling our teams to accomplish NASA's vision for SSERVI.

EXECUTIVE SUMMARY of TEAM REPORTS

As a bridge between exploration and science, SSERVI has brought together many communities. This executive summary of the 2016 team reports provides a high level look at some of the accomplishments enabled by the pairing of insightful scientists, engineers, technicians, pilots, and crews with instruments, rovers, and spacecraft. Such overarching collaboration underscores the value in developing new tools and techniques for exploring space and for providing stable research environments from which scientific inquiry can be made. Here we present 9 short synopses of the SSERVI team reports that follow.

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 the impact history and processes, geochemistry of regoliths, and age dating of regolith materials on the Moon and other airless bodies. They also focus on Near Earth Asteroid identification and characterization. In 2016, their work on airless bodies showed that the water in the lunar interior was delivered by asteroids, not comets, during the early evolution of the lunar magma ocean more than 4.3 billion years ago. They also showed that the peak-rings of lunar impact basins, like Schrödinger, were produced by the collapse and outward displacement of a central uplift that momentarily towered over the lunar surface. The team confirmed that model by drilling into Earth's Chicxulub impact crater, better known as the dinosaur killer. They studied the traverses around, and in between, five lunar landing sites proposed by the ISECG lunar surface architecture team and found that they could address a large number of SMD and HEOMD objectives.

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 studying the effects of hypervelocity dust impacts into refractory, icy, and gaseous targets. They are developing new laboratory experiments to address the effects of UV radiation and plasma exposure of the surfaces of airless planetary objects. They are also developing new instrumentation for future missions to make in-situ dust and dusty plasma measurements in space. The team lends theoretical and computer simulation support for the analysis and interpretation of laboratory and space-based observations. IMPACT provides access to its facilities to the space physics community and supports a large number of undergraduate and graduate students.

The Field Investigations to Enable Solar System Science and Exploration (FINESSE) team led by Dr. Jennifer Heldmann at NASA Ames Research Center focuses on software, hardware, and mission architectures required to optimize science return from human and robotic planetary missions. The FINESSE team benefits from collaboration with several astronauts (Jeff Hoffman, Steve Swanson, David St. Jacques) as well as leaders in robotic planetary exploration (Steve Squyres, Dava Newman). Exploration research at West Clearwater Impact Structure (WCIS) has focused on astronaut training in terms of pre-deployment training to enable effective sample collection at impact crater sites as well as the use of in-situ field instrumentation to optimize science return. Science research at WCIS benefits from the FINESSE fieldwork and collection of unique impact crater samples, which has allowed for a new understanding of the formation and evolution of WCIS and impact cratering processes on SSERVI Target Bodies. Work at Craters of the Moon National Monument and Preserve (COTM) has focused on both science (volcanics research as a planetary analog) and exploration (methodologies, instrumentation, and operations) for enabling human and robotic fieldwork at SSERVI Target Bodies. A focus of COTM work this year was also on the assessment of hand-held field instrumentation to optimize planetary field science. The team established a new laboratory at NASA Ames Research Center to support volcanic sample analysis, which includes capabilities for rock coring and determining bulk density, porosity, and thermal conductivity.

The Remote, In-Situ, and Synchrotron Studies for Science and Exploration (RIS⁴E) team led by Dr. Tim Glotch at Stony Brook University made substantial progress in 2016 in each of their four major areas of research. They used detailed laboratory and remote sensing analyses to shed new light on exotic lunar lithologies that are enriched in the mineral olivine. Collectively, these studies are providing new information of the evolution of the lunar interior and could influence future lunar landing and sample return site selection. In addition, their field team continued work to evaluate the role of field portable instrumentation for human spaceflight as well as to answer science questions about the December 1974 volcanic flow in the SW rift zone of Kilauea Volcano. They have established an ongoing collaboration with the Human Research Program (HRP)-funded Hawai'i Space Exploration Analog and Simulation (HI-SEAS) group to assist in the simulations of human exploration in lava tube environments. Their work has also progressed in the area of dust toxicity/reactivity and its relation to astronaut health. A major effort underway has been to optimize an antibody-based assay to quantify specific oxidative protein-DNA crosslinks formed in cells upon exposure to lunar dust simulants. Their collaborative effort between geosciences and medical personnel resulted in a 9-page white paper prepared for the NASA Human Research Program director William Polaski. Finally, detailed analyses of solar system materials at micro- and nano- spatial scales resulted in the discovery of the solar wind depositing Helium in 20 nm bubbles in lunar ilmenite grains. The results have implications for space weathering and surface alteration on airless bodies and future efforts for in-situ resource utilization.

The Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES) team led by Dr. Andy Rivkin at Johns Hopkins University/Applied Physics Lab continued its work toward understanding the origin of regolith and the incorporation and transport of volatiles in it. In 2016, they found that the distribution of ice near the lunar poles is not what we would expect given the present-day temperature conditions. Members of the VORTICES team have shown that the distribution can be explained if the Moon's north and south poles have shifted from their positions billions of years ago. They further suggest this shift could have been due to the weight of massive, long-lasting lava flows in the Procellarum region of the Moon. In addition to looking at large-scale phenomena on the Moon, VORTICES members also studied centimeter-scale processes on small bodies. They confirmed that the day-to-night temperature extremes found on asteroids are sufficiently large as to crack rock over time, and found that the composition and length of the asteroidal day are key factors in determining which size of rocks are most affected. They found that exposure of some carbon-rich meteorites to ultraviolet light and the solar wind might lead to creation of simple pre-biotic materials. They also found that the solar wind can penetrate deeper into lunar and asteroidal soils than previously thought. The team's work culminated in hosting an invitation-only workshop on Water on Airless Bodies involving 40 participants from within and external to SSERVI teams.

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 examines the complex three-way connection between the harsh space environment, the exposed surfaces of airless bodies affected by this environment, and human systems also at these exposed, affected surfaces. In 2016, they conducted an intramural study of the Martian moon, Phobos, focusing on space environmental effects at this unusually shaped object. The 'Space Environment in Stickney Crater' exercise lead to a number of papers, and directly addressed Phobos exploration topics like the near-surface plasma environment, astronaut charging, dust cohesion & removal, gas retention, high energy radiation surface modification, solar illumination, impact gardening, etc. Team members also produced new simulations of plasma-regolith interactions building new specialized particle-in-cell plasma codes of grain beds immersed in the solar wind. The results revealed the development of extraordinarily large electric fields between grains. Team members continue to monitor and model the unusual weakening of the solar cycle over decadal scales and have shown that both solar max and solar min have been weakening, thus allowing greater Galactic Cosmic Ray (GCR) flux to reach the inner heliosphere. This affects the number of allowable days for astronaut exposure, which is a key parameter derived from this work. DREAM2 possesses potent science tools, continually targeting their results toward exploration initiatives.

The SSERVI Evolution and Environment of Exploration Destinations (SEEED) team science and exploration activities, led by Prof. Carle Pieters at Brown University, encompass several integrated themes with both near- and long-term goals. A large fraction of research involves student or postdoc young scientists (e.g., first authors of 36% peer reviewed papers), an important aspect of SEEED structure. The team studies the chemical and thermal evolution of planetary bodies, the origin and evolution of volatiles, and space weathering of regolith in different environments. Integrated research found that floor-fractured craters are the products of shallow magmatic intrusions with features that are strongly influenced by the global tectonic state of the body and reflect the regional crustal and lithospheric structure. Analysis of data from the Moon Mineralogy Mapper (M3) across the enormous South Pole-Aitken Basin shows that the basin interior is pyroxene-rich (no trace of deep-seated olivine), but exhibits clear compositional zoning that reflects basin early evolution. A monumental paper, Generation, Ascent and Eruption of Magma on the Moon (1 & 2), provides a basis for understanding and testing many physical processes common across the terrestrial planets. A global analysis of M3 data, calibrated with a new thermal model, allowed OH/H2O features to be re-examined and several pyroclastic areas were observed to be OH-rich. A SSERVI cross-team group found evidence suggesting ongoing day-night migration of hydrogenous species. Research on regolith of airless bodies and space weathering summarized a complex array of processes involved and identified different space weathered products for different surface compositions and environments. On-going joint activities with Japanese collaborators surveying and analyzing the extensive Japanese collection of lunar meteorites has been highly productive and demonstrated visible-near-infrared spectrometer analyses provides valuable nondestructive in-situ lunar assessment.

The Institute for the Science of Exploration Targets (ISET) Team led by Dr. Bill Bottke at the Southwest Research Institute studies the origins, evolution, and properties of exploration targets including near-Earth asteroids (NEAs), Phobos and Deimos, and the Moon. They recently developed the most physically realistic simulation to date of the formation of the inner and outer planets in our solar system, providing new insights into how this process regulates the mass and composition of the asteroid belt. A key finding is that a substantial portion of small, volatile-rich bodies from the outer solar system become implanted in the asteroid belt as the early giant planet orbits migrate. This finding is critical if we are to identify and eventually develop NEAs capable of providing water to astronauts for propellant, life, etc. The team has explored how asteroid spins evolve due to radiation forces, fundamental to determining asteroid terrain stability for future astronaut missions, and how the irregular, regolith-covered surfaces of asteroids and Phobos/Deimos will affect the motion of landed vehicles and the spatial dependence of surface escape velocities. Team members have developed the first complete model of Phobos and Deimos's formation by a large impact with Mars, which suggests that the interiors of these moons will be water-poor. Studies of cratering rates in the inner solar system have provided revised estimates for early large impacts on the Moon and Mars, and new assessments of the evolution of the NEA population in recent times. This allows us to explore plausible sources of lunar water. Team members are actively conducting observational searches for "minimoons," which are small objects temporarily captured in cis-lunar space that may be promising targets for future Orion missions, and have developed a new model of the expected steady-state population of these objects.

The Center for Lunar and Asteroid Surface Science (CLASS) team led by Prof. Dan Britt at the University of Central Florida studies the physical properties of regoliths, including geotechnical properties, development of asteroid simulants, microgravity effects, impact ejecta, the dynamics, hydration, weathering, compaction, and the charging/mobilization of dust of Near Earth Asteroids and the Moon. The team provides most of the science team and the hardware for the STRATA 1 dust experiment now on the ISS. Their scientific leadership, in partnership with Deep Space Industries, is developing a family of asteroid simulants to support NASA exploration goals. CLASS PI Dan Britt supported the NASA Moons of Mars Human Spaceflight Architecture Team with relevant science input. The team is also working with the Asteroid Redirect Mission (ARM) to investigate thermal stress and breakdown on relevant simulant material, and has taken the lead on research to characterize the potential health effects of Polycyclic Aromatic Hydrocarbons in carbonaceous chondrites. Team members were named to the ARM Formulation and Assessment Team and supported its report development. The team recently published new research on the potential of asteroidal material for radiation shielding. They conducted experiments on the thermal cycling of lunar soil to learn how fast and how much it compacts in the thermal cycle that exists on the lunar surface. The team also studied the global evolution and dynamics of rubble pile asteroids as they interact and dissipate energy, and worked on atomic-scale modeling techniques to understand the dissipative and adhesive properties of mineral grains in asteroid regoliths. Finally, CLASS hosted 14 speakers in 2016 with in-person and online audiences, with viewers that spanned the globe from more than 35 different countries.

TEAM REPORTS

The SSERVI teams are supported through multiple year cooperative agreements with NASA (issued every 2-3 years) for long duration awards (5 years) 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.

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

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

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

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

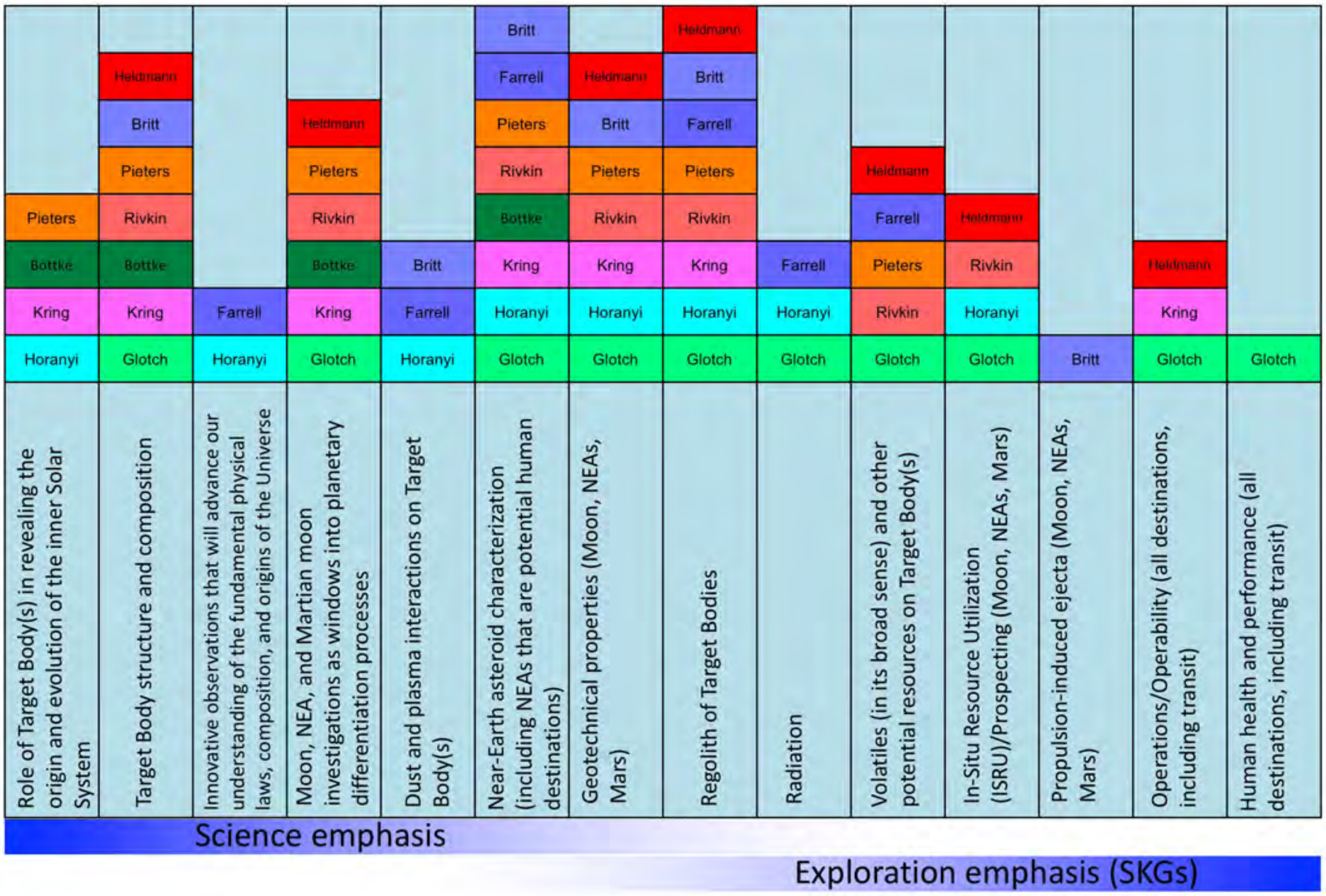
Andy Rivkin
Johns Hopkins University/Applied Physics Lab, Laurel, MD
Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES)

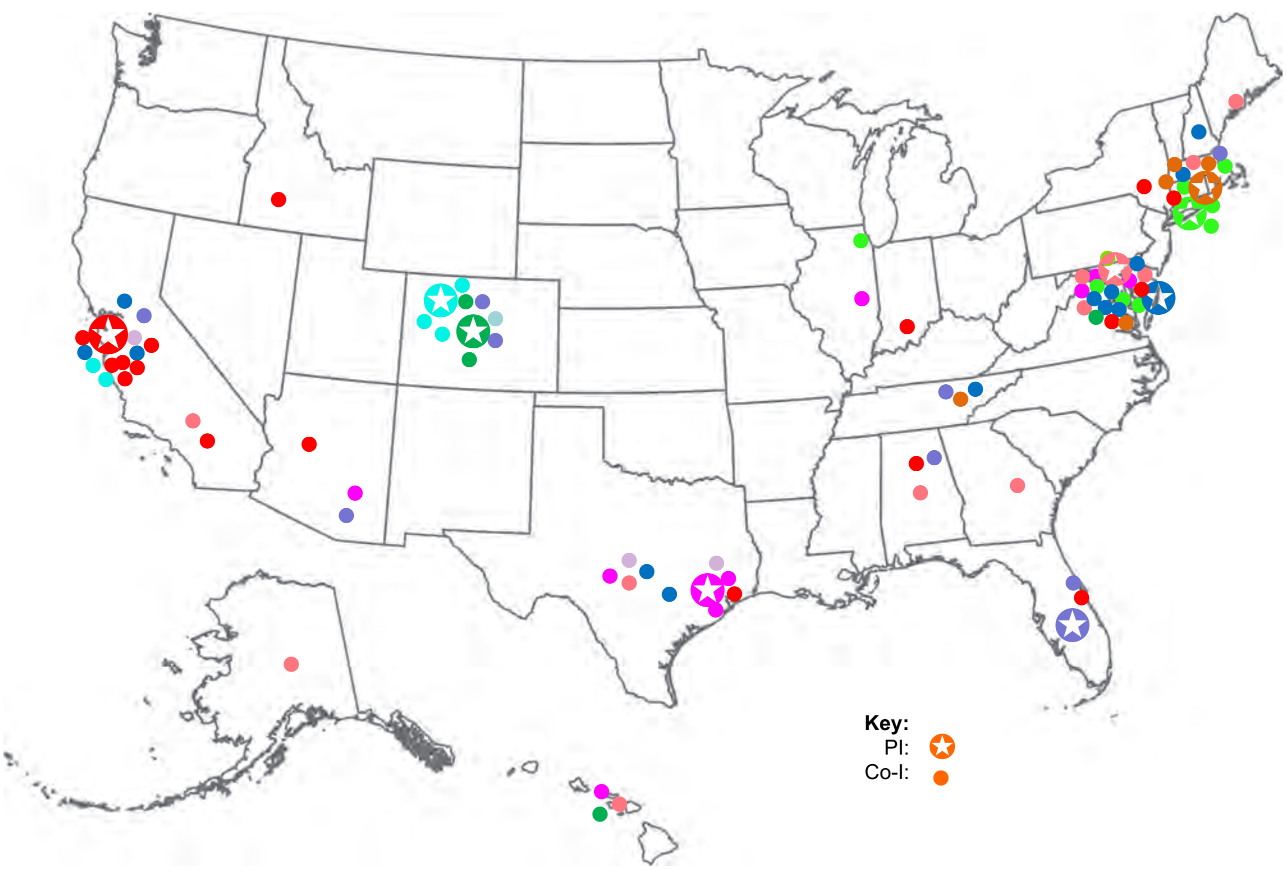
William Farrell
NASA Goddard Space Flight Center, Greenbelt, MD
Dynamic Response of Environments at Asteroids, the Moon, and Moons of Mars (DREAM2)

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

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

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





Focus of SSERVI CAN-1 team research and geographical distribution.

David Kring

Lunar and Planetary Institute, Houston, TX

Center for Lunar Science and Exploration (CLSE)

LPI-JSC Center for Lunar Science & Exploration

1.1 Science. The Center for Lunar Science and Exploration team had a banner year with two high-profile papers in Nature Communications, followed by a third paper in Science, amidst a larger collection of peer-reviewed papers (see complete list of Publications). Here we describe some of the highlights.

A significant portion of our team examined the delivery and evolution of water in the Moon (Fig. 1). In a paper led by one of our postdocs (Barnes et al., Nature Communications, 2016), we examined the stable isotopes in lunar samples and compared them with potential sources of water among comets and meteoritic fragments of asteroids. In general, comets contain more water, nominally estimated to be about 50% by mass. Many asteroids, however, also contain significant abundances of water, up to and exceeding 20 wt% (Fig. 2). By using the isotopic composition of the volatiles trapped in lunar samples, we were able to show that most of the water in the lunar interior was delivered by asteroids, not comets. Furthermore, that water was likely delivered early in lunar history, when impacting projectiles still had access to the lunar magma ocean. In a second paper, we also showed (Barnes et al., Earth and Planetary Science Letters, 2016) that some of the volatiles in the lunar magma ocean may have been lost when impacting asteroids punctured the crust and exposed the lunar mantle. In a paper published at nearly the same time by another postdoc (Robinson et al., Geochimica et Cosmochimica Acta, 2016), we showed that the water in the lunar interior is heterogeneously distributed, either due to the stochastic delivery of volatiles and inadequate mantle mixing, or due to differential loss. In preliminary reports (i.e., several meeting abstracts) we have also outlined the cycling of those volatiles to the lunar surface and deposition into permanently shadowed craters. Full reports are in production and should appear in the coming year.

After the crust of the Moon formed, asteroids and comets continued to hit the lunar surface, producing large impact basins. One of the most important targets for future

Fig. 1. The Moon contains small, but potentially significant amounts of water. Rock samples collected by the Apollo astronauts suggest the interior of the Moon contains 10 to 300 parts per million (ppm) water. Scientists are intrigued by the source of that water and when the Moon acquired it. Did the material come from asteroids, comets, or some other source? Lurking in the answer to that question may be additional clues about how the solar system formed, how the Moon accreted, and how impact bombardment affected the Moon when it was transitioning from a molten mass to a planetary body with a substantially-solid crust. LPI-CLSE.

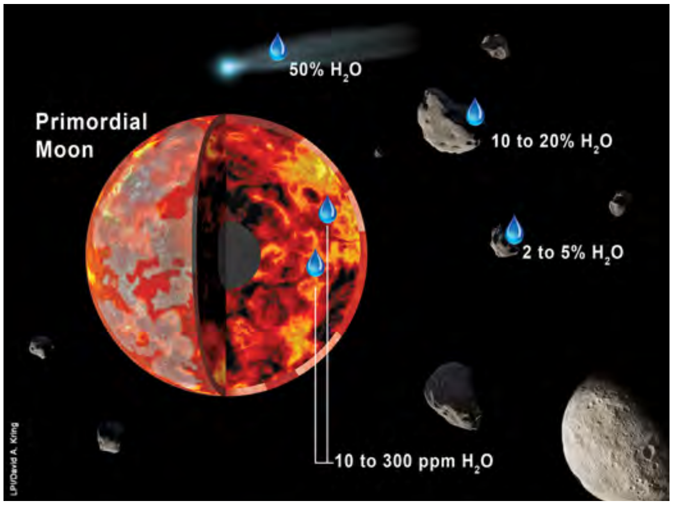


Fig. 2. The Moon may have obtained water when it was still partially molten (red to orange regions) and its primordial crust (gray to white regions on surface) was forming. At that time, the Moon was being pummeled by impacting asteroids and comets that could deposit water into the lunar interior. The isotopic compositions of volatile elements in samples from the Moon suggest asteroids were the dominant source of that water. In particular, the asteroids seem to have been similar to water-rich CI, CM, and CO carbonaceous meteorites. The CI and CM types of meteorites contain 10 to 20% water. Other types of carbonaceous meteorites, including CO type meteorites, contain 2 to 5% water. Although comets may contain more water (perhaps 50%) than asteroids, their isotopic compositions do not match that of the Moon's water. Thus, less than 20% of the Moon's interior water appears to be from comets. LPI-CLSE.

exploration is the Schrödinger basin, within the South Pole-Aitken basin, on the lunar far side. This ~320 km-diameter basin has a mountainous peak ring that rises up to 2.5 km above the basin floor (Fig. 3).

We published a detailed geologic map of a representative portion of the peak ring (Kring et al., Nature Communications, 2016) which, when combined with computer simulations of the impact event, showed that the peak ring likely formed when a central uplift rose above the basin floor and then collapsed to form a displaced ring of rock. If this model is correct, then the Schrödinger peak ring is an excellent locality for collecting samples to test the lunar magma ocean hypothesis and, perhaps, more directly measure the volatiles in the lunar interior. Toward the end of the year, we had an opportunity to test that displaced structural uplift (DSU) model for peak ring formation with

Fig. 3. The Schrödinger basin is ~320 km in diameter with an ~150 km diameter peak ring that rises 2.5 km above the basin floor. Credit: NASA Scientific Visualization Studio.

a new core that was recovered, here on Earth, by a project that drilled into the peak ring of the Chicxulub impact crater. While the drilling project was funded by other programs (International Ocean Discovery Program and the International Continental Scientific Drilling Program), we contributed a small, but significant amount of expertise with impact basins, like Schrödinger, to interpret the core. The initial results (Morgan et al., Science, 2016) showed that the Chicxulub peak ring, like the Schrödinger peak ring, was produced by a displaced structural uplift model. Thus, our studies of the Moon are helping our understanding of events that shaped the Earth (Fig. 4).

We published two other studies of the Schrödinger basin. We mapped a series of faults and boulder trails that

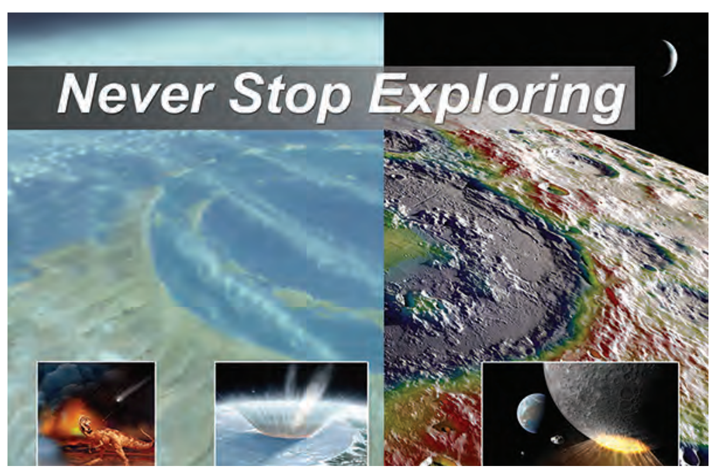


Fig. 4. The Schrödinger basin on the Moon (right) is a good analogue for the Chicxulub crater on Earth (left) and is being used to study the formation of those types of basins on all planetary surfaces in the solar system. LPI-CLSE.

indicated earthquakes had occurred within the past tens of millions of years (Kumar et al., Journal of Geophysical Research – Planets, 2016). The basin is a good candidate for the deployment of a seismic station to study the lunar interior. We also examined a magnetic anomaly over the basin (Hood and Spudis, Journal of Geophysical Research – Planets, 2016), which suggested the basin formed while the Moon's core dynamo was still active. This means the Schrödinger basin is a very good location to collect samples to measure the strength of the failing core dynamo at a calibrated point in time and, thus, provide an important constraint on the thermal evolution of the lunar interior.

Our team is also investigating the asteroids that impact the Earth-Moon system and may be targeted by future missions. While there are exploration components of our work (as described in subsection 1.3), we also approach these objects geologically to extract useful information. An important component of that effort is co-I Zolensky's characterization of C asteroid regolith breccia petrography and mineralogy, using e-beam, Raman, and synchrotron XRD techniques. We have been utilizing the best meteorite samples from C-class asteroid regoliths, including Kaidun, Sutter's Mill, Tagish Lake, LON 94101, and Jbilet Winselwan. One of our results has been to understand for the first time the full range of shock impact effects on regolith samples, and to better appreciate the polymict character of the samples, which is an expected result. However, we have also identified an unexpected, but rather common, association between C and E chondrites in these regolith samples.

This work has been significantly enhanced by collaborations between JSC and Japanese colleagues to make new, more realistic Vis-IR spectral measurements of the full range of C chondrites, including thermally metamorphosed and impact shocked samples, and mixtures of these. These studies include an analysis of organics in these meteoritic samples of the asteroids. Results are being compiled to predict the nature of the samples that will be returned from asteroids Ryugu and Bennu over the coming decade, and to thus better prepare for these samples.

We refer readers to the complete list of peer-reviewed publications, including scientific studies of mare basalt provinces of the Moon that can be used to evaluate the magmatic evolution of the Moon, impact melt lithologies at the Apollo 17 landing site that can be used to test the lunar cataclysm hypothesis, and the geologic evolution of several types of asteroids, including those that may be composed of materials like those to be collected by the Asteroid Retrieval Mission (ARM).

1.2 Exploration. We were tasked to evaluate a scenario that NASA and other agencies within the International Space Exploration Coordination Group (ISECG) have been exploring as an option to fulfill the Global Exploration Roadmap (GER). In this scenario, published by Hufenbach et al. (IAC 2015), there is a series of five human landing sites: Malapert massif, South Pole, Schrödinger basin, Antoniadi crater, and the center of the South Pole-Aitken basin (Fig. 5). In the mission sequence, two small pressurized rovers (e.g., Lunar Electric Rovers [LER]) are deployed to the surface at Malapert. Crew then land, conduct a 28-day or 42-day mission, before returning to an exploration Deep Space Habitat (eDSH) in orbit above the lunar far side. Crew then return to Earth with collected samples in Orion. The LER are than tele-robotically driven to a second landing site, a crew lands again, and so on. We were specifically asked to evaluate (i) traverse options for the tele-robotic

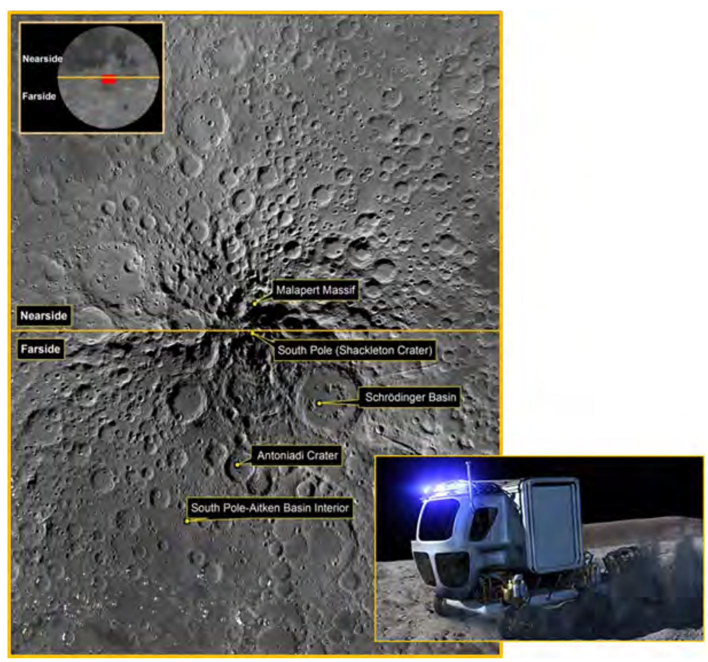


Fig. 5. An ISECG concept features the deployment of two LER that will be tele-robotically driven between five landing sites for crew, where four astronauts will conduct 28-day to 42-day missions and return samples to Earth repeatedly over that five-year interval.

phases between crew landings and (ii) design traverses for crew that respond to high-priority science and exploration objectives. Those issues were evaluated in a summer study and briefed to HEOMD and the ISECG Lunar Surface Architecture team. The study revealed that the LER has two rich opportunities to survey the lunar subsurface for deposits of water and other forms of ice in Cabeus and Amundsen craters. The study also revealed that most of the objectives in an NRC (2007) report, The Scientific Context for Exploration of the Moon, can be addressed along that traverse. If there was a single sortie mission rather than a series of five missions, the Schrödinger basin remains the highest priority target.

Throughout the year, we provided input regarding lunar regolith properties to the Resource Prospector mission when requested. We also continued to update the curriculum material that will be used for the 2017 class of astronauts.

Finally, we continued to survey the sky for asteroids that may be suitable for future missions. Team members with the Arecibo planetary radar group detected 63 near-Earth asteroids, 23 of which are potentially hazardous asteroids and 27 are Near-Earth Object Human Space Flight Accessibel Targets Study (NHATS) compliant, i.e., dynamically accessible and of interest to NASA for possible future robotic or crewed missions. Overall, the last five years account for ~60% of all NEA detections since 1998 and over 75% of all NHATS detections (Fig. 6). This work is primarily sponsored by another program, but is augmented with a contribution through our SSERVI-sponsored contract, with our particular interest being in the properties that astronauts may encounter and the properties that may affect our assessment of future impact hazards. The variety found among the NHATS objects reflects the heterogeneity found in the general near-Earth asteroid population. Rotation rates and sizes of NHATS objects detected in 2016 range from likely sub-10-meter asteroids (absolute magnitudes >28.0) that rotate in mere minutes, to the several-hundred meter scale contact binaries (85990) 1999 JV6 and (464798) 2004 JX20 that rotate on the order of several hours. A handful of objects are suggestive of elevated polarization ratios most likely belonging to the E or V taxonomic classes. Precise radar astrometry over multiple apparitions led to the detection of non-gravitational acceleration on (85990) 1999 JV6 (Giorgini et al., CBET 4279, 2016).

1.3 Training. A very important part of our team's activities are programs that are designed to train young investigators in the field of solar system science and exploration. This year we continued our Exploration Science Summer Intern Program (Fig. 7), which is designed for graduate students. Thus far, we have trained 65 students through this type of program. It is an intensive and immersive program that provides students an opportunity to study an exploration issue. In the 2016 edition of the program, the students studied the ISECG mission architecture concept that involves five human landing sites (Fig. 5). The students

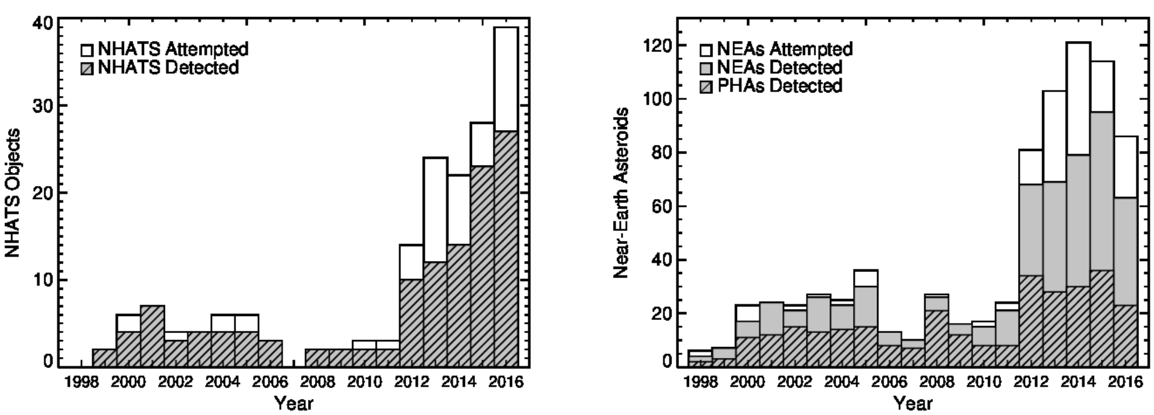


Fig. 6. Detections per year of near-Earth asteroids (left) and the subsets of potentially hazardous asteroids (left) and NHATS objects (right). The number of detections has grown substantially since 2011 under full programmatic support by NASA. Detections of 80 to 100 near-Earth asteroids and 20 to 30 NHATS objects per year are sustainable if the transmitter system is healthy.

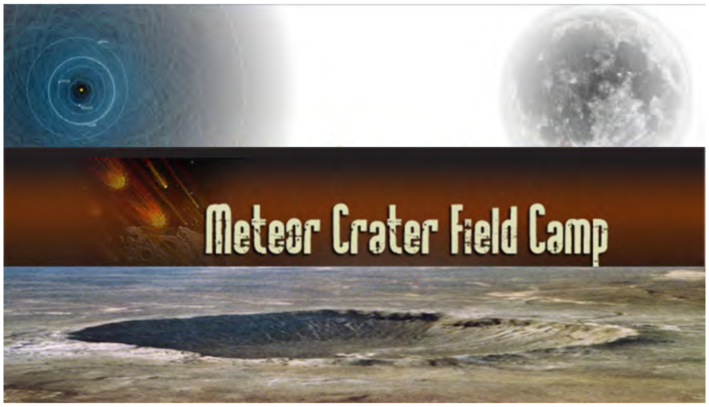


Fig. 7. Exploration Science Summer Intern Program.

utilized data from the Lunar Orbiter, Apollo, Lunar Prospector, Clementine, Kaguya, Chandrayaan-1, and Lunar Reconnaissance Orbiter missions. They worked with senior scientists at LPI and JSC and obtained additional input from the Orion team at Lockheed Martin Space Systems.

We also organized the fourth edition of our Field Training and Research Program at Meteor Crater. We were able to support fifteen graduate students in that program this year. After receiving several days of training – drawing on some of the same techniques that PI Kring uses with astronauts – the students began a study of the continuous ejecta blanket around the crater. In particular, they made field measurements to reconcile differences in the distribution of ejecta mapped by Gene Shoemaker and David Roddy. They students located several outcrops of ejecta not mapped by Shoemaker and will be reporting those results at the next Lunar and Planetary Science Conference.

Our field training and research programs at Meteor Crater, the Sudbury impact structure, and the Zuni-Banderas Volcanic Field have provided exceptional opportunities at some of the world's best planetary analogue sites for over 130 graduate students thus far.

Inter-team 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:

With international partners in India, along with Jim Head on the Brown-MIT SSERVI team, we reported sites where moonquakes possibly occurred along young lobate scarps in the Schrödinger basin (Kumar et al., Journal of Geophysical Research – Planets, 2016). Our analysis of Lunar Reconnaissance Orbiter and Chandrayaan-1 images revealed four lobate scarps in different parts of the Schrödinger basin. The scarps crosscut small fresh impact craters (<10–30 m) suggesting a young age for the scarps. A 28 km long scarp (Scarp 1) yields a minimum age of 11Ma based on buffered crater counting, while others are 35–82Ma old. The topography of Scarp 1 suggests a range of horizontal shortening (10–30 m) across the fault. Two scarps are associated with boulder falls in which several boulders rolled and bounced on nearby slopes. A cluster of a large number of boulder falls near Scarp 1 indicates that the scarp was seismically active recently. A low runout efficiency of the boulders (~2.5) indicates low to moderate levels of ground shaking, which we interpret to be related to low-magnitude moonquakes in the scarp. Boulder falls are also observed in other parts of the basin, where we mapped >1500 boulders associated with trails and bouncing marks. Their origins are largely controlled by recent impact events. Ejecta rays and secondary crater chains from a 14 km-diameter impact crater traversed Schrödinger and triggered significant boulder falls about 17 million years ago. Therefore, a combination of recent shallow moonquakes and impact events triggered the boulder falls in the Schrödinger basin.

With international SSERVI partners in the UK, we published several analyses of water in the Moon (Barnes et al., Nature Communications, 2016; Barnes et al., Earth and Planetary Science Letters, 2016; Robinson et al., Geochimica et Cosmochimica Acta, 2016).

With international SSERVI partners in the UK, we completed a review of the types of asteroid fragments that are preserved within the lunar regolith (Joy et al., Earth Moon and Planets, 2016).

With an international partner within the UK, we published an analysis of the peak-ring of the Schrödinger basin (Kring et al., Nature Communications, 2016).

With international partners in Australia, we completed an assessment of zircon crystals that will enhance our ability to interpret zircon-derived ages of impact events on the Moon (Timms et al., Earth Science Reviews, 2016).

SSERVI Postdoc Kretke is studying the growth of planets and planetesimals via a pebble accretion. She is based with the SwRI SSERVI team, led by PI Bottke, but is drawing on our team's familiarity with the meteoritic record and the constraints it puts on the accretion of material and subsequent mixing between inner and outer solar system locations. We anticipate the first results of that collaboration to appear next year.

Finally, working with Prof. Britt, PI of the UCF SSERVI team, and one of his students, we completed a preliminary study of the strengths of boulder-size asteroids based on the properties of meteoritic events. That result may help with the design of the Asteroid Retrieval Mission (ARM). A full report is being prepared and will be submitted next year.

Public Engagement (including EPO) Report

2015-2016 & 2016-2017 Exploration of the Moon and Asteroids by Secondary Students (ExMASS)Program

At the 2016 NASA Exploration Science Forum, ExMASS schools (Fig. 8) from the 2015-2016 academic year received honorable mention and third place in the student poster competition.

60 students from 10 schools across the country are involved in the current (2016-2017) program. Student research includes comparing Barringer Crater to the Chesapeake Bay Crater, searching for potential mining locations on the Moon, and identifying possible secondary craters from Tycho at the Apollo 17 site.

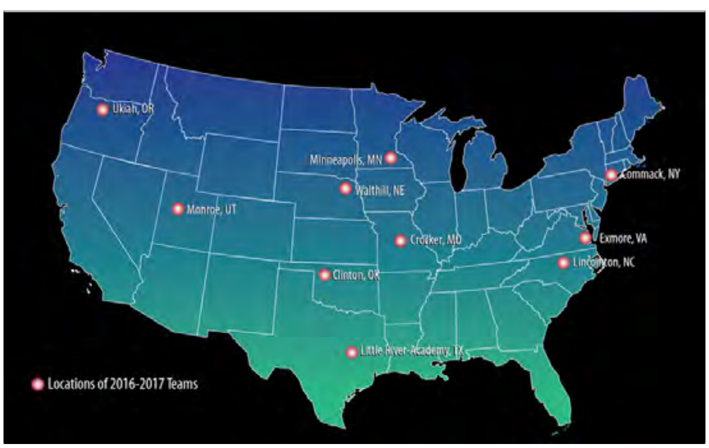


Fig. 8. Locations of 2016-17 ExMASS schools.

The current teams will submit their research posters to CLSE in April; top four posters selected soon after; those posters, along with the team with the best poster, will travel to the 2017 Exploration Science Forum at NASA Ames Research Center.

Traveling Library Exhibits

Ninth and newest exhibit, Meteorites: Messengers of Mayhem, debuted in 2016.

6 institutions across the nation displayed the exhibits in their programs, reaching an estimated 11,500 people this year.

CosmoQuest Google+ Hangouts

In 2016, these events moved from Google+ Hangout to YouTube Live events.

Reach: 100 live viewers, ~400 views of the recordings, estimated 17,000 podcast (audio only) downloads.

Public Night Sky Viewing Events

Continued leveraging LPI's Sky Fest program.

Events included International Observe the Moon Night (InOMN) and an event celebrating Juno's orbital insertion around Jupiter.

CLSE & SSERVI materials displayed during InOMN.

Public Lectures

PI Kring spoke twice as part of the Distinguished Lecture Series at the Houston Museum of Natural Science regarding (i) near-Earth asteroid impacts and (ii) exploration with the Orion vehicle.

On-line Educational Resources

Celebrating the silver anniversary of the discovery of the Chicxulub impact crater, perhaps the most famous NEA impact in the world, we released a library of classroom illustrations and a new version of our Chicxulub Impact Event website.

Continuing that theme, we published an on-line article "Chicxulub Crater, Twenty-Five Years Later" that summarizes the crater and the environmental calamity the impact produced.

We also produced an educational card that illustrated how studies of lunar craters (specifically the Schrödinger basin) have helped us understand the Chicxulub impact event on Earth.

Cross-team Synergies

EPO lead Shaner continued to serve as the InOMN Website/social media/listserv manager.

Guests for Google Hangouts involved team members from the RIS[4]E, FINESSE, DREAM2, and CLASS teams (and a SEEED participant was scheduled).

Scientists with CLSE, VORTICES, and ISET served as student team advisors for the ExMASS program.

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 Robinson (Open University)
4. Dr. Martin Schmieder (USRA-LPI)
5. Dr. Barry Shaulis (USRA-LPI)
6. Dr. Joshua Snape (Swedish Museum of Natural History)

Graduate Student Researchers

7. Sky Beard (University of Arizona)
8. David Burney (University of Notre Dame)
9. Emily Worsham (University of Maryland)
10. Connor Hilton (University of Maryland)

Exploration Science Graduate Student Interns

11. Elyse Allender (University of Cincinnati)
12. Natasha Almeida (Birkbeck College London)
13. John Cook (University of Houston)
14. Jessica Ende (University of Tennessee)
15. Oscar Kamps (Utrecht University)
16. Sara Mazrouei-Seidani (University of Toronto)
17. Csilla Orgel (Freie Universität Berlin)
18. Thomas Slezak (Brigham Young University)
19. Assi-Johanna Soini (University of Helsinki)

Undergraduate Student Researchers

20. Adeene Denton (Rice University)
21. Laura Seifert (University of Arizona)

Field Training and Research Program at Meteor Crater – Graduate Students

22. Samuele Boschi (Lund University)
23. Christy Caudill (University of Western Ontario)
24. Mitali Chandnani (University of Alaska Fairbanks)
25. Nicholas DiFrancesco (Stony Brook University)
26. Shannon Hibbard (Temple University)
27. Kynan Hughson (University of California Los Angeles)
28. Mallory Kinczyk (North Carolina State University)
29. Audrey Martin (University of Tennessee)
30. Ellinor Martin (Lund University)
31. Mélissa Martinot (Vrije Universiteit Amsterdam)
32. Cameron McCarty (University of Tennessee)
33. Kathryn Powell (Washington University)
34. Adam Sarafian (Massachusetts Institute of Technology)
35. Douglas Schaub (Stony Brook University)
36. Katherine Shirley (Stony Brook University)

Cross-team Postdoctoral Researchers

37. Dr. Katherine Kretke (Southwest Research Institute and USRA-LPI)
38. Dr. Debra H. Needham (formerly at USRA-LPI) – spent short amount of time as a postdoc with the GSFC team, working on papers with both teams, before obtaining her permanent position at MSFC.
39. Dr. Ross Potter (formerly at USRA-LPI) - now at Brown University, working on papers with both teams.

Mihaly Horanyi

University of Colorado, Boulder, CO

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

IMPACT Project Report

IMPACT 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 space physics community and supports a large number of undergraduate and graduate students.

1.1 Accelerator Projects

Gas Target Experiments: The amount of cosmic dust reaching our atmosphere remains poorly constrained, and it is currently estimated in the range of 50 - 150 tons/day. The largest uncertainty using ground-based radar observation is the ionization efficiency (β) of a micrometeoroid particle to generate a plasma trail, and for using optical telescopes is their luminous efficiency. Experiments at the dust accelerator using a moderate-pressure gas-target address these to enable improved mass estimates of micrometeoroids from these measurements. The gas target consists of a differentially pumped chamber kept at moderate background pressures, such that high-velocity (≥10 km/s) micrometeoroids are completely ablated within 10's of cm (i.e. within the measurement chamber). The chamber is configured with segmented electrodes to perform a spatially resolved measurement of charge production during ablation (Fig.1), and localized light-collection optics enable an assessment of the light production (luminous efficiency).

In a recent study (Thomas et al., 2016), we focused on producing fundamental data relevant to the interpretation of meteor radar observations, which has been an open problem for decades. In this study, we performed experiments to simulate micrometeoroid ablation in laboratory conditions to measure β for iron particles impacting N_2, air, CO_2, and He gases. This new data set was compared to previous laboratory data where we found agreement except for He and air impacts >30 km/s. We calibrated the commonly-used Jones model of β(v) and provided fit parameters to these gases, and found agreement

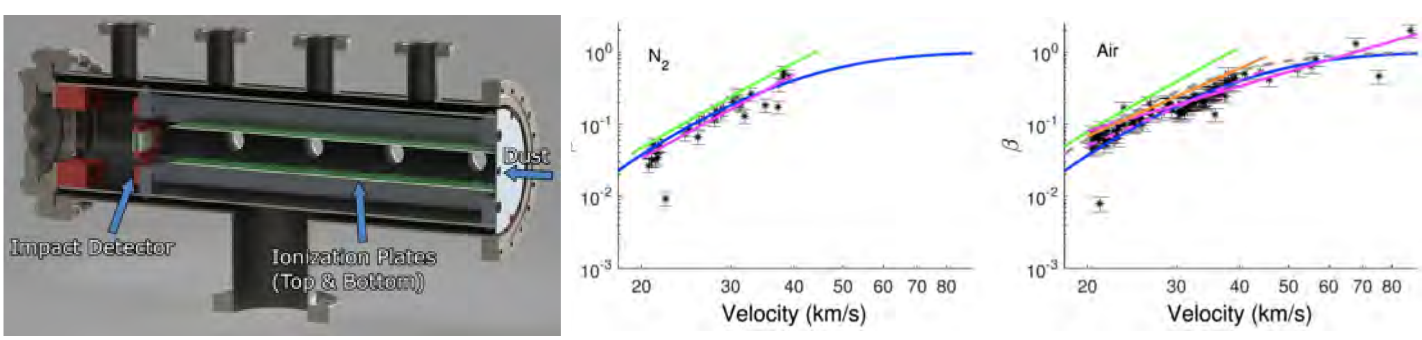


Fig. 1 Left: Cutaway diagram of the gas target chamber containing the ionization plates and the impact detector. Center, Right: β measurements from the gas-target experiment in N2 and Air (black points), compared to previously published datasets (green, blue, orange and gray lines), as well as current experimental data power law fits (magenta lines).

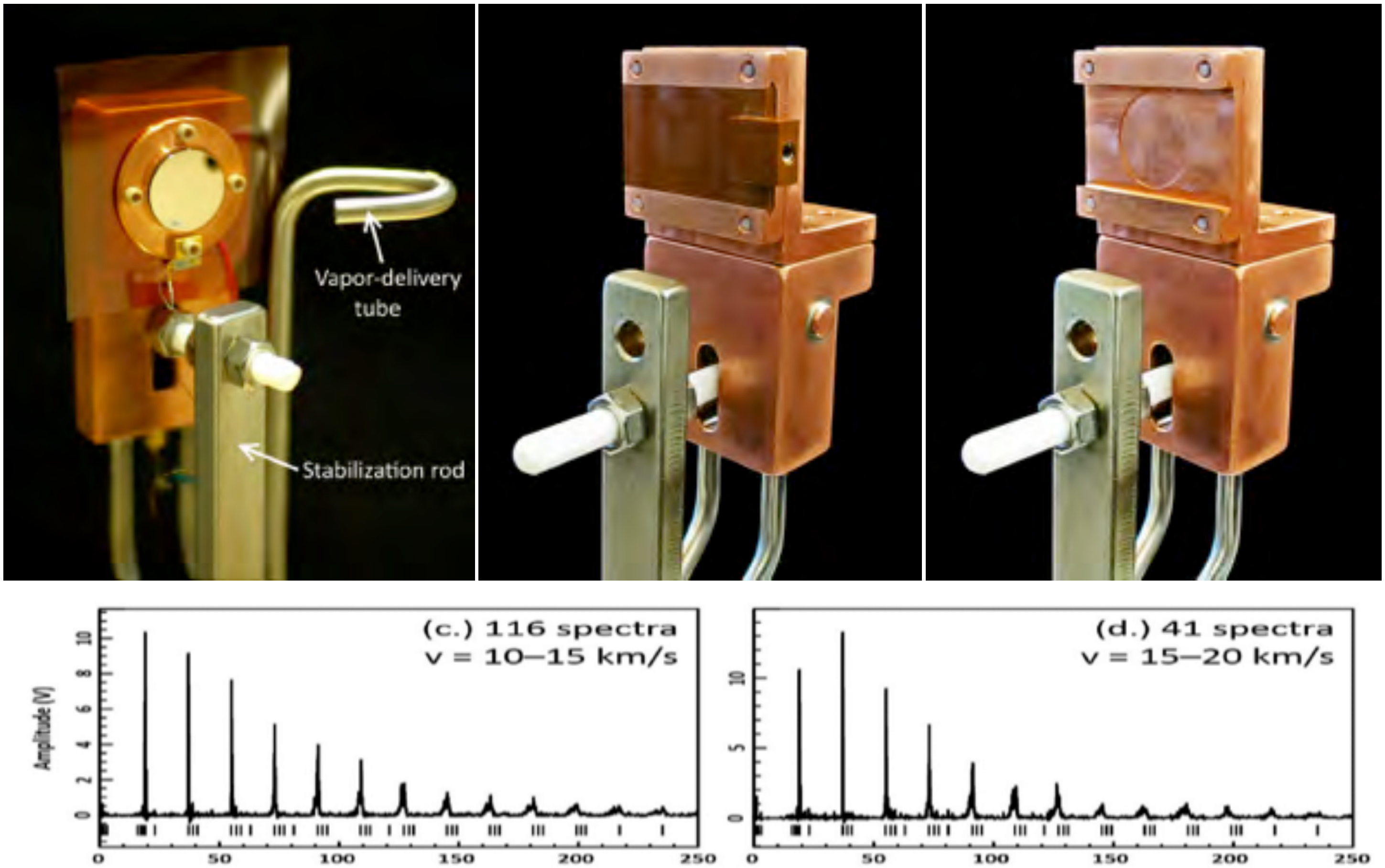


Fig. 2 Top row: Ice targets using vapor deposition (left) and flash-freezing cartridge (center, right). Bottom: Example data from a Time-of-Flight (TOF) mass spectrometer demonstrating the velocity dependence of water cluster formation from impacts of iron particles into water ice.

for all gases except CO_2 and high-speed air impacts where we observed $\beta_{air} > 1$ for velocities >70 km/s. These data therefore demonstrate potential problems with using the Jones model for CO_2 atmospheres as well as for high-speed meteors on Earth.

Ice Target Impact Experiments: We have recently developed a cryogenic ice target that can be exposed to particles from the dust accelerator (Nelson, et al., 2016). This capability is motivated by the need for a quantifiable experimental investigation into the hypervelocity micrometeoroid impact phenomena that contribute to the evolution of planetary icy surfaces. Capabilities granted by this facility are crucial to understanding the interesting complex chemistry and surface weathering effects that result from hypervelocity dust impacts and to calibrate instruments for space missions.

The ice target consists of a LN2 cryogenic system connected to both a vapor deposition system (Fig. 2, top left) and a movable freezer/holder for a pre-mixed liquid cartridge (Fig. 2, top center/right) for use in single-component ices or salty/multi-component mixtures, respectively. Impact products and chemistry are assessed with an integrated time-of-flight mass spectrometer. Such studies can be used to predict and interpret chemical signatures from impact products at planetary surfaces containing similar component materials, and can be used to explore the possibility of creating complex and possibly organic compounds on planetary surfaces through impact shock mechanisms.

Charge Measurements from Micrometeoroid Impacts onto Spacecraft: High-velocity dust that impacts a spacecraft body or antennas releases charged plasma clouds that can create voltage perturbations that are measured by electric field instrumentation. These voltage perturbations are characterized by a relative maximum and minimum, which correspond to body and antenna charge recollection, respectively. We have undertaken a series of experiments that explore the basic processes by which this happen, as well exploring how specific spacecraft replicas (complete with scaled models of the antennas and duplicates of the spacecraft antenna electronics) respond to impacts at various locations (Thayer et al., 2016). The charge recollected by the antenna relative to the total recollected charge is found to correlate with the potential difference between the spacecraft and the antenna. From data analysis that spanned 2007–2013 on the STEREO-A spacecraft, a positive correlation was found. This relationship will support future dust analysis with electric field instrumentation because it defines a critical spacecraft property that affects relative charge recollection.

1.2 Small-scale Laboratory Experiments

Our laboratory efforts remained focused on: a) optimizing the data interpretation of in-situ plasma diagnostic tools (Beadles et al., 2016); b) the charging, mobilization and transport of dust on the surfaces of airless planetary bodies (Schwan et al., 2016; Wang et al., 2016); and c) the completion of our new Colorado Solar Wind Experiment (CSWE) to study the interaction of the solar wind plasma flow with dust and regolith surfaces, and magnetic fields (Ulibarri et al., 2016).

Dust Charging and Mobilization New laboratory experiments (Schwan et al., 2016; Wang et al., 2016) shed light on dust charging and transport that have been suggested to explain a variety of unusual phenomena on the surfaces of airless planetary bodies. We have recorded micron-sized insulating dust particles jumping to several centimeters high with an initial speed of ~0.6 m/s under ultraviolet illumination or exposure to plasmas, resulting in an equivalent height of ~0.1 m on the lunar surface that is comparable to the height of the so-called lunar horizon glow. Lofted large aggregates and surface mobilization are related to many space observations. We experimentally showed that the emission and re-absorption of photoelectrons and/or secondary electrons at the walls of micro-cavities (Fig. 3) formed between neighboring dust particles below the surface are responsible for generating unexpectedly large negative charges and intense particle-particle repulsive forces to mobilize and lift off dust particles.

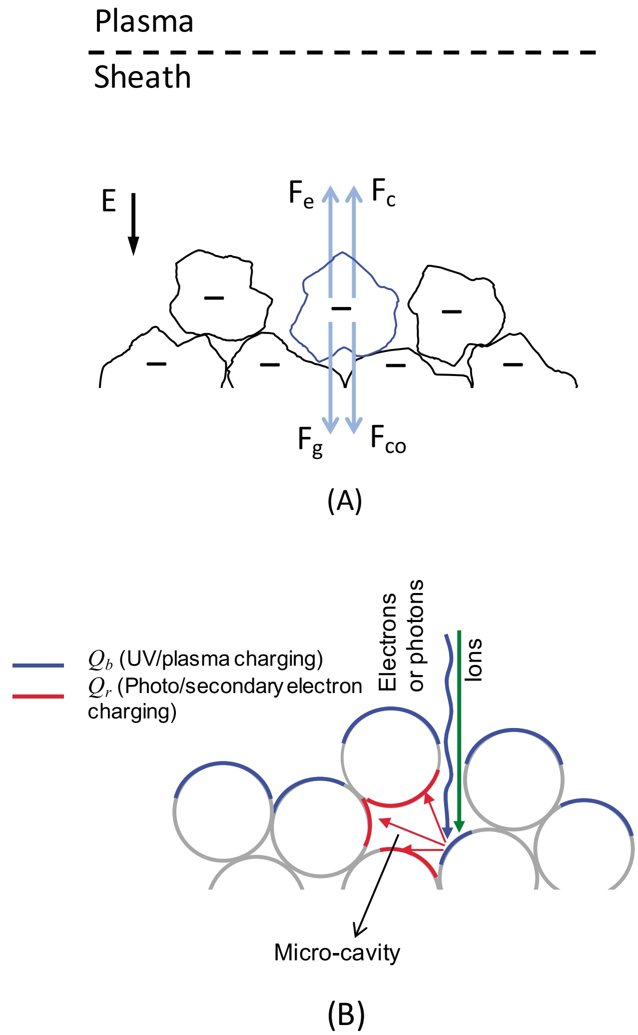


Fig. 3 Illustration of charges and forces on dust particles. (A) The customarily assumed charging models. An electric field E is created in a plasma sheath formed above a dusty surface. In this case, the dust particles are charged negatively. Forces acting on a top dust particle (blue) are Fe = QE, the sheath electric field force; Fc, the particle-particle repulsive force; Fg, the gravitational force; and Fco, the cohesive force between contacting particles. (B) Our new patched charge model. Dust particles (gray circles) form a micro-cavity in the center. Photons and/or electrons and ions are incident on the blue surface patches of the dust particles, charging them to Qb and simultaneously emitting photoelectrons and/or secondary electrons. A fraction of these emitted electrons are re-absorbed inside the micro-cavity and collected on the red surface patches of the neighboring dust particles, resulting in a negative charge Qr (from Wang et al., 2016).

The Colorado Solar Wind Experiment (CSWE) is a large ion source for studying the interaction of solar wind plasma with planetary surfaces and cosmic dust, and for the investigating plasma wake physics. A large cross-section

Kaufman ion source is used to create a steady-state plasma flow to model the solar wind in an experimental vacuum chamber. The plasma beam has a diameter of 12 cm at the source, ion energies of up to 1 keV, and ion flows of up to 1 mA/cm2. Chamber pressure can be reduced to 4 × 10−5 Torr under operating conditions to suppress ion-neutral collisions and create a uniform ion velocity distribution. Diagnostic instruments such as a double Langmuir probe and an ion energy analyzer are mounted on a two-dimensional translation stage that allows the beam to be characterized throughout the chamber (Fig. 4).

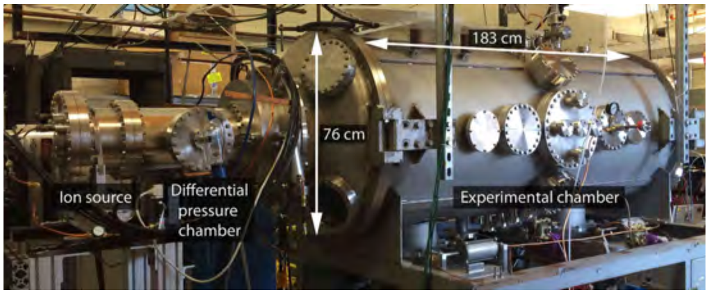


Fig. 4a A photo of the CSWE chamber. Ionized gas is created in the ion source, and an accelerating potential pulls the ions into the experimental chamber. A differential pressure chamber prevents excess gas buildup in the experimental chamber.

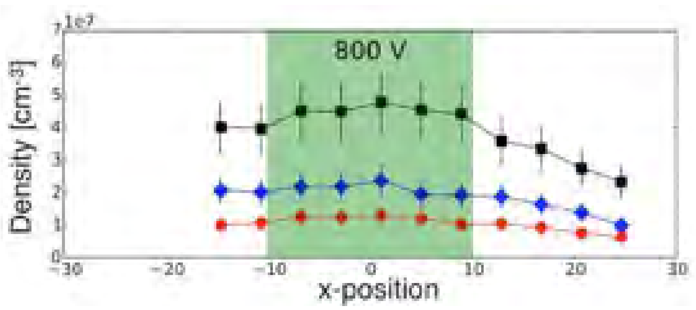


Fig. 4b The electron density across the plasma beam from Langmuir probe measurements. The green shaded region denotes the designated experimental space. The emission current was set to: 20 (red), 40 (blue) and 80 (black) mA.

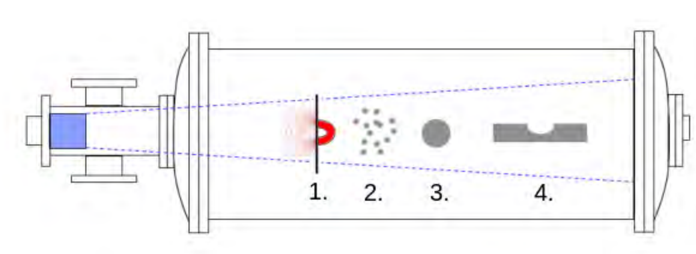


Fig. 4c A diagram of the planned experiments. 1. Solar wind interaction with magnetic anomalies. 2. Dust charging and dynamics. 3. Plasma wakes. 4. Topographical wakes.

In-Situ Resource Utilization Experimental Probe (IEP) Development

A prototype of the IEP was completed, integrated, and installed inside the 18-inch diameter vacuum chamber at the Colorado School of Mines (CSM), leaving the IEP apparatus fully operational. The IEP is now being used to study the physical interaction of mechanical probes with regolith and boulder/solid surfaces (Fig. 5). This system is built to fit inside similarly sized vacuum chambers at IMPACT for future experiments that include UV and plasma exposure. The IEP has been developed with the philosophy that an integrated approach between fundamental experiments, numerical simulations, and system-level hardware development lead to mission success.

The IEP consists of a three-axis translation stage with a 50-mm travel distance. A six-axis force-torque sensor, with up to a 280 N load, is mounted to the translation stage. A variety of probes (simulating penetration, scraping, and anchoring operations on a lunar or asteroidal surface) are mounted to the force-torque sensor and interact with regolith simulant surfaces below the stage. The force-torque sensor uses an arrangement of strain gauges to determine three orthogonal forces and torques about each axis. The complete system is rated for operation down to 10^{-7} torr. Stepper motors give the stage sub-micron resolution at up to 12 mm/s and up to a 300 N load. With a 5-mm diameter probe, the IEP can deliver 15 MPa pressure to the sample surface. The IEP structure has been designed to minimize flexure at these loads and provide probe-to-surface interaction angles from normal to 45°. A fourth motor can be brought in to provide probe rotation. Probe interaction with the surface inside the vacuum chamber can be recorded on video through a viewing window. Stage position, six forces and torques, video, pressure, and five temperatures readings are recorded simultaneously. Motion control using force feedback can be implemented to simulate interaction at a constant force or fixed spacecraft inertia (Fig. 5).

An example of IEP performance is shown in Figure 6 using a cone penetrometer. A lunar mare simulant, JSC1-A, was used as the testing sample in air and vacuum under low-compaction (1.4 g/cm^2) and high compaction (1.8 g/cm^2) levels. Penetration resistance force reached 30 N in

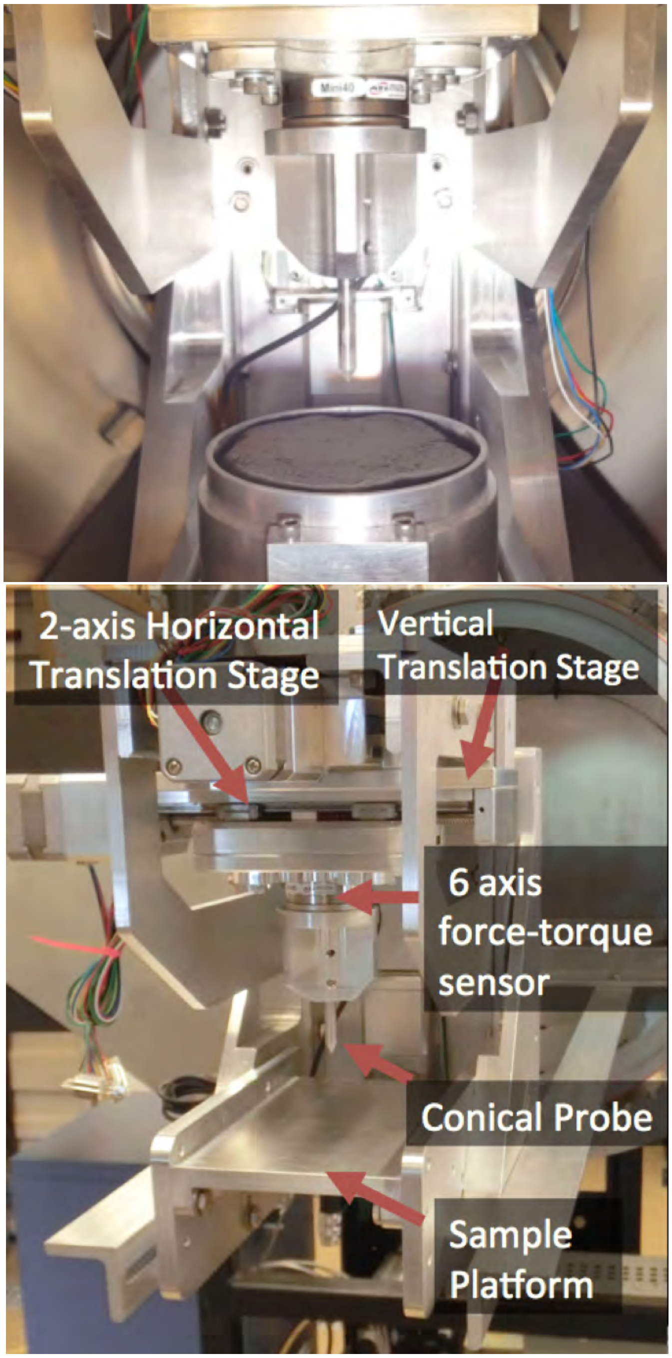


Fig. 5 ISRU Experimental Probe (IEP) inside CSM's 18"-diameter vacuum chamber at the Colorado School of Mines.

compacted JSC1-A, equivalent to 1 MPa with this probe, while with the same IEP configuration, a low-compaction JSC-1A surface produced a peak penetration resistance force of 0.3±0.1 N at 3.3 cm, equivalent to 10 kPa with this probe. In vacuum, a low-compaction JSC-1A surface produced a peak penetration resistance force of 0.45±0.05 N at 3 cm. These results are consistent with penetration resistance forces measured on the lunar surface by the Apollo astronauts at similar regolith bulk densities.

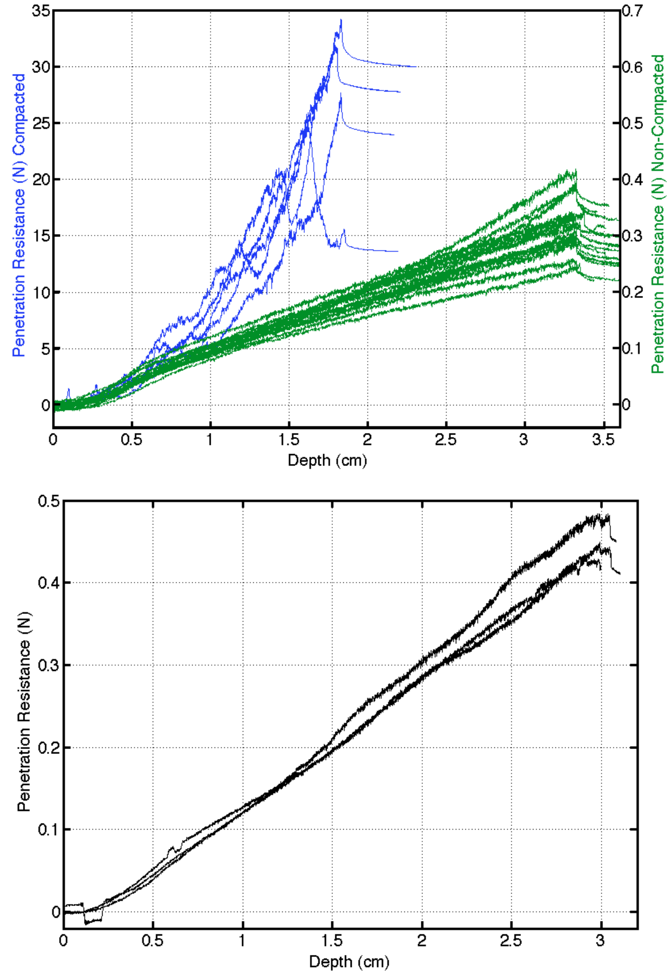


Fig. 6. TOP: Penetration resistance in air through JSC1-A simulant inside the IEP, with 6-mm diameter, 30° cone half-angle probe, and with simple linear motion into the simulant bed. Compacted bed on left axis and low compaction bed on right axis. BOTTOM: Penetration resistance into low compaction bed of JSC-1A simulant in vacuum at 50 mtorr. The penetration force declines after the peak due to surface relaxation after the probe stops moving (at a depth equal to the peak penetration).

Inter-team Collaborations

DREAM-2 and IMPACT: We continued our collaborations with Andrew Poppe and Jasper Halekas on the analysis and interpretation of LADEE/LDEX and ARTEMIS measurements. We are pursuing close collaborations on plasma simulations of magnetic anomalies and the comparisons of these with both laboratory experiments and space observations.

CLASS and IMPACT: We continued our collaboration with D. Britt and A. Dove to discuss micrometeoroid bombardment experiments addressing the physical properties of icy-regolith surfaces.

ISET and IMPACT: We continued our discussions with D. Nesvorny on the interpretation of LDEX measurements providing a new test case for evaluating model predictions of the various interplanetary dust sources bombarding the Earth/Moon system.

International Partners

We continued our close collaborations with our international partners at the University of Stuttgart (Prof. R. Srama, PI) for developing new dust composition analyzer instrumentation, and the University of Leuven, Belgium (Prof. G. Lapenta) for the development of numerical plasma simulation codes. We started discussions with A. Zakharov (IKI, Russia) about supporting the development of their dust/plasma instrumentation for a future lunar mission.

We have submitted a proposal for the Korean Path Finder Lunar Orbiter (KPLO) mission. The proposed Korean Dust Experiment (KDEX) for the KPLO mission is a replica of the Lunar Dust Experiment (LDEX). LDEX has successfully flown on the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. LDEX discovered a variable, but permanently present dust exosphere engulfing the Moon. LDEX followed a near equatorial orbit in the period of September 2013 - April 2014. KDEX was proposed to measure the spatial and temporal variability of impactors to the lunar polar regions. We are awaiting the results of the selections.

Public Engagement

Junior Aerospace Engineering program: In the second summer of IMPACT's three-year program, 10 middle school students and two fifth-graders built a 3-meter high rocket to launch at the end of the 2-week long camp (http://www.lavozcolorado.com/detail.php?id=8757 and http://noticiasya.com/colorado/2016/08/11/jovenes-hispanos-en-programa-de-cohetes/).

The students enjoyed their experience, as well as the opportunity to be on live TV. The launch was scheduled to take place on August 20 in Pueblo, CO after the camp was completed, but it was scrubbed due to weather safety concerns. We will try again next summer!

Junior Aerospace Engineering camp participants at the State Fair in Pueblo, CO on August 20, 2016.

InOMN: Since its start in 2009, we at IMPACT (and its predecessor (NLSI/CCLDAS) participated in the International Observe the Moon Night event, setting up telescopes on the pedestrians only Pearl Street Mall in Boulder. For the first time in 7 years, the weather was not cooperating, and we had to give up before after a short period of time.

Student/Early Career Participation

(http://impact.colorado.edu/people.html)

Graduate Students **Project**

Edwin Bernardoni Plasma theory

Leela O'Brien Detector design and fabrication

Evan Thomas Micrometeoroid ablation phenomena

Marcus Piquette Surface/plasma interaction modeling

JR Rocha Instrument development

Ben Southwood Dust dynamics modeling

Michelle Villeneuve (graduated 2016) Instrument development

Zach Ulibarri Ice target experiments

Lihsia Yeo Solar wind experiments

Michael DeLuca Micrometeoroid ablation experiments

Joseph Samaniego Langmuir probe measurements

Andrew Germer Instrument development

Alex Barrie Instrument data analysis

International Visiting Graduate Students

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

Maryam Khalil (U. Stuttgart) Dust impact studies

Undergraduate Students

Forrest Barnes Control software development

John Fontanese Small accelerator experiments

William Goode Accelerator diagnostic design

Andrew (Oak) Nelson (graduated 2016) Ice target development

Andrew Seracuse Beam detector development

Joseph Schwan Dust dynamics in plasma

Robert Beadles (graduated 2016) Langmuir probes in sheath

Juliet Pilewskie Dust dynamics modeling

Michael Gerard Lunar swirls modeling

Alexandra Okeson Dust instrument software development

Jared Stanley (graduated 2016) LDEX modeling support

Ethan Williams (graduated 2016) Instrument development

Eric Junkins (graduated 2016) Instrument development

Jia Han Solar wind experiments

Zuni Levin SIMION studies

Ted Thayer Antenna signals from dust impacts

Elizabeth Bernhardt Accelerator experiments

Max Weiner Mass-spectra

Chad Eberl Instrument development

Anthony Tracy Instrument development

Zach Burton Instrument development

Summer Undergraduate Students

Mikayla Roth Impact flash experiments

Jack Hunsaker Impact plasma formation

Riley Nirem Gas target PMT development

Postdocs

Jan Deca Computer simulations of plasma - surface interactions

Retired Volunteer Scientist

Dr. Richard Dee Ice target development

Jennifer Heldmann

NASA Ames Research Center

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

FINESSE Project Report

The following is a summary of the Science and Exploration research that has been conducted by the FINESSE team over the period of January 1, 2016-December 31, 2016.

A. Volcanic analogs at Craters of the Moon National Monument and Preserve, Idaho

The FINESSE project pursued multiple research themes at Craters of the Moon National Monument and Preserve (COTM) during 2016. Fieldwork was conducted August 5-13 and included collaborative efforts with the Canadian Space Agency (CSA), the VORTICES and BASALT teams, and Idaho Space Grant Consortium (ISGC), University of Western Ontario, Idaho State University, Carleton University, and University of Arizona. Scientific research themes are covered in the following sections.

i) Lava morphology classification: Graduate student researcher Hester Mallonee (ISU) used high-resolution imagery from UAV flights to create cm-scale Digital Terrain Models (DTMs). Surface textures were analyzed via code written to measure RMS height, area ratios, and linear Hurst exponents; progress on codes to measure Hurst exponents across anisotropic surfaces is ongoing. Results indicate that even simple approaches such as area ratios can provide useful classification information over a range of scales (0.1-2m). Work is ongoing to combine model approaches for an objective classification tool that can be used to automatically map lava morphology on Earth, the Moon, Mars, and other planetary bodies. Research results were presented at GSA and LPSC, with a manuscript in progress.

ii) Self-secondary impacts: The VORTICES Team (JHU/APL) partnered with FINESSE to conduct a survey of self-secondary impact features at Kings Bowl as an analog for these types of features on the Moon and Mars. At the Kings Bowl lava field, Alexandra Matiella Novak (JHU/APL) surveyed and studied the spatial distribution of over 350 hemispherical squeeze-ups, aka “mushroom caps,” resulting from self-secondary impacts of volcanic ejecta when Kings Bowl erupted. 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 in an effort to better understand these unusual features and how they play a role in regolith formation and degradation. Preliminary results were presented at LPSC in 2016 by Dr. Novak.

iii) Links between lava composition and morphology: Graduate student Gavin Tolometti (UWO) collected rock samples from multiple flows in northern COTM while collaborator Kukko used one-of-a-kind backpack mobile LiDAR to measure corresponding topography at the cm-scale. Tolometti has generated a series of petrographic thin sections, which he is evaluating for mineralogy and microtexture, with results to be correlated against Kukko’s DTMs and TextureCam output from R. Francis (NASA JPL). Results have been prepared for presentation at the 2017 LPSC.

Postdoctoral researcher Alexander Sehlke (NASA Ames) mapped lava flow morphology (pahoehoe, transitional, and \`a\`a) of a ~2.5 km long channelized lava flow at the Craters of the Moon (ID), and collected 28 samples from vent (spatter cones) to flow terminus. These samples are being used to investigate the thermo-physical properties (density, crystallinity, chemistry, viscosity, and thermal conductivity) that control the surface morphology of lava flows. Several new analytical techniques were established at ARC to measure these properties. For example, we measured density and porosity (total, interconnected, and isolated), chemistry via a portable x-ray fluorescence (XRF) and used a vis-NIR-spectrometer purchased with FINESSE funds this year. Our findings can be used to pre-survey lava flows observed on other planets and moons for future robotic and human exploration missions. First results will be presented at the 48th LPSC in 2017.

iv) Mapping lava tubes via Lidar: Brent Garry (NASA GSFC) completed surveys at Indian Tunnel, Beauty Cave, and Surprise Cave (surface only) at Craters of the Moon. This year, we completed an additional 24 scans to finish up our field project at Indian Tunnel (~250 m long), for a total of 46 scans between 2015-2016. The final point cloud is ~898 million points. This is one of the first complete scans of a lava tube system using LiDAR that captures the surface and subsurface relationship at ~1-2 cm resolution (Fig. 1). Co-I Garry presented talks about exploring lava tubes with LiDAR at the Exploration Science Forum (July, 2016) and at the Geological Society of America annual meeting (Sept. 2016). National Geographic featured an article about the FINESSE Team's research on lava tubes.

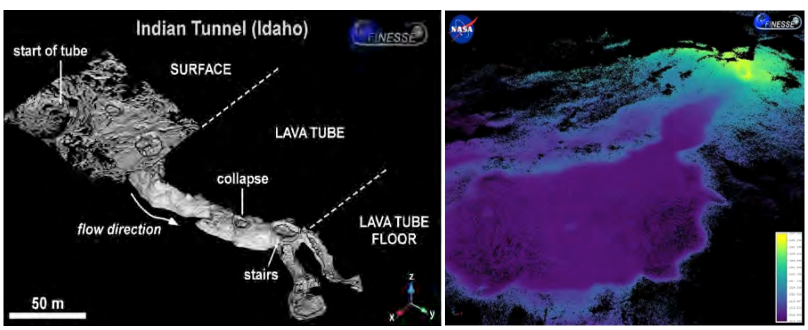


FIGURE 1. (left) LiDAR point cloud of Indian Tunnel lava tube (250 m long). (right) LiDAR point cloud of Papadakis Pond (400 m wide, 1.2 km long) along Inferno Chasm Rift Zone (elevation: dark blue = low, 1510m, yellow = high, 1547 m).

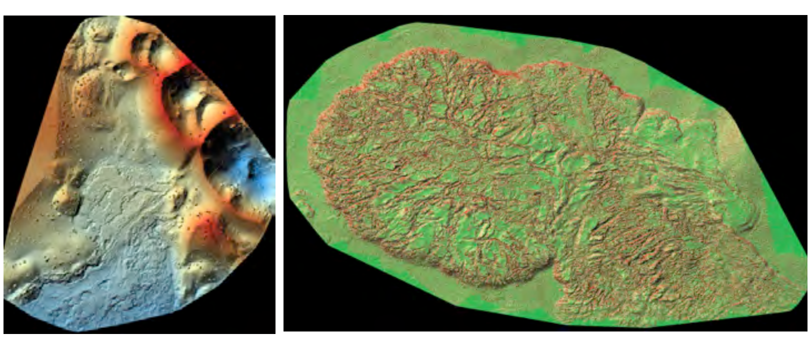


FIGURE 2. DEMs derived from images acquired during UAV flights of (left) Big Craters vent region and proximal lava flows, and (right) Highway Flow.

v) Topography of features in Inferno Chasm Rift Zone: Brent Garry collected 12 scans over two days at Papadakis Pond (Fig. 1), a lava pond along Inferno Chasm Rift Zone, just north of Kings Bowl. Our 3D topographic model of this lava pond completes a series of digital elevation models we have produced using LiDAR and Unmanned Aerial Vehicles (UAVs) to document the different morphologies of vents that erupted along Inferno Chasm Rift Zone as analogs for similar volcanic features in southeastern Mare Serenitatis on the Moon.

vi) Data mapping using UAVs: NASA Kennedy Space Center completed UAV flights over lava flows at Kings Bowl, Inferno Chasm, and areas surrounding Craters of the Moon visitor center (Fig. 2). Flights collected data to create detailed 1-5 cm/pixel resolution DTM models and orthophotos of over 1500 additional acres since the 2015 field deployment. These data were then processed in the hours after flights to allow for mission traverse planning for the BASALT-FINESSE June 2016 field outing. Depending on the area of interest, flights operated between 150' and 400' above ground level. NASA aircraft were issued a Certificate of Authorization to operate by the FAA.

vii) Radar for traverse planning: Undergraduate R. Maj (UWO) created an ArcGIS project with all relevant remote sensing data sets for our study site. Satellite imagery included: (1) Landsat-8 OLI imagery, (2) ASTER emissivity and thermal inertia data, and (3) RADARSAT-2 quad-pol imagery (obtained through CSA's SOAR-E program). We also used aircraft data obtained from the NAIP and AIRSAR programs. Maj used this data to plan scientifically relevant but safe traverses for the 2016 field team, a technique that will help to guide future exploration of other planets. We executed these traverses during our field season in August 2016, plotting our coordinates with GPS and comparing them to the planned routes. Maj will report on her findings at the Lunar and Planetary Science Conference in March 2017.

viii) Lava tube detection for the Moon and Mars: During the August 2016 field season, graduate student Chris Brown (CU) and Claire Samson (CU) conducted reconnaissance at COTM. The goal of their work is to test the ability of gravity data acquired on the surface of the ground to delineate the geometry of a lava tube at depth. The Indian Tunnel lava tube was selected based on its size (average diameter ~20 - 25 m, length ~200 m, opening large enough to allow access to its interior), the availability of 3D LiDAR images of its interior walls (Brent Garry, this project), and its relative accessibility (a few hundred meters from a parking lot).

ix) Kings Bowl as an analog for dike intrusion and explosive pits: Shannon Nawotniak (ISU) and undergraduate/graduate student Christian Borg (ISU) continued detailed mapping of the Kings Bowl ejecta and fissure, specifically focusing on differentiation of small, overlapping block fields and discerning parts of the fissure that experienced blasting from those that only demonstrate drain-back of lava. We are refining our interpretations of the blasts and improving model-calculated blast conditions. Typical blasts had ejection velocities of 50-100 m/s, regardless of pit size; based on tephrostratigraphy (by undergraduates Erin Sandmeyer and Allison Trcka, ISU) and model output, larger pits are interpreted to be the result of repeated blasts caused by interaction between groundwater and the hot rock, not by larger blasts. Preliminary results were presented at LPSC and the Rocky Mountain GSA section meeting. Results are currently being written into a manuscript.

x) Lava spatter as a record of eruption conditions: Postdoctoral researcher Erika Rader (NASA Ames) collected measurements of 8 spatter outcrops (Fig. 3) at Craters of the Moon and Kings Bowl volcanic areas with the purpose of classifying the thermal regimes that control spatter formation. In additional to numerical modeling, eighteen experiments were conducted at the Syracuse Lava Project (Syracuse University) to connect morphological characteristics to thermal conditions. Preliminary results were presented at the American Geophysical Union (AGU) Fall Meeting in 2016, and research results will be extended to Lunar landscapes in the coming months.

FIGURE 3. Mapping and measurement of welded lava spatter at COTM compared to simulated spatter experiments conducted at the Syracuse Lava Project.

xi) Development of Thermoluminescent dating techniques: Derek Sears (NASA Ames) led research to explore the use of induced thermoluminescence (TL) as a method for dating volcanism. The commonly used method for TL dating, involving natural TL which is used routinely for dating archeological artifacts, fails with volcanic rocks because of anomalies in the mechanism. A trend between induced TL and age was reported in 1971 but has never been confirmed or further explored. Mechanisms and preliminary results were presented at LPSC and the SSERVI Science and Exploration forum. Research results confirmed the 1971 data and found consistent trends for rocks from Hawaii and Idaho. The Idaho results have been accepted for publication in JGR subject to moderate revision, which is now complete. In addition, we published two other papers based on data from the thermoluminescence laboratory that is supported by FINESSE funds. The first was a large paper in Geochimica et Cosmochimica Acta describing a detailed study of the metamorphic history of the CO chondrite meteorite group, and the second, in Meteoritics & Planetary Science, was small paper on the effect of CT scanning on meteorite TL, which has implications for the handling of returned samples.

xii) High-precision measurement of lava flow margin geometry: Identification of a lava flow's morphologic type (e.g., smooth pāhoehoe) provides insight into the dynamics, rheology, and effusion rate of the flow at the time of emplacement. However, because flow type is primarily identified by submeter textures, there is currently no way to reliably infer flow type from orbital data. We are therefore developing a technique that leverages fractal (scale-invariant) margin geometry to infer flow type at the coarse scales resolvable from orbit. Led by Ethan Schaefer (graduate student, University of Arizona), we collected high-precision traces of lava flow margins using differential GNSS (global navigation satellite system) at Craters of the Moon National Monument and Preserve in August 2016. We also collected notes on the geology and context of the flows, such as the flow type, stratigraphic relationship with adjacent flows, and substrate topography. We collected these data and notes for three traces ~400–2400 m long from two different flows, one blocky lava and the other rubbly to slabby pāhoehoe. The precision and length of the traces allowed us to describe margin geometry across a range of scales. Combined with similar notes and data from fieldwork in Iceland and Hawaii, the results suggest that pāhoehoe can usually be identified without ground truth at resolutions of 80 m/pixel, possibly coarser. This raises the potential that some of the highest resolution Io, Mercury, and Venus data may be suitable, in addition to global data from Mars and the Moon. These results were presented at the fall 2016 AGU meeting, and a final report will be submitted for publication in the Bulletin of Volcanology in March 2017.

xiii) Compositional diversity and magma dynamics along volcanic rift zones: Geochemical and lithologic variability along the Great Rift and Inferno Chasm rift zones indicate highly complex magmatic processes that may be analogs to volcanic features on the Moon and Mars. Continued geochemical, lithologic and morphological analyses of lava flows by Scott Hughes (ISU) and FINESSE team members are being used to evaluate possible magmatic models. Analog models are being developed primarily for magmatism along Lunar rilles (including floor-fracture craters) and Martian fossae. Preliminary results were presented at LPSC in 2016 and submitted to LPSC for 2017.

xiv) Exploration Ground Data System (xGDS) support for FINESSE science: The FINESSE team uses xGDS to organize maps of Idaho field sites, data collected in the field, metadata about samples collected in the field, and notes associated with data. The site offers an online collaborative repository for science data that the team can use, share, and interact with (Fig. 4).

B. Impact cratering studies at the West and East Clearwater Lake impact structures, Quebec, Canada

The FINESSE project continued to pursue multiple research themes at West and East Clearwater Lake impact structures, Quebec, Canada, during 2016. No fieldwork was conducted. Instead, laboratory work continued on samples collected in 2014, and supplemented by samples from drill cores from the Geological Survey of Canada. Scientific research themes are covered in the following sections.

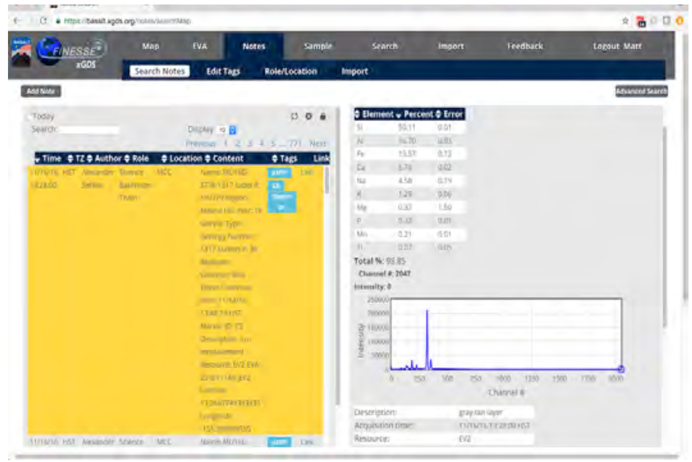


FIGURE 4. Image of BASALT-FINESSE xGDS notes and PXRF data interface.

i) Characterization of impact melt veins in the central uplift: MSc student Rebecca Wilks completed her geochemical and petrographic study of melt veins at the West Clearwater Lake impact structure. It has been hypothesized that impact-generated melt may have a significant role in weakening the rock of a crater floor to allow for uplift, but it is uncertain if this melt rock is a product of in-situ melting or injected melt. In this study, melt veins within surface and drill core samples of target rocks from the West Clearwater structure were analyzed using optical microscopy, electron microprobe analysis, and bulk chemistry analysis to determine their formation process. Mixing model results suggest that melt vein structures within the very center of the crater, collected from the surface and at depth exhibit in-situ melting; whereas veins around the periphery of the central uplift are formed by the injection of impact melt. While not disproving the importance of acoustic fluidization, this study does show that melt is important in supporting mechanisms that can weaken the crater floor and accommodate central uplift formation. This work was presented at the Lunar and Planetary Science Conference in March 2016 and a journal publication will be submitted in February 2017.

ii) Impact-generated hydrothermal activity: MSc student

Mary Kerrigan has continued her work on the potential for impact-generated hydrothermal activity at both the East and West Clearwater lake structures. While secondary mineralization has previously been noted at West Clearwater, no study has focused on the hydrothermal system of this impact structure. Evidence for hydrothermal activity has been identified within each of the impact-related lithologies in the form of (1) vugs and veins within impact melt rocks, (2) sulfide alteration within uplifted basement rocks, (3) concentrated alteration zones, and (4) pervasive alteration within impact melt rocks. By far the most common hydrothermal deposits found in the field were quartz-filled vugs and veins within the impact melt rocks, most abundant in the clast-rich and clast-poor fine-grained impact melt rocks. As the entire East Clearwater structure is currently submerged, the only impact sites available to study are from two drill cores, one (1-64) from the central uplift that goes through basement gneisses and one (2-63) from just east of the central uplift which penetrates the impact melt sheet. The samples used in this study are from a section of the melt sheet from core 2-63. Evidence for hydrothermal activity has been identified in the form of (1) cavity filling mineralization and (2) oxide and sulphide mineralization. Two journal publications are in preparation.

iii) Shock pressure distribution with numerical modelling: PhD student Auriol Rae is continuing his investigations into the central uplift at both West and East Clearwater structures. A paper on the West Clearwater was accepted in December 2016 in the journal Meteoritics & Planetary Science. In this study, samples of shock-metamorphosed quartz-bearing lithologies at the West Clearwater Lake impact structure, Canada, were used to estimate the maximum recorded shock pressures in three dimensions across the crater.

iv) Accurate and Precise Determinations of the Age of the West Clearwater Impact Structure: One of the greatest challenges of establishing the impact histories of planets and other bodies in the solar system is accurate and precise isotopic dating of the rock products at impact structures. The FINESSE team is working to develop optimal protocols for such work through studies of impact melt rocks from the East and West Clearwater structures. Recently published 40Ar/39Ar data for samples from both structures (Schmieder et al., 2015) suggested that these adjacent twin impact structures—long regarded as an impact doublet—are actually of very different ages: ca. 285 Ma for West Clearwater and ca. 458 Ma for East Clearwater. In our experience, the interpretation of results from a single isotopic chronometer as an accurate indication of an impact age is often unwise due to the effects of incomplete isotopic homogenization during impact and radiogenic isotope loss during subsequent thermal events (including post-impact hydrothermal activity). We are working to replicate the Schmieder et al. (2015) results through laser ablation 40Ar/39Ar techniques (that provide higher spatial resolution than the methods of Schmieder et al.), and we are working to evaluate the robustness of the 40Ar/39Ar results by applying three additional geochronologic methods: U/Pb on zircon, (U-Th)/He on zircon, and radiation damage of zircons. Our first publication resulting from this effort (Biren et al., 2016) reports (U-Th)/He data for both craters that are consistent with the previously reported 40Ar/39Ar results (280 ± 27 Ma for West Clearwater and 450 ± 56 Ma for East Clearwater) but less precise, as is typically the case for the (U-Th)/He zircon chronometer.

C. Other Research Activities

Lab setup: Several new analytical capabilities have been established at NASA ARC (N-245, Room 33). In collaborative effort sharing the NASA Ames Meteorite Laboratory, established by D. Sears in support of the NASA Asteroid Threat Assessment Project (ATAP, Lindley Johnson, Executive), post-doc Alexander Sehlke established measurements to determine the bulk density of rocks. Newly purchased equipment includes a 10" drill press, capable of drilling rock cores of various diameters and lengths. Archimedean principle allows us to measure the total porosity of these rock cores, as well as quantify the amount of connected and isolated porosity within the sample. Moreover, a previously non-functional thermal conductivity meter was restored by Alexander Sehlke, enabling us to measure the heat transport of solid materials, such as (basaltic) rocks or meteorites.

Instruments: Two portable science instruments, a visible to near-infrared (VNIR) and a x-ray fluorescence (XRF) spectrometer, were purchased in 2016. Both instruments (in addition to a Fourier transform infrared [FTIR] from team member S. Kobs Nawotniak), were deployed during the 2016 field campaigns of NASA BASALT (Biologic Analog Science Associated with Lava Terrains, PI D.S.S. Lim) to evaluate their performance in the field. Field sites were Craters of the Moon (COTM) and Mauna Ulu, Kilauea volcano, Hawaii, providing a large variety in composition and alteration products. Both basaltic lava fields are terrestrial analogs to planetary surfaces, such as early Mars. In addition to the field work, the strength and weaknesses of these instruments are currently evaluated under standardized (laboratory) conditions. Evaluating these instruments in the field and under standardized conditions provides requirements for integrating these instruments in future human exploration missions to other planetary bodies.

Inter-team Collaborations

The following are ongoing and new collaborations for the FINESSE team with other SSERVI Teams, including collaborations with SSERVI International partners. We have also listed other team collaborations outside of SSERVI funded teams.

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 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.

JPL

FINESSE has teamed with Raymond Francis and his team to integrate new JPL technology into our field deployments. The JPL-developed TextureCam hardware and software was first tested with our team during our Mojave Volatiles Prospector fieldwork and has been further integrated into the FINESSE 2016 Idaho field studies.

BASALT

The FINESSE team works in close collaboration with the BASALT project (Biologic Analog Science Associated with Lava Terrains, PI D. Lim) to conduct in-simulation fieldwork in Idaho to study volcanic terrains. The BASALT project brings the ability to conduct high-fidelity exploration mission simulations to the field deployments, which greatly enhances both the scientific and exploration research of this field site.

UNIVERSITY OF ARIZONA

Ethan Schaefer (ASU) joined the FINESSE team for the 2016 deployment to Idaho to collect high resolution lava flow traces to identify lava flow type and thereby characterize flow dynamics, rheology, effusion rate, etc (see above). Schaefer and his team have been integrated into the FINESSE project for increased scientific productivity.

The FINESSE team has been collaborating with the following International Partners:

Canadian Lunar Research Network based at the University of Western Ontario.

FINESSE has teamed with Collaborator Gordon Osinski (University of Western Ontario, UWO) as the lead of the Canadian Lunar Research Network, an official SSERVI international partner. Our partnership with UWO has helped to enable the impact cratering studies based at the West Clearwater Impact Structure in northern Canada. Osinski has a long history of leading field campaigns to various impact sites around the world and is a valuable FINESSE partner given his experience and expertise in conducting terrestrial analog studies of impact craters. Collaboration with the University of Western Ontario has also allowed UWO graduate students to interact and conduct research with U.S. colleagues to broaden their scientific and networking bases. Our teaming arrangement with UWO facilitated an extremely complex deployment to West Clearwater Impact Structure in Year 1 of this project. The FINESSE WCIS deployment marked the first geology study of this impact structure in nearly 40 years. WCIS was specifically chosen as a FINESSE field site because it has not been well-studied recently for impact science (for example, studies of the various impact sites at Clearwater have not been conducted with modern-day analytical techniques and the most accurate map available of the WCIS is 1:50,000 in scale. Plus, the age of the impact remains poorly constrained). 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.

In addition, FINESSE Collaborator Catherine Neish has recently accepted a position at the University of Western Ontario. Neish's work focuses on using radar data and studying transitional lava flows as potential analogs for lunar impact melts. Neish has deployed to Craters of the Moon with FINESSE (2015, 2016) and continues to analyze both satellite and ground truth data.

CARLETON UNIVERSITY

The 2016 FINESSE deployment to Idaho included a graduate student and professor from Carleton University (Ottawa, Canada) to test the use of gravity data to map and characterize subsurface volcanic structures such as lava tubes. Our CU colleagues collaborated with our team to mutual benefit since they brought new gravity measurement techniques to the field that could be ground-truthed via the ongoing FINESSE LiDAR lava tube characterizations led by FINESSE Co-I B. Garry (NASA).

KIGAM (Korea Institute of Geoscience and Mineral Resources).

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 and collected basaltic samples for subsequent XRF analysis. She has benefitted from FINESSE by being granted an opportunity to field test her newly developed XRF instrument while simultaneously conducting true scientific research. FINESSE is also pleased to collaborate with Dr. Kim and help facilitate continued partnerships with KIGAM as Korea continues to develop and expand its lunar and planetary science programs.

FINESSE Public Engagement Report

A) FINESSE Spaceward Bound.

FINESSE Spaceward Bound engages teachers and students in authentic science research experiences, in the field with the FINESSE science team. Through a partnership with the Idaho Space Grant Consortium, we bring students and teachers into the field to conduct science and exploration research in Craters of the Moon National Monument and Preserve (COTM) in Idaho with the FINESSE science team. They work side-by-side with NASA researchers, hiking with them through lava flows, operating field instruments, collecting data, and participating in science discussions. Support from the FINESSE team continues after teachers return to their classrooms, through activities and resources we recommend, opportunities for continued engagement that we suggest, and individual connections the teachers maintain, as well as the FINESSE-related projects and programs they produce and share.

In 2016 five K–12 teachers and a high school student participated in the program, alongside 32 scientists

FIGURE 5. FINESSE scientists, teachers, and students survey a drained lava pond (top) and collect samples (bottom) in COTM summer 2016. Credit: Erika Rader.

(including a VORTICES collaborator) and a NASA education specialist. Three of the teachers were FINESSE Spaceward Bound alumni, returning to continue their work with the team. Another teacher had participated in LRO's Lunar Workshop for Educators the previous summer and wanted to build on her experience. Tiffany Sheely, the education director at the Palouse Discovery Science Center in Pullman, WA, wrote an article "Exploring Craters of the Moon" describing what she learned from her experience in FINESSE Spaceward Bound for the July-August 2016 issue of Dimensions, the bimonthly magazine of the Association of Science-Technology Centers. Her experience and enthusiasm to widely share what she learned are similar to what was found in evaluation of the 2015 FINESSE Spaceward Bound program. A full evaluation of the 2016 program is underway.

B) Collaborations with Craters Of the Moon.

In 2016 COTM celebrated the Centennial of the National Park Service (NPS) with a variety of special events. One of the highlights was a NASA Community Day event in the gateway town of Arco. NPS staff collaborated with FINESSE scientists to provide tours of the Mobile Command Center and scientific demonstrations in a community park in Arco followed by a "Lunar Ranger" activity and a presentation by a scientist at the park visitor center. Approximately 200 people attended each venue. FINESSE research at the park was also highlighted by Astronaut Steve Swanson in a presentation he gave at COTM (http://bit.ly/2jo4xvs), with in-park displays, and also in the regional and national media. This Outside Science podcast is a great example of some of the media coverage, created by a reporter who joined the FINESSE team on our 2016 field season in COTM: http://bit.ly/2jL7eXK. The video was posted to the NPS Explore Nature Facebook page on 11/17/16. As of 1/18/17, it has been viewed over 15,000 times.

C) Team Outreach.

The FINESSE team is committed to publicly sharing our research and interest in planetary science and exploration. We support a SSERVI Seminar Speaker Series, through which we highlight FINESSE and SSERVI science and exploration highlights for the NASA Museum Alliance and NASA solar system Ambassadors, who in turn share this content with their audiences in venues around the country and the world. In 2016, the series included contributions from the FINESSE, VORTICES, IMPACT, and RIS4E SSERVI teams.

The team shared FINESSE research with a number of audiences, including students and seniors in Idaho, in a talk on the NASA Hyperwall at AGU, through public outreach events such as International Observe the Moon Night, and through media outlets, such as the FINESSE website and social media accounts. FINESSE scientists led a field trip for the Geologists of Jackson Hole in October 2016, and a FINESSE collaborator shared FINESSE research in teacher professional development workshops in Korea.

Student/Early Career Participation

High school students

1. Chanel Vidal (Iowa City West High School) Assisted with field projects and prepared geologic samples for geochemical and petrographic analyses in the lab. Also participated in BASALT project.

Undergraduates

1. Christian Borg (transitioned to graduate student status during the year) (ISU). Researched ballistic blocks at Kings Bowl. Also participated in BASALT project.
2. Erin Sandmeyer (ISU). Researched tephrostratigraphy at Kings Bowl and spatially variable rock textures at Highway Flow. Also participated in BASALT project.
3. Allison Trcka (ISU). Researched tephrostratigraphy at Kings Bowl.
4. Caleb Renner (ISU). Used aerial imagery to identify potential lava coils at COTM, planning a future field season to perform ground-truthing.
5. R. Maj (CWO). Tested use of radar to plan field traverses for summer deployment.
6. Trevor Miller (CSU). Lava margin mapping team member.
7. Omar Draz (UWO). Conducted an undergraduate honors thesis on impact breccias and impact melt rocks at the East and West Clearwater Lake impact structures.

Graduate students

1. Hester Mallonee (ISU). Developed objective tool for lava texture classification based on methods to measure roughness. Lidar survey team member at Inferno Chasm Rift Zone and Beauty Cave.
2. Gavin Tolometti (UWO). Researched the connection between petrographic texture and lava flow morphology.
3. Ethan Schaeffer (UA). Led student research team measuring fractal dimensions of lava margins using differential GPS.
4. Chris Brown (CU). Began study of lava tube detection via micro-changes in gravity.
5. Meghan Fisher (ISU). Developed a new model to simulate explosive eruptions in planetary conditions. Funded by Idaho Space Grant Consortium for work in collaboration with FINESSE.
6. Ali Bramson (UA). Lava margin mapping team member.
7. Sean Peters (ASU). Lava margin mapping team member.
8. Mary Kerrigan (UWO). Investigating the impact-generated hydrothermal system at the East and West Clearwater Lake impact structures.
9. Rebecca Wilks (UWO). Researched the origin of impact melt veins in the central uplift of the East and West Clearwater Lake impact structures.
10. Auriol Rae (UWO/Imperial College London). Numerical modelling and shock barometry studies of the central uplifts at the East and West Clearwater Lake impact structures.
11. Audrey Horne (ASU) Field studies and geochronologic sample collection, West Clearwater Lake impact structure.
12. Anna Brunner (ASU) Field studies, sample collection, laboratory analysis, and multimethod geochronology of East and West Clearwater Lake impact structures.

Postdoctoral fellows

1. Alexander Sehlke (NASA Ames). Studied the connection between lava flow morphology and physical properties of the flow. Evaluated the field and laboratory use of various analytical instruments to help planetary exploration. Also an active participant in the BASALT project.
2. Erika Rader (NASA Ames). Developed a method to evaluate eruption conditions via interpretation of welded spatter.
3. Michael Sori (UA). Lava margin mapping team member.
4. Mark Biren (ASU). Geochronology of East and West Clearwater Lake impact structures.

Faculty

1. Shannon Kobs Nawotniak (ISU). Modeled ballistic ejecta at Kings Bowl, advised ISU students, and Geology Co-Lead.
2. Alexandra Matiella Novak (JHU/APL). Used impact-generated squeeze-ups to study self-secondary impact events.

Catherine Neish (UWO). Coordinated Canadian research team, advised UWO students, researched roughness of terrestrial and planetary lava flows via radar.

Timothy Glotch

Stony Brook University

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

RIS4E Team Project Report

The RIS[4]E team is organized into four distinct themes, which in addition to our E/PO efforts, form the core of our science and exploration efforts. Results from the second year of RIS[4]E activities for each of the four themes are discussed below.

Theme 1: Preparation for Exploration: Enabling Quantitative Remote Geochemical Analysis of Airless Bodies. The major activities in this theme have focused on (1) synthesis and characterization of new mineral standards, (2) acquisition of mid-IR (MIR) emissivity and temperature-dependent visible/near infrared (VNIR) reflectance spectra in simulated lunar/asteroid environments, (3) testing and validation of advanced light scattering and radiative transfer models for quantitative interpretation of remote spectral data, and (4) remote sensing analyses of SSERVI Target Bodies.

(1) Our team, led by Co-I Hanna Nekvasil, collaborator Donald Lindsley, and Stony Brook Graduate students Douglas Schaub and Tristan Catalano, has successfully synthesized samples of the Ca-poor clinopyroxene mineral pigeonite. The samples span a range of compositions: Wo8, with X=20; Wo10, X=20; Wo8, X=30; Wo10, X=30; Wo8, X=40; Wo10, X=40; Wo8, X=55; and Wo10, X=60; with X= Fe/(Fe+Mg). Grain sizes range between 10 and 60 µm and available quantities range from 0.4-5.2 g. These samples have already been made available for use by other researchers. Several 100 mg quantities of each composition are currently being analyzed using Mössbauer spectroscopy by Co-I Dyar and will then be sent to SEEED PI Carlé Pieters for visible/near-IR (VNIR) spectral analysis at Brown University.

(2) We have continued acquiring spectra of minerals in a simulated lunar/asteroid environment (SLAE). The bulk of this work has been carried out by graduate student Katherine Shirley at Stony Brook, who has been focusing on understanding the effects of particle size on infrared spectra of common silicate minerals in SLAE. In recent work, she and PI Glotch acquired spectra of several size fractions of pulverized silicic volcanic rocks including andesite, rhyolite, obsidian and pumice. The spectra of these samples were compared to data collected by the Diviner Lunar Radiometer Experiment covering silicic volcanic domes on the Moon. We resampled all of our spectra so that we can compare our results directly to the remotely acquired data from Diviner. We parameterized our spectra using a simple, commonly used "concavity index" that indicates highly silicic compositions. The initial results of this work (Figure 1) demonstrate that the silicic lunar domes, which all have strongly positive concavity index values, cannot be composed of andesite, an intermediate volcanic rock type. Pumice, obsidian, rhyolite, or a combination of all

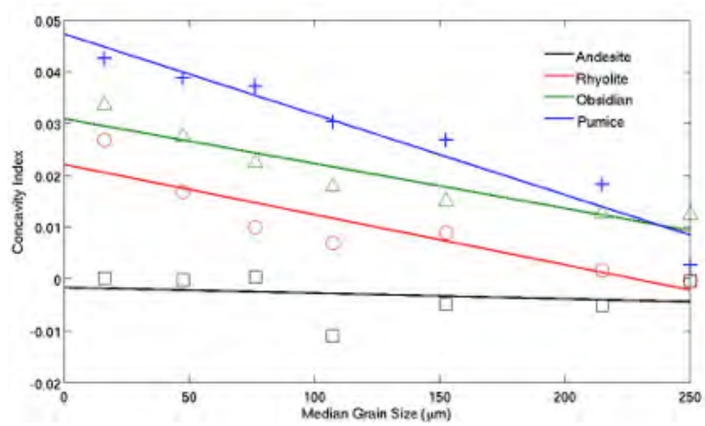


Figure 1. Variations in spectral concavity index as a function of particle size for seven size fractions of various silicic volcanic rock particulates. The results demonstrate that characterization of lunar silicic domes can be influenced by particle size as well as composition.

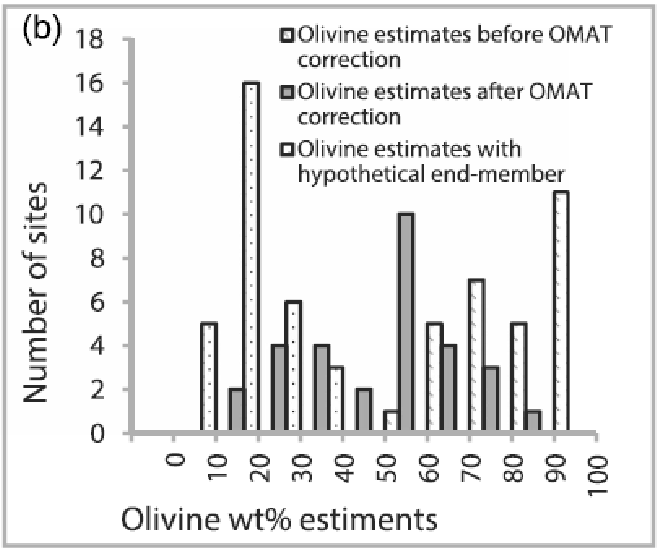


Figure 2. Lunar olivine abundance estimates. Three sets of abundance estimates are given based on CF values prior to optical maturity correction (stripes) CF values after optical maturity correction (grey) and CF values of a hypothetical olivine end-member with a CF of 9 μm (dots), estimated to correspond to a Fo40 olivine composition.

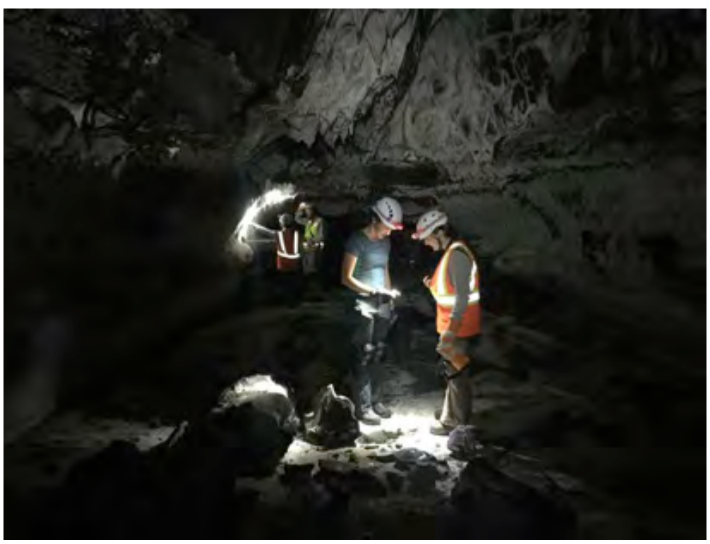


Figure 3. RIS4E scientists aided the HI-SEAS team's investigations of Hawaiian lava flows as potential safe-havens for planetary explorers.

of these highly silicic rock types are consistent with the data acquired by Diviner. However, the degree of spectral concavity is dependent on particle size, a result which has not been recognized until now. Therefore, care must be taken when interpreting Diviner data.

(3) The PI's research group at Stony Brook has also continued its efforts to develop VNIR and MIR scattering models making use of a coupled T-matrix/Hapke code to better understand the physics of light scattering in laboratory and remotely sensed spectra. Hardgrove et al. (2016) used a hybrid model to explain the odd spectra of microcrystalline quartz. The strange spectra occur due to multiple scattering associated with microcrystalline roughness that is on the same scale as the wavelength of light interacting with the mineral. This work demonstrates the utility of the hybrid T-matrix/Hapke model for understanding mid-IR spectral phenomena. Glotch et al. (2016) used the same model to constrain the relative abundances of halite (NaCl) and silicate minerals in Martian chloride salt deposits. Although this work pertained to Martian mineralogy, it is the first use of the T-matrix/Hapke hybrid model to constrain composition of a planetary regolith. Development and use of such hybrid models was a major goal for RIS^{4}E Theme 1 work. Finally, this same model has been extensively tested by a laboratory study conducted by Stony Brook graduate student Gen Ito. This work, recently submitted to JGR Planets, compares theoretical spectra of enstatite (orthopyroxene) to laboratory spectra for several size fractions. This work demonstrates the clear superiority of the T-matrix/Hapke method over the more commonly used Mie/Hapke model for the finest particle sizes and identifies the need for further improvements for coarser particle sizes.

(4) A highlight of our remote sensing and data analysis efforts is a paper by former Stony Brook graduate student and current Oxford postdoctoral researcher Jessica Arnold. Arnold et al. (2016) used both Diviner Lunar Radiometer and Moon Mineralogy Mapper (M3) data to investigate occurrences of olivine on the Moon. Lunar olivine exposures are particularly interesting because they might be signs of lunar mantle rocks that have made it to the surface via impact processes. An important conclusion of the Arnold et al. (2016) paper is that, after correction for space weathering, none of the olivine exposures identified in the study (Figure 2) are consistent with dunite (>90 wt.% olivine). This means that either there are no exposures of mantle on the lunar surface, or that lunar mantle materials have been substantially mixed with crustal materials, reducing the overall olivine abundance.

Theme 2: Maximizing Exploration Opportunities. Development of Field Methods for Human Exploration. The major activities of Theme 2 this year included our final field deployment on the Big Island of Hawai'i, and our first "scouting trip" to our field site for the remainder of our CAN 1 work, the Potrillo Volcanic Field in New Mexico.

Following up on previous field excursions to the December 1974 lava flow on the flank of the Kilauea Volcano, our field team continued work to evaluate the role of field portable instrumentation for human spaceflight, as well as to answer science questions about the December 1974 volcanic flow in the SW rift zone of Kilauea Volcano. Scientific areas investigated included how the flow was emplaced, how the flow interacted with the pre-flow terrain, how two large pits on the western margin of the flow formed, how the active Kilauea plume interacts with the bulk flow, and how hydrothermal deposits found throughout the flow formed and evolved. One of the major tools involved in our exploration and scientific activities at Kilauea is the handheld X-ray fluorescence (XRF) spectrometer. The work on this and previous field excursions to Kilauea led to a published invited review of handheld XRF technology by Goddard postdoc Kelsey Young (Young et al. 2016). Dr. Young additionally has a paper in preparation on the incorporation of field portable instrumentation into crewed planetary surface exploration that will soon be submitted to Acta Astronautica. An additional paper on the incorporation of portable infrared spectral imaging into planetary geological field work will soon be submitted to the same journal by Stony Brook graduate student Gen Ito. This year's field deployment also included, for the first time, Stony Brook graduate student Nicholas DiFrancesco. Working with Theme 1 Co-Investigator Hanna Nekvasil, Nick is trying to understand the role of magmatic volatiles in the alteration of surface rocks. This work is relevant to both the Moon and Mars, which are now thought to have contained volatile-rich magmas that degassed at their surfaces. While in Hawaii, Nick found several unmapped fumaroles, collected samples of altered rock and fumarole gas, and is now comparing these samples to laboratory standards that he synthesized in the lab using an "experimental fumarole" that he developed.

In addition to our primary field activities RIS^{4}E Theme 2 members conducted several activities aimed at increasing the efficiency and safety of future human exploration of SSERVI's target bodies. Primary among these efforts was RIS^{4}E collaboration with the Hawaii Space Exploration and Analog Simulation (HI-SEAS) team, an HRP-funded project designed to simulate future planetary exploration practices. RIS^{4}E scientists assisted the HI-SEAS crew in exploration of several Hawaiian lava tubes on the Mauna Loa volcano.

During 2016, Goddard Co-I Bleacher and postdoc Young also worked to integrate RIS^{4}E studies of the use of portable instruments on EVA timelines with NASA's Human Architecture Team—studies of Low Latency Telerobotic (LLT) timelines. This work included concepts that involve human surface operations on Phobos or Deimos while operating robotic assets on the surface of Mars. The study has relevance for LLT science operations on the lunar surface with operators in cislunar space.

Goddard Postdoc Young also supported the NEEMO 21 NASA analog mission, serving as a member of the mission's science team. The mission ran from July 21-August 5 and consisted of a crew living under water in the Aquarius Reef Base off of the FL coast, testing science operations concepts, technology, and science drivers for future crewed planetary space flight. Apparently, she doesn't like her apartment in Washington, DC, because Dr. Young also completed a week of fieldwork in the San Francisco Volcanic Field, AZ, deploying seismometers, ground penetrating radar, magnetometers, and a handheld XRF to investigate the geologic history of the region. The work included astronaut Don Pettit through the Astronaut Field Assistant Program.

Finally, in November, Co-I Bleacher was invited to attend the Office of the Chief Engineer's (OCE) Human Space Flight Knowledge Sharing Forum held in Huntsville. Dr. Bleacher was the only scientist in attendance and was able to lend a critical scientific perspective to OCE's human space flight planning efforts.

Theme 3: Protecting our Explorers. Understanding How Planetary Surface Environments Impact Human Health. In our third year of work, we have continued testing the toxicity and reactivity of lunar simulants. We developed new protocols to test the genotoxicity (mitochondrial and

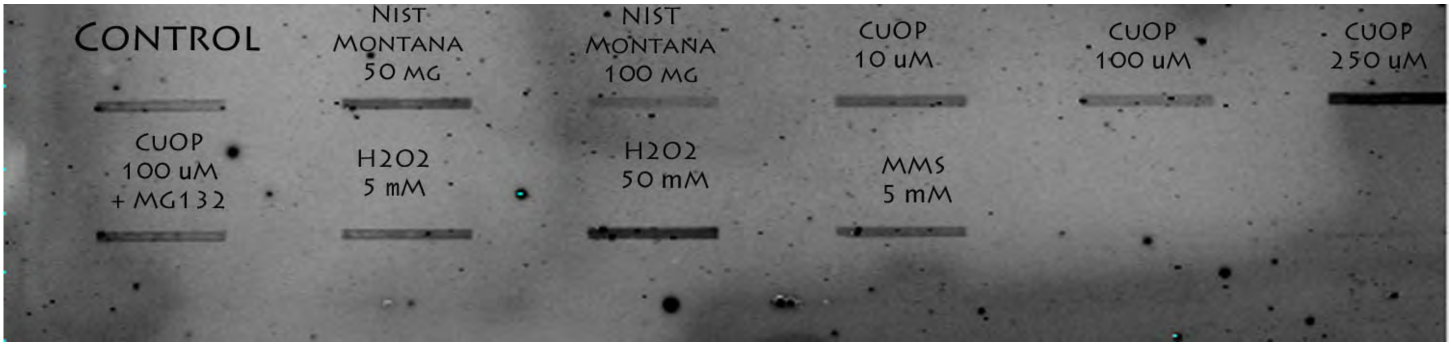


Figure 4. Tests for oxidative damage of DNA by lunar soil simulant. Darker colored bars indicate more damage. The simulant (NIST Montana) generated some DPC, while CuOP gave a stronger signal (as expected). Both are stronger than the negative control.

nuclear DNA damage) and cytotoxicity (cell damage) using mouse lung cell and brain cell tissue.

While we have continued our work on assessing the reactivity of lunar simulants using electron paramagnetic resonance (EPR) spectroscopy, major advances have resulted from our work in understanding how lunar-like materials affect the DNA of exposed cells. SBU graduate student Rachel Caston has been working to optimize an antibody-based assay to quantify specific oxidative protein-DNA crosslinks formed in cells upon treatment with lunar dust stimulants. Simluants vary substantially in chemistry and physical properties, but a primary point of this work is to develop tests that can generate robust results for eventual use (Years 4 and 5) on actual lunar regolith samples. This particular assay detects with high sensitivity a lesion that is characteristic of free radical damage, which other evidence indicates is a primary effect of the simulant treatment. The next step is for rat lung slices from Co-I Tsirka's group to be assayed in this system.

As part of this work, freshly prepared mouse lung slices were treated with one of several simulants, the DNA oxidant copper-orthophenanthroline (CuOP), the general oxidant H_2O_2, and a simple methylating agent as a negative control (Figure 4). MG132 is a compound that blocks a protein-digesting enzyme that we know is part of the initial clearance mechanism in cells. Caston initially used the NIST Montana standard based on previous experiments. The simulant generated some DNA-Protein Crosslinks (DPC), while CuOP gave a stronger signal (as expected). DPC is an important marker because the accumulation of the DPC is cytotoxic, and it can consume as much as 50% of the target repair enzyme, thus limiting cellular repair capacity in general. The latter effect may result in further genetic damage and the accumulation of mutations, thus increasing cancer risk and fomenting neurodegeneration and other age-dependent processes. In further experiments, Rachel will test whether a pre-incubation with MG132 enhances the DPC signal (which it should). These are technically difficult experiments, primarily because of the dusty material that can interfere with some procedures and because extracting the DNA from tissue samples is more problematic than getting it out of cells grown in culture.

In an effort to address the difficulties listed above, new tests by SBU Co-I Demple and graduate student Caston are utilizing a human lung tumor cell line grown in culture to test for DNA damage due to exposure to lunar soil simulants. These new tests are less technically challenging than previous mouse lung slice tests and are the first to use human cell cultures.

In October 2016, This and other work in our Theme 3 portfolio was described in detail in a 9-page white paper prepared for the NASA Human Research Program director William Polaski. This paper was submitted to the SSERVI central office on October 7, 2016. Finally, members of the RIS⁴E Theme 2 and Theme 3 teams collaborated on a NASA PSTAR proposal to evaluate health hazards associated with fumaroles in Hawai'i Volcanoes National Park. This is a great example of a SSERVI-facilitated collaboration that likely would not have happened without the virtual institute.

Theme 4: Maximizing Science from Returned Samples. Our Year 2 work focused on X-ray absorption spectroscopy

(XAS), transmission electron microscope (TEM) analyses, and confocal Raman analyses of synthetic samples, returned Apollo samples, and meteorites. Confocal Raman microscopy has been a standard tool in PI Glotch's lab since 2011. However, SBU postdoctoral researcher Mehmet Yesiltas (who returned to his home country of Turkey in July 2016) developed a 3D Raman spectral imaging technique that allows us to investigate samples at new levels of detail. For this particular project, Yesiltas investigated the Moss meteorite, a CO3 chondrite. The generally low organic content of Moss suggests a higher degree of metamorphism than other CO3 chondrites. However, CO3 chondrites are thought to originate from a single parent body asteroid, which is puzzling. Yesiltas, working with Collaborator Denton Ebel at the American Museum of Natural History, is investigating organic and inorganic constituents of the Moss meteorite in order to understand metamorphic conditions that took place on the CO3 parent asteroid. Our 3D Raman tomography maps (Figure 5) shows that Moss contains abundant carbonaceous material that seems to surround olivine, seen not only on the surface but also in the interior of Moss. Derived Raman spectral parameters suggest a higher peak metamorphism temperature for Moss (CO3.6) than that of CO3.7 chondrites, indicating Moss' complex relationship with the CO3 group.

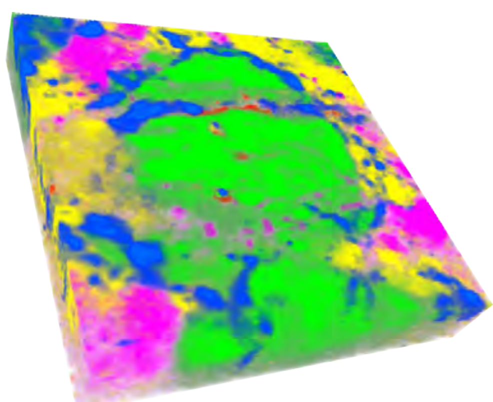


Figure 5. 3D Raman tomography image of a section of the Moss CO3 chondrite. Different colors indicate different minerals and organic constituents. Using our confocal Raman imaging system, we can construct 3D representations of the mineralogy and carbon content of meteorite sections. Blue = carbon; green = olivine; yellow = pyroxene; pink = high fluorescence material.

Additional Raman spectroscopy work included analyses of a secondary silica deposit in a shocked basalt from Lonar crater, India. This work, published by Stony Brook graduate student Steven Jaret (Jaret et al., 2016), demonstrated that the impact shock resulted in the secondary silica deposit transforming to a mixture of amorphous silica glass and coesite, a high temperature and high pressure polymorph of SiO_2. Interestingly, this work strongly suggests that coesite formed as a result of crystallization of melted SiO_2 rather than from a solid-state transformation, as suggested by numerous other studies. We also believe that this paper is the first description of a shocked secondary mineral in the literature.

Numerous other sample analyses were carried out using high precision and high spatial resolution techniques. We continued our X-ray absorption spectroscopy (XAS) work at X-ray synchrotron sources at national laboratories. We analyzed glasses and amphiboles and showed that XAS can be used to determine the Fe oxidation state in these systems. This work, led by Co-I Dyar (2016 GSA Gilbert Award winner!!), with support from Co-I's Lanzirotti and Sutton, clearly demonstrates that XAS measurements are comparable in precision to Mössbauer spectroscopy, the recognized gold standard for Fe oxidation state measurements.

Co-Investigators Stroud and De Gregorio and postdoc Burgess at the Naval Research Laboratory, have continued to advance the state of the art in aberration scanning transmission electron microscopy (STEM) analyses of extraterrestrial samples. Co-I's Stroud and De Gregorio have developed an x-ray computed micro-tomography (XCTM) technique to enable targeted TEM studies of specific grain features. Postdoc Burgess used the TEM based electron energy loss (EELS) spectroscopy technique to identify concentrations of solar wind-deposited He in mature lunar regolith grains (Figure 6). These data will eventually enable estimation of the length of time different faces of individual grains were exposed to the solar wind, to better understand space weathering, regolith gardening, and how He is stored on the Moon.

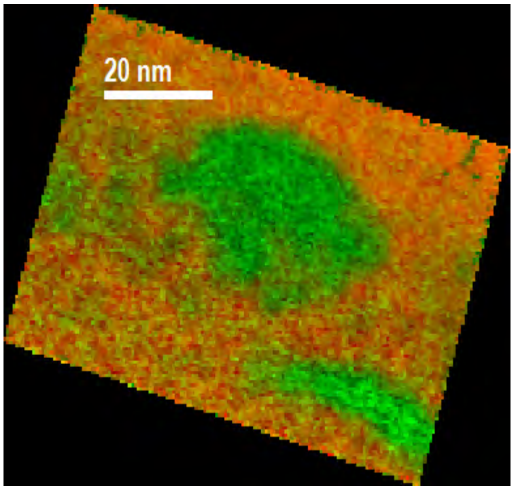


Figure 6. Map of He signal sum (green) and sample thickness (red) showing voids filled with He.

Inter-team Collaborations

The RIS⁴E team is dedicated to the concept of inter-team collaboration within the overall structure of SSERVI. Our experiences in Year 3 have provided evidence that the whole of SSERVI is greater than the sum of its parts.

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 have begun discussions that we believe will lead to a successful collaboration. Glotch and his postdoctoral researcher, Mehmet Yesiltas, started the work of preparing mineral samples, a reflectance standard, and a portable VNIR spectrometer for integration with the CU dust accelerator facility. A first year Stony Brook graduate student, Jordan Young, is continuing the work. We have purchased the necessary vacuum fiber optics and feed-throughs for our spectrometer and finalized the preparations of vacuum-clean mineral samples. Young will travel to the University of Colorado in February 2017 to finalize the design of our joint experiment. Our goal is to acquire in-situ VNIR spectra of samples as they are being continuously bombarded by dust grains in the accelerator. Results from this experiment 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.

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 will be turned over to SEEED PI Carlé Pieters for VNIR spectral analysis in the Brown RELAB facility. PI Glotch has also been working with SEEED Co-I Jack Mustard on a book chapter focused on the theory of reflectance and emittance spectroscopy. This chapter is part of a new "Remote Compositional Analysis" book to be published by Cambridge University Press in 2017.

International Collaborations: Dr. Ed Cloutis (University of Winnipeg) is a RIS⁴E collaborator and a Canadian Lunar Research Network (CLRN) team member, providing a link between the two teams. In each of the first three 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 RIS⁴E collaborator, providing a link to the UK and broader European solar system science and exploration communities.

Public Engagement

During the 2016 year, the RIS⁴E team continued to engage with the public in several meaningful ways. These included new content on our website, public lectures by RIS⁴E team members, support for local events attended by students, their parents, teachers, and other members of the public, and direct contact with elementary school students.

The RIS⁴E website hosts a blog/journal page at https://ris4e.labs.stonybrook.edu/journal/. Two new entries to this journal were provided by Naval Research Laboratory postdoc Katherine Burgess and Stony Brook Geosciences student Donald Hendrix. Kate's blog post provided an update on her research using electron energy loss (EELS) spectroscopy to understand the oxidation state of extraterrestrial materials at very fine spatial scales. The blog posts provides a very helpful primer on the techniques she uses and the ultimate goal of the research as well as a more human element that describes some difficulties she encountered and overcame over the course of the research. In the second blog post, Donald describes his experience preparing for his first conference. Donald submitted an

Stony Brook University graduate student Steven Jaret (red t-shirt) explains the geologic time scale to attendees of the 2016 Eastern Long Island Mini Maker Faire.

abstract to the 2016 HRP Guest Investigators workshop and asked for a poster, as many first year graduate students do. Instead, he got an oral presentation. In the post, Donald describes his initial feelings of unease, moments of awkwardness at his first conference, and his eventual presentation and feelings of relief after. Overall it is a great example of the kinds of training experiences SSERVI is providing to the next generation of scientists and explorers.

The majority of RIS⁴E outreach activities involved presentations to local groups, including teachers, students, and other members of the public. Two Stony Brook Geosciences graduate students, Melinda Rucks and Katherine Shirley, created Graduates for Education and Outreach (GEO). Along with graduate students from other departments on campus, they bring hands-on science lessons to 5^{th} grade classrooms in economically disadvantaged school districts on Long Island. Funding for their materials and travel is provided by RIS⁴E. Stony Brook's graduate college shared a story about their work at https://www.grad.stonybrook.edu/News/GEO.shtml.

On June 4, 2016, PI Glotch and several graduate students hosted an activities booth at the Eastern Long Island Mini Maker Faire (http://easternlongislandmakerfaire.com/). The RIS⁴E-sponsored booth included several hands-on science and engineering activities for young children as well as a demonstration of how scientists can use infrared cameras to study the composition and physical properties of materials.

Team members also gave other public presentations. In April, PI Glotch gave the keynote address to the annual meeting of the Science Teachers Association of New York State (STANYS) at Brookhaven National Laboratory. The address focused on the joint roles of science and exploration in helping to unlock the secrets of our closest neighbors in the solar system. NASA Goddard postdoc Kelsey Young gave a presentation about herself and the future of planetary surface exploration at the Library of Congress: https://blogs.loc.gov/inside_adams/2016/10/the-future-of-planetary-surface-exploration-october-19th-lecture-with-nasa-research-scientist-kelsey-young-ph-d/. She also gave a series of virtual presentations to elementary and middle school students about RIS⁴E activities. Additional presentations to young students were given by RIS4E Co-I's Lora Bleacher, Jacob Bleacher, and Andrea Jones, all at NASA Goddard, who met with 28 middle school students in December to discuss NASA's preparations for future human exploration of the solar system.

Finally, in August, the Stony Brook University Center for Planetary Exploration (CPEx) held its grand opening. Along with RIS⁴E Co-Investigators Deanne Rogers and Joel Hurowitz, PI Glotch accepted official commendations from the New York State Assembly and the Suffolk Count Legislature for their work in establishing the center and advancing space science and exploration in New York. Local media attended the event and produced several print and web stories, including a piece at http://www.tbrnewsmedia.com/stony-brook-faculty-and-students-reach-for-the-stars/ .

Student/Early Career Participation

A. Undergraduate Students

1. Daniel Applin, University of Winnipeg; Geography undergraduate researcher (2016-present)
2. Paul Szymanski, University of Winnipeg; Geography undergraduate researcher (2016-present)
3. Laura Brightenfeld, Mount Holyoke College; Astronomy undergraduate researcher (2016-present)
4. Isabel King, Harvey Mudd College; RIS⁴E summer intern (2016)
5. Marco White, University of Vermont; RIS⁴E summer intern (2014-2016)

6. Marina Gemma, Columbia University, RIS^{4}E summer intern (2016)

7. Katie Karnes, Colgate University; RIS^{4}E summer intern (2016)

8. Katherine Winchell, Western Washington University, RIS^{4}E summer intern (2016)

9. Ramyaprabha Bondalapati, Stony Brook University; Pharmacology undergraduate researcher (2014-2016)

10. Stefania Filio-Gourzi, Stony Brook University; Pharmacology undergraduate researcher (2016-present)

11. Katie Luc, Stony Brook University; Pharmacology undergraduate researcher (2016-present)

11. Dylan McDougall, Stony Brook University; Geology undergraduate researcher (2015-present)

B. Graduate Students

1. C. J. Carey, Computer Science, University of Massachusetts Amherst (2014-present)

2. Thomas Boucher, Computer Science, University of Massachusetts Amherst (2016-present)

3. Nathan Smith, Astronomy, Northern Arizona University (2016-present)

4. Rachel Caston, Pharmacological Sciences, Stony Brook University (2014-present)

5. Kaitlyn Koenig, Pharmacological Sciences, Stony Brook University (2016-present)

6. Gen Ito, Geosciences, Stony Brook University (2014-present)

7. Steven Jaret, Geosciences, Stony Brook University (2014-present)

8. Melinda Rucks, Geosciences, Stony Brook University (2014-present)

9. Katherine Shirley, Geosciences, Stony Brook University (2014-present)

10. Douglas Schaub, Geosciences, Stony Brook University (2015-present)

11. Donald Hendrix, Geosciences, Stony Brook University (2015-present)

12. Carey Legett IV, Geosciences, Stony Brook University (2015-present)

13. Tristan Catalano, Geosciences, Stony Brook University (2016-present; former RIS^{4}E summer intern)

14. Jordan Young, Geosciences, Stony Brook University (2016-present)

15. Melissa Sims, Geosciences, Stony Brook University (2016-present)

C. Postdoctoral Researchers

1. Katherine Burgess, Naval Research Laboratory (2014-2016); just promoted to full time federal employee

2. Jillian Nissen, Pharmacological Sciences, Stony Brook University (2014-present)

3. Elizabeth Sklute, Mount Holyoke College (2014-present)

4. Kelsey Young, Goddard Space Flight Center (2014-present)

5. Mehmet Yesiltas, Stony Brook University (2015-2016)

Andy Rivkin

Johns Hopkins University/ Applied Physics Lab, Laurel, MD

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

VORTICES Team Project Report

Theme 1: Volatiles

The VORTICES team made significant progress in its first theme, "Volatiles in the Solar System: Sources, Processes, and Sinks." Research is divided into three areas: characterizing the lunar/asteroidal thermal conditions as relevant to volatile stability, modeling creation and transport of volatiles, and measuring volatiles in the lab or via remote sensing.

Thermal Conditions: Christopher Magri's efforts during 2016 focused on validating his thermophysical modeling software, SHERMAN, against analytical results derived mathematically in 2015. Three basic classes of models were tested. The simplest was ellipsoids with extremely high or extremely low thermal inertia, with or without small spherical-section craters placed across the surface in order to model the "infrared beaming" effect. The second class tests the program's output for craters by examining asteroid surfaces that contain a single crater taking up an entire hemisphere. The third and most general class, which allows for arbitrary thermal inertia values, involves a family of solutions to the heat equation for which density, specific heat, and thermal conductivity can vary with depth and/or temperature. A paper (Magri et al., 2017) describing the software and setting out these successful validation results has been completed and will be submitted in January 2017, together with a companion paper (Howell et al., 2017) in which the software is used to analyze the thermal emission from a contact binary near-Earth asteroid (NEA), 1996 HW1. The latter paper demonstrates SHERMAN's versatility in resolving ambiguities between optical properties, thermal properties, and the degree of small-scale roughness. Dr. Magri was also involved in the analysis of thermal emission from another NEA, 2000 ET70 (Marshall et al., 2016).

Additionally, Chris Magri and Paul Hayne collaborated to resolve discrepancies between lunar temperatures at ~ 1 m depth predicted by their respective software packages. Although this analysis is not complete, we now suspect that the discrepancy between the models has been resolved. SHERMAN is designed to iterate as needed until temperatures far beneath the surface—which vary quite slowly—reach their correct values, and this is important for predicting the presence vs. absence of subsurface ice. Hayne also continued his research on thermal environments and possible exposures of ice detected in some of the Moon's permanently shadowed regions. Finally, Co-I Hayne has made advancements in the study of water ice darkening due to sublimation lag formation, with applications to the Moon, Ceres, and Mercury.

Matt Siegler began this year with a collaboration with Co-I's Miller, Lawrence and others on a Nature paper possibly explaining much of the hydrogen on the Moon as being ancient, pre-dating a period of polar migration (true polar wander), described below. This model, if accurate, has profound implications for regolith gardening and/or hydrogen stability in the regolith. Siegler also measured thermal conductivity of Apollo 11 regolith samples at cryogenic temperatures. These measurements, presented at AGU, show a previously unknown temperature dependence of silicate regolith thermal properties at low temperatures (<150 K).

Volatile Creation and Transport Modeling: Hurley applied her impact gardening model to the retention and burial of lunar ice deposits at the poles of the Moon. She evaluated the impact gardening output in terms of the evolution of a preexisting ice layer over time and how it would appear to remote sensing instrumentation on the surface and from orbit. Her results were presented at AGU and have been submitted to JGR and are currently in revision. Kulchitsky at U. Alaska Fairbanks modeled solar wind implantation into lunar regolith, varying incidence angles, regolith void ratios, and regolith grain size distributions and found a basic exponential shape of the proton implantation rate. Analytical considerations show the implantation rate as a function of depth and confirmed the distribution function expression for the implantation rate with extensive digital elevation model (DEM) simulations. A wide grain size distribution allows protons to penetrate deeper into the lunar regolith compared with a narrow distribution. Analysis of the horizontal distribution shows that protons concentrate unevenly around larger particles that allow a longer, free path around them.

The Georgia Tech group (Orlando et al.) has focused on understanding the interaction of solar protons and water with lunar regolith. Orbital data show an infrared absorption feature at 2.8 µm indicating the presence of hydroxylated silicates, which may have formed by solar wind proton implantation. This formation mechanism was modeled in conjunction with diffusive transport and chemical and radiation losses and compared to the lunar observations. The model, which takes into account a weak temperature dependent of the first-order OH removal process, shows general agreement with the spatial (latitude) variation in observed hydroxyl abundances. The modeling approach is self-consistent with a general predictive capability for solar-wind induced processes and may also be used to make predictions regarding OH abundances on other airless solar system bodies such as asteroids and Mercury.

Measuring Volatiles: Over the last year, the capability of the Laboratory for Spectroscopy under Planetary Environmental Conditions (LabSPEC: Co-I Hibbitts PI of laboratory) at APL has been expanded for conducting experiments investigating the spectral nature of water on lunar and asteroid analogs. There are new capabilities to irradiate materials with energetic electrons, at appropriate energies, to simulate particulate bombardment from within planetary magnetospheres and irradiation by the solar wind. Lower energy electron bombardment studies are particularly relevant to understanding potential solar wind processes occurring on evolved asteroids. This facility is being upgraded to enable the sample to be held at cryogenic temperatures for up to several days, while under bombardment. This cryogenic capability will permit us to explore the irradiation effects on lunar analog materials at temperatures relevant to the lunar permanently shadowed regions (PSRs).

A key component of VORTICES has been a continuing study of volatiles using orbital geochemistry techniques. The principal focus of the geochemistry team (Miller, Lawrence, Siegler et al.) has been bulk distributions and processes associated with lunar volatiles. This research builds on an extensive archive of neutron and gamma-ray spectroscopy measurements made in-situ from lunar orbit by multiple spacecraft. One aspect to note is an attempt to better understand the distribution of hydrogen in the highlands and how apparent variations can be explained as a function of topography and/or geology.

A key breakthrough made during the past year was the recognition that the bulk polar hydrogen deposits may display a record of true lunar polar wander. Specifically, our analyses showed that to high-statistical significance the distribution of these volatiles (presumably water ice) is consistent with an ancient reorientation of the Moon caused by the formation of the Procellarum KREEP Terrane (PKT). Using our derived bulk hydrogen maps we have localized the lunar paleo-poles (pre-PKT) and constrained the magnitude and direction of polar wander. This work represents the first use of surface and near-surface volatiles to infer the structure and evolution of a planetary interior and provides an explanation for the antipodal distribution of lunar polar hydrogen, connecting polar volatiles to the geologic and geophysical evolution of the Moon and the bombardment history of the early solar system. This work was published in a high-impact journal and received significant press (Siegler, Miller, Keane, et al., 2016. Nature, 531, 480). If this interpretation is correct, it implies that hydrogen at shallow depth (meters) has been stable against regolith turnover and loss for time scales of billions of years. The presence of hydrogen at shallow depth in ancient terrain implies either a considerably lower gardening rate than has been suggested or that the hydrogen can be retained during turnover.

Another important aspect of our work has been to compare and contrast the characteristics of bulk volatiles on multiple airless planetary bodies. Both the Moon and Mercury have PSRs at their poles. While volatile enhancements have been detected and characterized at both planetary bodies, the volatile concentrations at Mercury's poles are significantly larger than at the Moon's poles. One of the most important unanswered questions is why the PSR volatile concentrations at the Moon and Mercury are so different. These similarities and differences were recently reviewed by D.J. Lawrence (Lawrence, J., Geophys. Res. Planets, 2016. 122, doi:10.1002/2016JE005167) in an effort to constrain the open issues and obtain new insights regarding the contrasting observations. This review spans more than 60 years of theoretical and experimental efforts, and ultimately suggests new measurements and studies that are needed to answer the remaining open questions about PSR volatiles on airless planetary bodies.

The Georgia Tech group measured desorption of water from annealed lunar samples. They previously demonstrated that water can exist in a weakly adsorbed state on both highland and mare materials. The amount of water adsorbed to highland samples is significantly higher relative to mare samples. Specifically, the amount of water, adsorbed (desorbed) after the same exposure to "fresh" samples, was significantly less for the mare sample. This was investigated further by pre-annealing the lunar samples to 600K prior to the water adsorption and desorption experiments. Repeated annealing changed the adsorption properties of grain surfaces. The TPD peak also shifts to higher temperature, consistent with a decrease in the number of hydroxyl sites after annealing to 600K. The increase in the hydrophobicity of the mare regolith after annealing can be a result of the lower thermal stability of surface hydroxyls in the minerals dominating mare samples (i.e. Ti, Fe – containing oxides and aluminosilicates).

Klima has been continuing research on searching for expressions of "internal" lunar water (i.e. water in minerals from depth now exposed at the surface) from orbit using Moon Mineralogy Mapper data. In February, she was invited to contribute to a small workshop, organized by the Royal Society of London, to examine water throughout the solar system. She has been examining geographic anomalies in the strength of the 2.8 μm feature on the Moon that might correlate with specific lunar lithologies. A small number of anomalies in the 2.8 micron band depth, potentially associated with internal water, occur across the Moon. These are primarily found in association with lower crustal material. The results of this work have recently been accepted for publication by the Royal Society. She was invited to speak further on this topic to a broader audience at the European Lunar Symposium, and was also invited by JAXA to present at the Hayabusa 2 symposium in November.

Theme 2: Regolith

VORTICES research in 2016 on Theme 2, "Regolith: Origin and Evolution on Airless Bodies," focused on the creation of regolith via disaggregation of blocks from thermal stresses and space weathering processes: both on water- and carbon-rich asteroids. Such asteroids are targeted by in-progress sample return missions (OSIRIS-REX) and the planned Asteroid Redirect Mission, and on the Moon via synergistic combination of radar and optical data.

It was recently demonstrated by VORTICES collaborators Delbo et al. that thermal fatigue can disrupt rocks orders of magnitude faster than fragmentation by classical impact mechanisms, in terms of breaking down cm-sized rocks on small airless bodies. Larger (10 cm-size) rocks were shown to potentially break up faster than smaller (cm) rocks, an observation that contrasts with the predictions of mechanical disruption models. This observation is justified by the existence of higher internal thermal stresses resulting from the larger temperature gradient in larger rocks, but it is not clear that this conclusion can be extrapolated or scaled for meter-sized boulders or very small clasts.

In the current work by Co-I Ramesh and his team, the length and timescales involved in the thermally-driven fatigue crack growth were investigated, and a critical length-scale, comparable to the thermal skin depth, was identified, after which thermal fatigue becomes slower, providing bounds on the thermal fragmentation mechanism. A simple scaling method to estimate the time required for thermal fatigue-induced rock breakdown was developed while accounting for the composition and thermomechanical

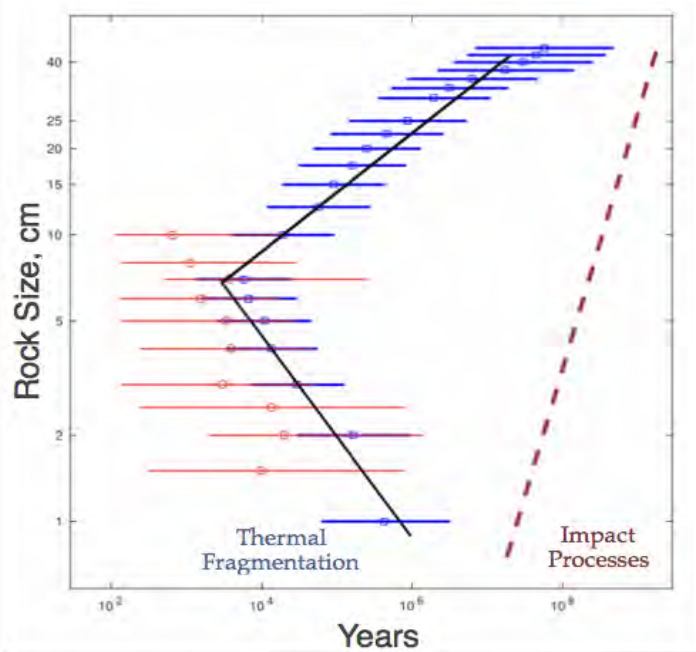


Figure 1: Improved models for thermal fragmentation of rock (blue points) show that this process has a characteristic size at which it is most efficient. In this model for NEO conditions, the size is ~5 cm.

properties of the rocks, and the asteroid's heliocentric distance (see Figure 1), providing insight into likely size distributions on the surfaces of these bodies.

In calendar year 2016, VORTICES Co-I Cahill along with Co-I's Lawrence, Stickle, and Greenhagen collaborated on work relevant to examining regolith maturity across multiple perspectives. In the past, lunar surface maturity has been consistently and pervasively examined using the NIR optical maturity parameter (OMAT). However, the NIR only provides a perspective of the upper microns of the lunar surface. Recent studies of Lunar Prospector (LP) and LRO thermal infrared, S-band radar, and epithermal neutron data sets are now demonstrating additional measures of maturity with sensitivities to greater depths (~2 m). Interestingly, each of these data sets measured parameters or abundances directly comparable to OMAT despite each measuring different aspects and depths of the regolith. With this in mind, areas of enriched-H are mature, while areas of depleted H are immature (Figure 2).

To better understand how the lunar regolith is weathering in the upper 1-2 m of regolith with time, they have examined a number of non-polar highlands regions (~35 localities), including the Orientale impact basin. The work is ongoing, and was presented at the New Views of the Moon 2 and the Goldschmidt Conferences in 2016.

Co-I Hayne developed a new version of his thermal model (used by several VORTICES and SSERVI Co-Is) written in the more accessible and widely used MATLAB language. This is a versatile and user-friendly model for calculating surface and subsurface temperatures on airless bodies, including the Moon, asteroids and Ceres. During the latter part of 2016, we tested and validated the model, and circulated a draft manuscript detailing its development and application to lunar regolith properties (to be submitted to Icarus).

The Hawaii group (Gillis-Davis, Kaluna, et al.) explored how carbonaceous materials react to space weathering by conducting nanosecond pulsed laser irradiation experiments and proton irradiation on various powdered samples. While both Allende and NWA 3118 are in the same

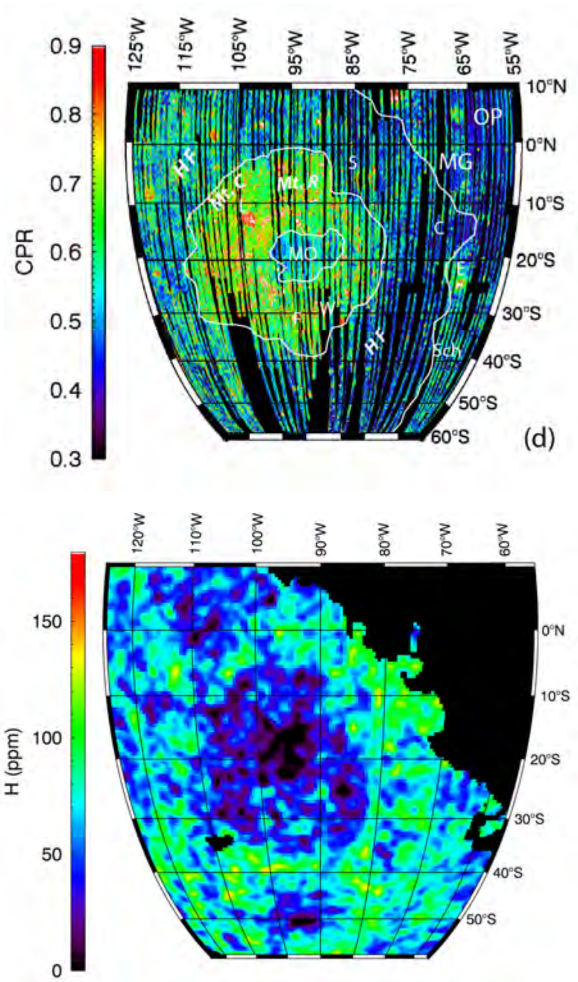


Figure 2: Orientale impact basin in (TOP) Lunar Prospector derived Hydrogen, and (BOTTOM) Mini-RF derived CPR maps.

carbonaceous chondrite class CV3 (e.g., exhibiting similar carbon content in matrix, comparable major mineralogy, and presence of CAIs), the effects produced by the laser weathering experiments are different. Spectral effects of Allende are controlled by dispersal of sulfides, which are a minor component of NWA, while possible dispersal of the micron to submicron Fe-rich olivine crystals in NWA 3118 by the laser causes its 1-µm band to increase.

Kaluna studied the effectiveness of experimental methods in reproducing the spectral trends observed in lunar soils. In particular, she compared the visible and NIR trends of Apollo soils to the trends from different types of space weathering experiments performed on lunar (68416) and lunar analog materials. She also investigated the origin of contrasting spectral trends (e.g. reddening vs. bluing) on asteroids by simulating space weathering on a subset of minerals found in volatile-rich carbonaceous chondrites meteorites. The presence of npFe0 and the possible catalytic nature of cronstedtite (an Fe-rich phyllosilicate) likely promotes the synthesis of carbon-rich, organic-like compounds. These experiments indicate that space weathering processes may enable organic synthesis reactions on the surfaces of volatile-rich asteroids. Also, we found that the Fe- and Mg-rich samples in these experiments produced contrasting spectral slope, which may indicate that space weathering trends of volatile-rich asteroids have a compositional dependency that could be used to determine the aqueous histories of asteroid parent bodies.

Grad student Parker Crandall conducted experiments irradiating percholrate (ClO_4^-) samples with deuterium. The experiments were done in an attempt to understand why similar experiments with silicates were not yielding OH or H_2O. The experiments serendipitously yielded evidence for perchlorate's role in the lack of Martian organics. In this study, magnesium perchlorate hexahydrate ($Mg(ClO_4)_2 \mu 6H_2O$) samples were irradiated with beams of 5 keV electrons and D2+ ions to simulate the effects of galactic cosmic ray exposure of perchlorates. When samples were irradiated sequentially, the production of D_2O_2 was dependent upon the sample being irradiated with D2+ ions prior to electrons. These experiments show that perchlorates are capable of producing multiple oxidizing agents (O_2, D_2O_2) which may also account for the lack of organics on the Martian surface.

Themes 3 and 4: Resources and SKGs

Work on the final VORTICES themes, "Resources: Identification and Exploitation" and "Closing Strategic Knowledge Gaps," centered on concept studies looking at future possible lunar bases, involvement with the nascent asteroid mining community, and participation in NASA special action teams.

In the past year, Spudis et al. have completed and published a major paper, investigating the use of NASA's forthcoming SLS launch vehicle, commercial transport for crew to low Earth orbit, and propellant depot/habitats in both Earth orbit and lunar orbit (Lavoie and Spudis, 2016). Employing a reusable in-space cis-lunar crew stage and a reusable human lunar lander, a crew can be launched commercially by any of several providers and returned 6-months later using the Commercial Crew service module. As a consequence of this strategy, we develop more capability to harvest lunar water for propellant compared to the previous architecture; at the end of the 16-year first phase of the architecture, we produce more than 300 metric tons of lunar water per year (twice as much as our previous production level of 150 tons per year; Spudis and Lavoie, 2011), with a total production capacity of 500 metric tons per year. We use aerobraking during Earth return to recover the reusable cis-lunar crew stage; this non-propulsive maneuver removes excess energy for an insertion to Low Earth Orbit to transfer crew to the commercial crew vehicle before returning home. We take advantage of a LEO fuel depot, loaded by commercial or government water deliveries to the depot from Earth, to fuel the cis-lunar crew stage on its way to the Moon. The use of both commercial crew and commercial water transferred to the LEO fuel depot allows the campaign to better use and stimulate commercial space industry, transferring technology and experience from NASA to the commercial sector regarding the ability of humans to use local (off-planet) resources in an effective way to explore and grow off-planet. The revised estimated total cost for this new architecture is $ 87.7 billion, only about $550 million more than our previous plan. With possible international contributions, the peak NASA funding could be reduced to $5.5 billion per year while reducing the total program cost to $69 billion.

In addition to this work, Spudis et al. have developed a robotic architecture designed specifically to address issues in prospecting for harvestable ice in the lunar polar regions (Spudis, 2016; in preparation). Robotic missions include new orbital missions with next-generation active and passive sensors, hard-landing robotic probes to provide point measurements of water concentrations over select areas, soft-landed fixed stations to provide point measurements and environmental monitoring, and a long-lived roving vehicle equipped to map out promising prospects in detail. After presentation of this architecture in the 2015 LEAG meeting, a manuscript detailing this approach is currently in preparation.

Rivkin attended the Asteroid Science Intersections with In-Space Mine Engineering workshop in Luxembourg, bringing 90 asteroid scientists, engineers, asteroid mining company employees, and venture capital representatives together for a discussion of the needs of the newly-forming asteroid mining community. Rivkin presented a contributed talk and is an author on the white paper resulting from this workshop (posted on arxiv).

Rivkin also served as a member of the SBAG Special Action Team convened by HEOMD to consider the contributions the ARM mission would make toward completing Decadal Survey tasks and closing Strategic Knowledge Gaps. In addition to that team, Rivkin served as SBAG representative to the HEOMD update of SKGs for Phobos and Deimos, convened through SSERVI.

Inter-team Collaborations

SSERVI Water Workshop: Rachel Klima and Dana Hurley organized and executed the SSERVI Water Workshop, hosted by VORTICES at APL on 15-17 Nov, 2016. They planned the workshop structure, invited participants, honed the discussion questions, and arranged logistics. Many VORTICES team members participated in the workshop, including Hurley, Klima, Rivkin, Lawrence, Greenhagen, Hibbitts, Orlando, and Hayne. They contributed to the discussions (all), gave summary presentations (Klima, Hurley), and facilitated sessions (Orlando). Hurley, Klima, and Orlando coauthored with others a meeting workshop summary for submission to EOS. This effort included members of many other teams.

Hayne: As an outcome of the work with Magri to resolve differences in thermal modeling software, Co-I Hayne is currently developing a model in collaboration with W. Farrell, PI of SSERVI's DREAM2 team, to better understand the stability and migration of volatiles on airless bodies with "sticky" surfaces due to small-scale surface roughness.

The Ramesh group has been working closely with Collaborator Marco Delbo at Cote d'Azur Observatoire in Nice, France on the thermal modeling of asteroids, and more recently have begun collaborating with Rebecca Ghent and her student Sara Mazraoui of the University of Toronto on thermal modeling for the Moon.

Hurley: Working with the DREAM2 team on understanding the interactions between water/OH molecules and lunar regolith, and working with Kring on modeling the migration of vented volatiles from Schrodinger basin to lunar permanently shadowed regions.

Gillis-Davis: Working with Dan Britt (CLASS) on characterizing his synthetic meteorite samples, Hope Ishii (CLASS) on irradiation effects on dust and regolith, and Jeff Taylor (CLSE) on lunar/meteorite mineralogy and compositions. Also started international collaborations with Ernesto Palomba who is a research scientist, at the Institute of Astrophysics and Planetary Science-INAF, Rome, Italy, and working closely with Harold Connolly, sample scientist on the Osiris-REx mission.

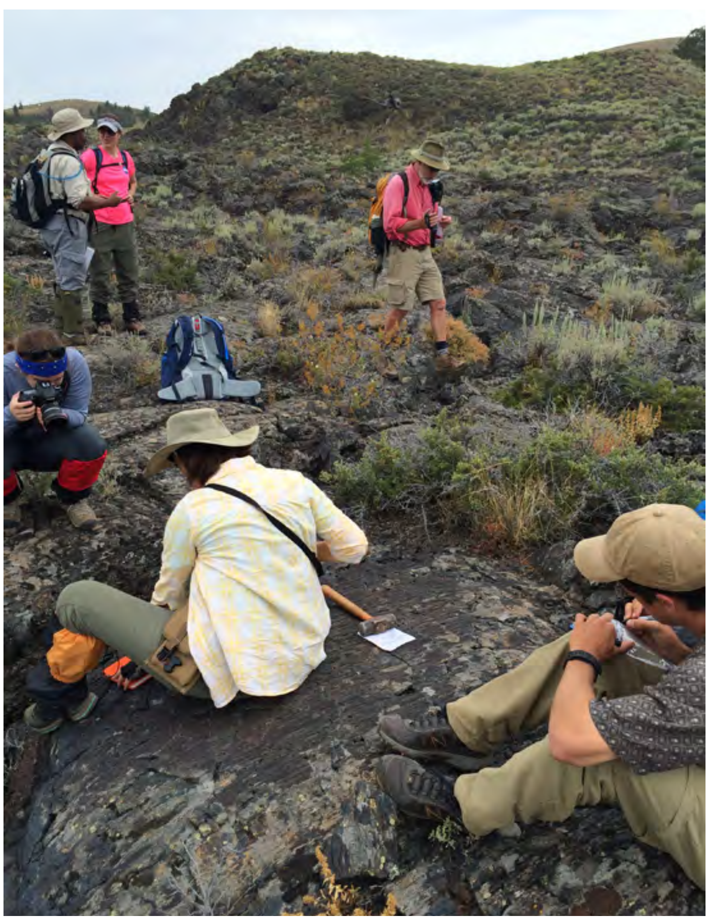
Outreach: as described in more detail below, VORTICES partnered with the FINESSE team to help facilitate field research experience for educators at Craters of the Moon National Monument, Idaho.

Public Engagement

Third year Public Engagement and Education activities built upon past SSERVI partnerships and leveraged resources to continue implementing a program that targets a diverse audience. Our activities engaged students, educators and the general public with SSERVI and VORTICES science and engineering themes.

Student engagement activities included research experiences for high school students and presentations on solar system exploration to middle school classrooms. Our high school student, Michelle Castro (now a 1st year student at Univ. of Maryland, College Park) assisted in a research project looking at boulder size-frequency counts and regolith evolution in lunar data, including Mini-RF, Diviner and LROC data. Additionally, the VORTICES team facilitated a student engagement event with the Magic Planet at Old Mills Middle School in Millersville, MD. About 100 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 partnered with the FINESSE team in 2016 to help facilitate field research experience for educators through the Spaceward Bound educator professional development program at Craters of the Moon National Monument, Idaho. VORTICES provided classroom resources and research experiences for the educators that connected SSERVI research themes on planetary science and exploration to the field work being done by the FINESSE science team. VORTICES also facilitated opportunities for field research experience for graduate students from Idaho State University.



For public engagement, the VORTICES Team organized an International Observe the Moon Night (InOMN) event at the Maryland Science Center on October 7. Over 60 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. The high school intern, Castro, also assisted in this event, giving her experience in science communication and engagement.

In addition to the work based at APL, Gillis-Davis and Kaluna took part in HI STAR, a Student/Teacher Astronomy Research program conducted by the University of Hawaii that has trained high school students in research skills for the last ten years. Each year in HI STAR, a group of 12 - 20 high school students attend a week-long residential program where they learn astronomy basics and begin a research project with their astronomer mentor. Afterwards, they carry out a long-term research project for submission to a local science fair. Instructors and mentors include faculty, staff, and graduate students at the IfA and HIGP. Among astronomy outreach programs in the US, HI STAR is unique in the degree to which the students design and direct their research projects while receiving the training and support they need to be successful. In the past five years, up to 93% of students have completed their long-term projects. In 2015 and 2016, 10 alumni earned the right to compete in the International Science and Engineering Fair and a few have contributed to peer-reviewed publications.

HI STAR attracts diverse students from across the state of Hawaii. 60% of HI STAR students have been women, ~30% are from underrepresented minority groups and 3 have had learning disabilities.

Student/Early Career Participation

Charles El Mir (graduate student) has been doing the computational work with the Ramesh team, and is now approaching the final stages of his thesis research.

Dr. Kavan Hazeli, the postdoc who was involved with the experimental work with the Ramesh team, has now moved on to a faculty position as Assistant Professor at the University of Alabama in Huntsville.

Heather Kaluna (post doc with the Gillis-Davis team) has just accepted a tenure track faculty position at the University of Hawaii in Hilo department of astronomy.

Parker Crandall (grad student with Gillis-Davis team), working as described in Theme 2 subsection.

Gillis-Davis also mentored a Hawaii Space Grant student for spring semester 2016, Amber Mokelke, who did a project on laser weathering and measuring spectral reflectance of Ceres analogs.

William Farrell
NASA Goddard Space Flight Center, Greenbelt, MD

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

DREAM2 Team Project Report

In its third year, the DREAM2 team continued its unique study of the space environmental effects at exposed bodies—with an emphasis on a universal approach (different bodies, different mass, different solar wind flow, etc). Herein, we outline our stunning research achievements over the past program year—many of which are also presented on the DREAM2 website (http://ssed.gsfc.nasa.gov/dream/). We first report on our DREAM2 themes, and then report on a large cross-team study of Phobos called 'The Space Environment in Stickney Crater (SEinSC)'.

Theme Reports

Space Plasmas & Surfaces. Every airless body in our solar system interfaces with a plasma (solar wind or magnetospheric plasma). Understanding the plasma-surface interactions not only lays the groundwork for future explorers who are also immersed in this conductive medium, but also strengthens our grasp of fundamental processes at airless bodies throughout our solar system.

The plasma team conducted fundamental data analysis and theoretical investigations focused on airless bodies. Highlights include fundamental investigations of pickup ion measurements from multiple spacecraft (Poppe et al., 2016a; Halekas et al., 2016; Collier et al., 2016), revealing new aspects of the structure and variability of both the tenuous exosphere and near-surface electromagnetic environment of the Moon. DREAM2 plasma team members also studied solar wind interactions with small-scale magnetic fields (with applications to space weathering) (Poppe et al., 2016) and solar wind interactions with the regolith (with applications to surface charging and dust levitation) (Zimmerman et al., 2016). DREAM2 members also made a first-of-kind measurement of heavy ion outflow from the Earth at the Moon, revealing a potentially important source of nitrogen and oxygen at the Moon (Poppe et al., 2016). The resulting paper was a GRL editor's highlight.

These investigations resulted not only in fundamental scientific advances, but also in advances in computational tools, with DREAM2 postdoc S. Fatemi creating the first three-dimensional self-consistent kinetic model of plasma that runs entirely on graphics processing units (GPUs) and only uses a single CPU, and DREAM2 Co-I M. Zimmerman creating a revolutionary grain charging model suitable for investigating a variety of regolith physics (see Figure 1 of E-field that forms between grains).

Exospheres and Corona. Exospheres are a direct indication of the dynamics any exposed surface is undergoing via space environmental erosion. Space plasmas, micro-meteoroids, UV radiation and energetic particles all energize an exposed surface, and in response the surface will release neutral and ionized gases into the space above – forming an exosphere.

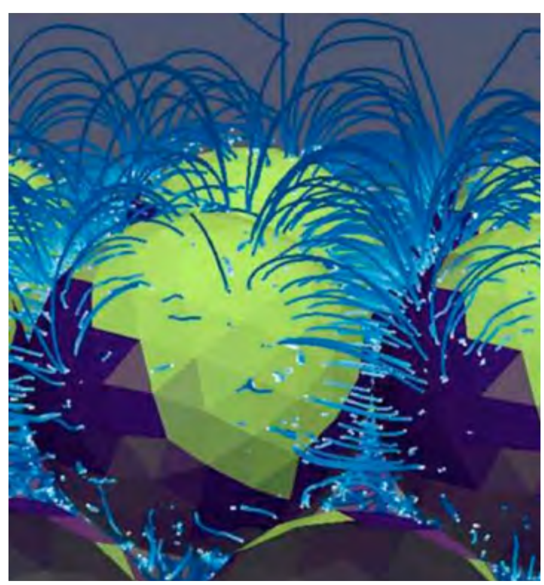


Figure 1. Model E-field about a surface dust grain

The DREAM2 exospheres team made several important contributions to the understanding of the lunar exosphere in PY3. One important result was the discovery of methane in the lunar exosphere (Hodges, 2016). It has a very short lifetime (about 1 day) and hence a low concentration, peaking at about 400 molecules/cc in early morning. Methane escape can account for 25-76% of the global influx of solar wind carbon. A second important result is the discovery of how surface composition and meteoroid impacts mediate sodium and potassium in the lunar exosphere (Colaprete et al., 2016). Observations of lunar exospheric helium from LRO/LAMP and ARTEMIS contributed to our understanding of the source and loss of helium (Grava et al., 2016). Using simultaneous observations from LRO, LADDEE and ARTEMIS, it was shown that the primary driver for variability in the helium exosphere throughout the LADEE mission was the solar wind alpha flux. The solar wind contributes 64% of the helium to the lunar exosphere, with the remaining from radiogenic helium from the interior of the moon (Hurley et al., 2016). Hurley also developed a statistically-based water plume model created by micro-meteoroid delivery for comparisons to LADEE NMS data. In support of the ARM mission, the gas-surface interaction of a human-occupied spacecraft with a near-Earth object was a timely study leading to understanding of contamination issues of human systems visiting small bodies (Farrell et al., 2016.) (See Figure 2). We continued our remote observations of the lunar sodium exosphere throughout 2016 via a ground-based observatory.

Radiation at Exposed Surfaces. Particle radiation has significant effects for astronauts, satellites and planetary bodies throughout the solar system. Acute space radiation hazards pose risks to human and robotic exploration. Radiation weathers the regolith of the Moon and other airless bodies, and is a source of chemical modification in the atmosphere of Earth, Mars, and other planets.

Figure 2. Outgassing human systems near a small body

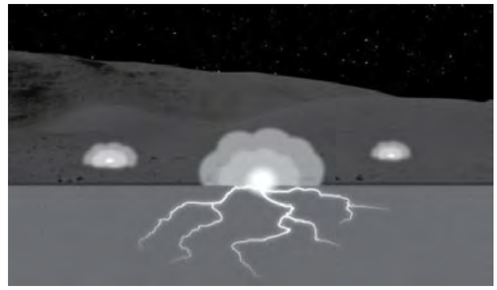


Figure 3. Deep dielectric discharge at the Moon

In PY3, the radiation team made a set of key advancements, including the publication of a set of papers on the deep dielectric discharge weathering of regolith (Figure 3) at the Moon and Phobos (Jordan et al., 2016, 2017). The team also advanced their radiation propagation models for applications to the Moon and Mars (Schwadron), updated the Virtual Energetic Particle Observatory, examined the Ulysses-measured radiation environment at 1.5 AU for Phobos applications (Cooper), and discovered a possible enhanced proton albedo and diurnal effect associated with hydrated layers (Schwadron). They also examined radiation effects at Saturn's rings (Cooper) and the Earth (Joyce et al., 2016).

The team continues the critical examination of Cosmic Ray Telescope for the Effects of Radiation (CRaTER) observations on the Lunar Reconnaissance Orbiter (LRO) to derive the implications of the unusual weakening solar conditions over future solar cycles for human space exploration and for planetary bodies throughout the inner solar system. Galactic cosmic ray radiation is expected to remain a significant and worsening factor during this weakening period that limits mission durations (as describe previously in Schwadron et al., 2014). As galactic cosmic ray fluxes rise, the GCR doses also increase down to ISS and aircraft altitudes. This work on the effect of the weakening solar cycles remains a very high priority DREAM2 science-exploration study.

Surface Response to the Space Environment. PY 3 saw the advancement of a number of surface interaction studies, including the completion of a dedicated Ar^{+} 1 MeV beam line at the GSFC radiation facility. This DREAM2 funded two-beam experiment lead by Loeffler and Hudson is designed to create crystal defects in lunar samples, to then determine if such defects affect the ability of the sample surface to retain low energy (1 keV) deuterium implantations. The low energy deuterium is the analog for solar wind hydrogen implantations. Farrell et al. also created a model for hydrogen retention in defected silica to be used in conjunction with the lab experiments. This model was presented at LEAG and the paper is under review.

McLain and Keller are further advancing their adsorption chamber with the aid of some added DREAM2 funding (to supplement pilot study funding). The chamber will be an online system that helps researchers examine how atoms and molecules stick onto dusty smokes and other samples.

The team continues to assist and support the space suit designers at JSC on requirements for the suit's outer skin. DREAM2 models on astronaut and rover charging have been used in this effort. In June 2016, Farrell gave a SSERVI Director's Seminar at NASA HQ on the interaction of space plasma charging and human systems, detailing the need of the suit to electrically 'ground' itself to the conductive plasma (similar to spacecraft). These DREAM2 models on astronaut charging were also recently applied to an explorer visiting Phobos (see below).

Team members Glenar and Stubbs continue to analyze LRO and LADEE observations for lofted dust, using Glenar's light scattering models as a basis. For example, DREAM2 funded Glenar's effort on the Wooden et al. (2016) paper showing the possible presence of nanograins detected by the LADEE UVS that were ejected from the Moon during the Quadrantid meteoroid stream.

Mission Applications. DREAM2 Team members continue to have their feet firmly established in ongoing and future missions and HEOMD studies. Pamela Clark is the lead Science PI of the Lunar Ice Cube cubesat (Figure 4) to be released during the EM-1 mission spearheading the endeavor to obtain new measurements on the hydroxylation and hydration state of the Moon. Mike Collier and colleagues presented a novel new idea on the use of tethered cubesats at the Moon to obtain simultaneous high- and

Figure 4. Lunar Icecube

low-altitude observations over magnetic anomalies, cold polar traps, and terminator regions. Many team members were active in the recent call for smallsat concepts—which indicated just how potent DREAM2 is in seeding new ideas. Team members continue to contribute to LRO especially LAMP (Hurley) and CRaTER (Jordan, Stubbs, Schwadron, Wilson, Spence, Winslow). Many DREAM2 team members provide critical support for LADEE (Elphic, Delory, Colaprete, Sarantos, Glenar, Stubbs, Hurley) and play major leadership and science roles on ARTEMIS (Halekas, Poppe, Fatemi, Delory). A mission that has provided stunning new insights into the Mars-Phobos space plasma environment is MAVEN with DREAM2 team members active therein (Halekas, Poppe, Fatemi, Delory).

In the area of human exploration, DREAM2 team members are in collaboration with JSC's Space Radiation Analysis Group (SRAG), continuing their critical analysis of the radiation environment in the ever-weakening solar cycle conditions. Team members are also involved in updating the lunar strategic knowledge gaps (SKG studies), and interact with JSC space suit designers to provide environmental information in support of suit designs. Team members

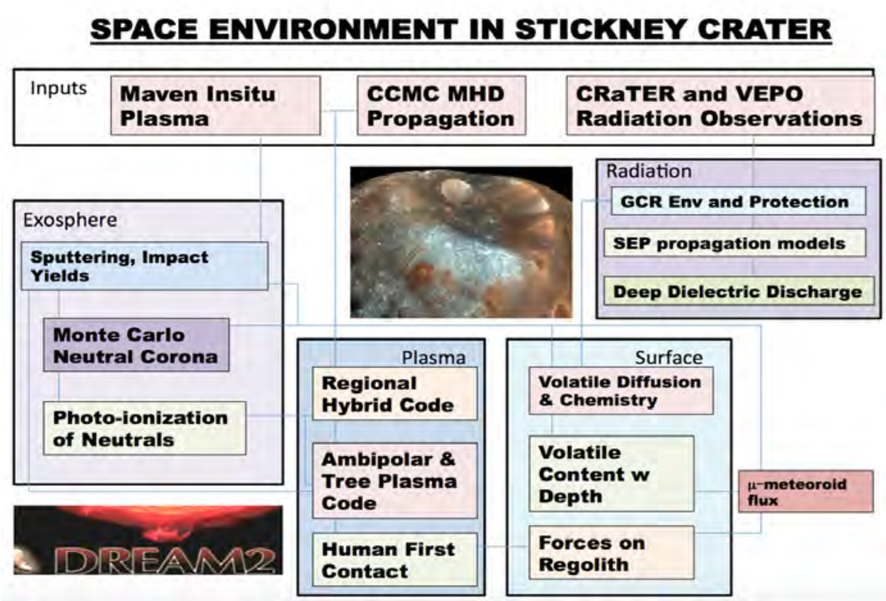


Figure 5. Layout of the various data sets and modeling tools applied by DREAM2 team members to examine issues like astronaut charging and first-contact with the regolith, solar energetic particle environment, exospheric formation, volatile diffusion, deep-dielectric breakdown, etc.

recently published an exosphere-surface paper on the effect the volatile outgassing of Orion may have on the captured asteroids—and provide key recommendations to assess and limit such forward interactions. In our Phobos study (below), we as a team also assessed the harsh space environment that affects all future explorers.

Special Topic: DREAM2 Intramural Study on the Space Environment at Phobos

This intramural study on the space environment at Phobos involved over 30 investigators who are part of DREAM2. The title of this intramural study is the 'Space Environment in Stickney Crater (SEinSC)' that addressed the space environment at Phobos. Stickney crater was targeted as an ideal regional scale feature for examination.

In 2015-2016, team members undertook this systematic study, including the development of plasma, exosphere, and surface interaction models, run in sequence and in common space environmental conditions to understand the effect the radiation, space plasma, and micro-meteoroid environment has at and on this exposed irregularly-shaped ~22 km body. The team presented findings at an intramural workshop in April 2016.

Specifically, the SEinSC study used inputs from the Mars Atmosphere and Volatile Evolution (MAVEN) mission, models of the inner heliospheric solar wind from the Community Coordinated Modeling Center (CCMC), University of New Hampshire radiation propagation models, and data from the Virtual Energetic Particle Observatory. These contextual data sets were used as inputs to the detailed tactical DREAM2 models such as hybrid plasma simulations of the Mars-solar wind interaction, kinetic models of the Phobos-plasma interactions, neutral gas and photo-ion models, radiation-induced deep dielectric discharge models, and radiation/human effect modeling. Impact gardening and solar illumination/temperature models of Phobos were also developed to examine volatile retention and longevity. Models of solar wind hydroxylation at Phobos were also developed to better understand the previous observations of a 2.8 micron absorption feature in the NIR spectra from a possible OH veneer (Fraeman et al., 2014). Possible Phobos missions that might provide validation or further context of the SEinSC findings were also discussed.

A key finding was that the exposed surfaces at Phobos

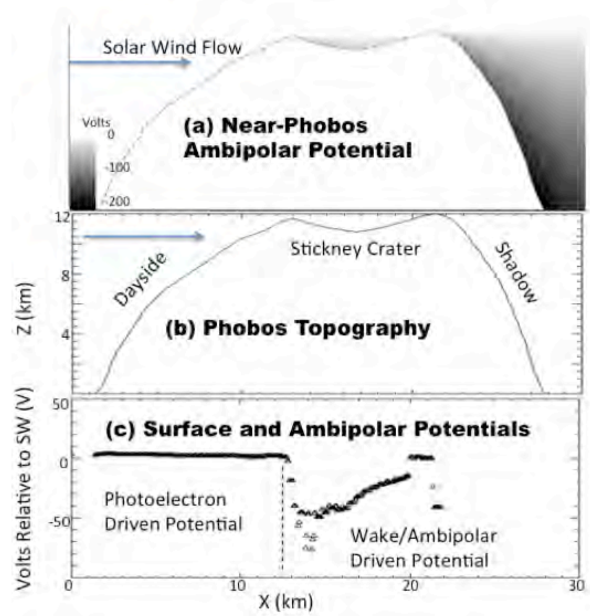


Figure 6. The electrostatic potential in the shadowed regions of Phobos (moon located at 10 hr LT in from of Mars)

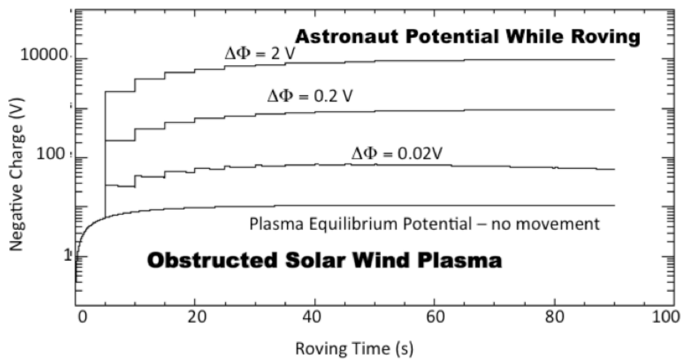


Figure 7. Astronaut charging vs time in shadowed region of Stickney Crater for various work function differences

will become charged in the solar wind (Figure 6), and this surface potential will intensify during a passing solar storm, especially in shadowed regions of the moon. An astronaut in a shadowed region (like Stickney Crater when Phobos is on the Martian dayside) will also charge strongly negative as they rove due to regolith-boot contact electrification effects which have been modeled by DREAM2 team members. The intensity of boot charging depends strongly on the difference in work function between materials in contact (see Figure 7, with largest potentials associated with largest material work function differences).

The results from this astronaut electrostatics modeling were then fed to a separate model (by C. Hartzell) of astronaut glove/dust interactions to determine the forces involved in causing a dust grain to stick to an astronaut space suit. The results therein indicate that dust cohesion is the strongest force acting on grains less than 3 mm in radius. The forces are even greater than electrostatic forces for a charged astronaut at ~10 kV.

A unique study performed in this analysis was to determine the acceleration and frequency of astronaut motion to 'shake off' dust grains adhered to a glove. We can think of this analysis as 'first contact' with the regolith. It was found that the ability to shake grains off an astronaut glove is a strong function of grain size, with those grains above 1 mm being easily shaken off with an arm motion of ~1 Hz. However, grains smaller than 0.1 mm cannot be easily shaken off, even for arm motion as fast as 10 Hz, since the inertial force applied cannot offset the grain-to-glove cohesive forces.

The solar wind also has another interesting effect at Phobos: to possibly sputter neutrals from the surface, which then form a low density neutral gas torus that encircles about Mars at 2.76 Mars radii. Figure 8, from Poppe et al. (2016) shows a model result of the iron atom torus forming along the Phobos orbit. The iron atoms are released from the moon via the energy imparted by solar wind and Martian tail plasma. Such DREAM2 models of the near-Phobos neutral and plasma environment have been used for prediction purposes in support of MAVEN.

Summary

DREAM2 had another successful year. At any given instant, there are nearly 30 ongoing activities, many using more than 24 models, 8 data sets and 4 labs at DREAM2's access. However, the strength of such a center is the ability to organize members and their assets into larger intramural efforts that go well beyond efforts that are possible via tactical awards—like was done for the systematic study of the space environment at Phobos. Entirely new findings regarding moon charging, hydroxylation, impact gardening, radiation environment have been discovered during the DREAM2 intramural activity, leading to a set of new papers to be released shortly.

In the next program year, we anticipate performing

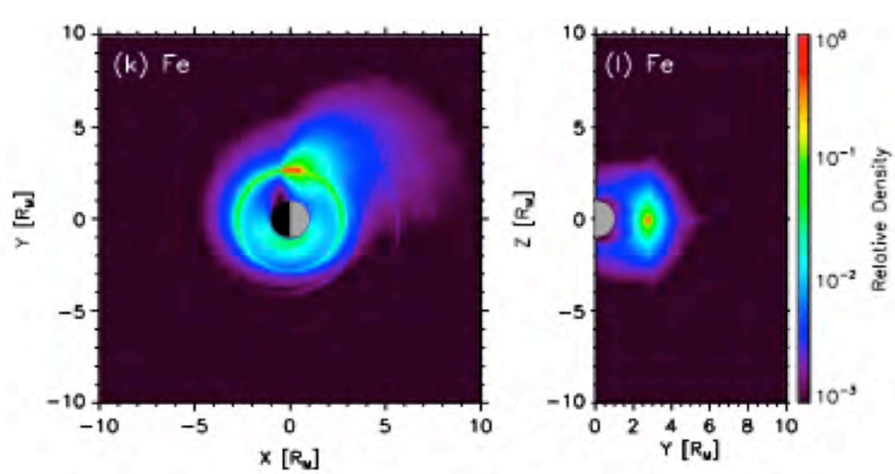


Figure 8. Model of Phobos sputter-created neutral iron torus surrounding Mars (Poppe et al., 2016). The left panel shows a top view and the right panel a side cut-away view.

organized environmental studies of the locations being considered for the Resource Prospector traversals—providing critical science support for that HEOMD effort.

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:

VORTICES: Strong collaborating work on solar wind/body interactions, volatile interactions, and Orion/asteroid interactions and lunar pits. Strongest collaborations with individuals Zimmerman, Hurley, Orlando, 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. Work with RISE4 team to pursue opportunities to architect, design and build future exploration-oriented field instrumentation for astronaut use.

IMPACT: PIs Hornayi and Farrell co-lead the SSERVI Dust and Atmosphere Focus Group. 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 working with IMPACT modelers on magnetic anomaly studies.

FINESSE: We share co-Is in Colaprete and Elphic, who under FINESSE perform field studies for their Resource Prospector mission, while DREAM2 provides support with modeling studies on wheel-regolith interactions and volatile transport modeling.

CLSE: DREAM2 exospheric modeler Hurley examined the possible evolution and deposition of the gas release from vent regions in Schrodinger crater—a target for a sample return mission designed by CLSE team members.

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.

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. DREAM2 UCB postdoc, Shahab Fatemi, was a student in Kiruna who was advised by Mats Holmstrom and now works with Poppe and Delory—all part of the exchange of talent between the Kiruna group and DREAM2. We continue to team with our Kiruna partners in our cubesat proposals, like the SIMPLEX HALO proposal lead by Collier.

UK: The DREAM2 team at UCB is interacting with Rosetta scientist Tom Nordheim on understanding the plasma interactions at a cometary body.

DREAM2 Public Engagement Report
Undergraduate Internship Program

Summer 2016 marked a third successful DREAM2 Undergraduate Internship Program. Team members at GSFC (R. Killen, M. Sarantos, M. Collier, T. Stubbs, R. Hudson, M. Loeffler) hosted five students, including one from DREAM2 partner, Howard University (see Section 4). 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.

Two students presented their research at the 2016 Exploration Science Forum. One student continued their DREAM2 research into the academic year. Two students plan to return to GSFC in summer 2017 for a second DREAM2 internship.

Feedback gleaned from a survey issued at the end of the internship indicated that 100% of the participants either agreed or strongly agreed that, as a result of their participation in a DREAM2 internship, they have a better understanding of the practice of science, a better understanding of the different types of NASA careers available to them, and are more interested in getting a job in science, technology, engineering, or math.

DREAM2 Explore Educator Professional Development Workshop

The DREAM2 Education and Public Engagement Team also led the second annual DREAM2Explore Educator Professional Development Workshop, which took place from July 11-15th, 2016. Twenty-one 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, D. Hurley, J. Cook, and J. Nuth. 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 Lunar Reconnaissance Orbiter Camera exhibit, A New Moon Rises, at the National Air and Space Museum.

A survey was issued at the workshop's conclusion to gauge its success. 100% of the participants agreed that they acquired activities that they will use with their students. 91% agreed that they feel confident in implementing the activities, and that they acquired a new understanding of planetary science and exploration that will be valuable when working 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." "This will literally change how I teach and what my students will learn!"

The DREAM2 team supported GSFC's annual International Observe the Moon Night event on October 8th. Over 374 members of the public attended.

Public Engagement

DREAM2 Student/Early Career Participation

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 herein.

GSFC 2016 Undergraduate Summer Interns funded by the DREAM2 E/PO budget

Anastasia Newheart, St. Marys (Mentor: Mike Collier)

Keenan Hunt-Stone, Howard Univ. (Mentor: Tim Stubbs)

Alexandra Cramer, College of William and Mary, (Mentor: Menelaos Sarantos)

Cassandra Hatcher, Oregon State (Mentor: Rosemary Killen)

Katarina Yocum, Kutztown University (Mentor: Reggie Hudson)

GSFC 2016 Year-around undergraduate interns from Howard University.

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 (Mentor: William Farrell/GSFC Code 695)

John Henry Clark (Mentor: John Cooper/GSFC Code 672)

Sirak Fessehaye (Mentor: Timothy Stubbs/GSFC Code 695)

Nikolas Rassoules (Mentor: Michael Collier/GSFC Code 695)

Zahraa Lopez (Mentor: Rosemary Killen/GSFC Code 695)

Graduate Students

Heidi Fuqua, UC Berkeley

Colin Joyce, U. New Hampshire

DREAM2 Post-Docs

Shahab Fatemi, UC Berkeley

Reka Winslow, U. New Hampshire

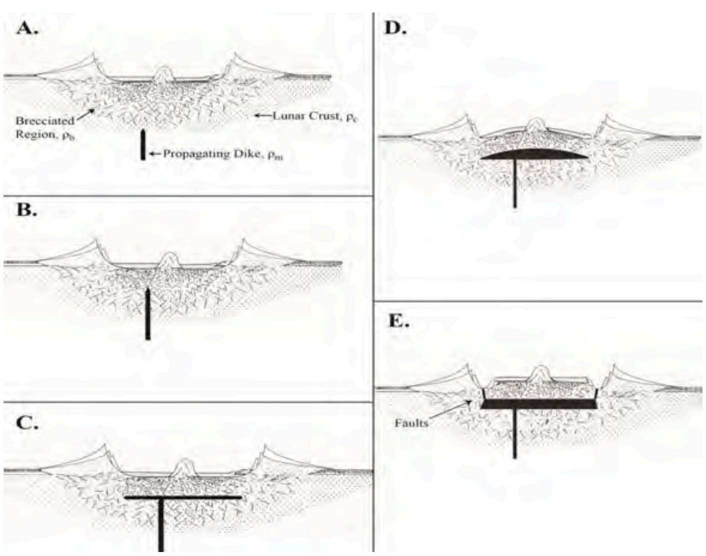
Carlé Pieters

Brown University, Providence, RI

SSERVI Evolution and Environment of Exploration Destinations (SEEED)

SEEED Projects and Activities

Our SSERVI Evolution and Environment of Exploration Destinations (SEEED) team is hosted by Brown University with major contributions from Co-Investigators at MIT and five other academic institutions. We partner with collaborators from another four institutions as well as seven foreign countries. Altogether, SEEED participants include 24 Co-Is and 19 Collaborators. This report covers the third year of SSERVI activities [January 2016 - January 2017]. We draw on the strength of ongoing and proposed research activities of a diverse and highly talented team coupled to a philosophy of strong mentoring of young scientists and engineers. Our principal objective is to create a virtual center of excellence focused on the science and environment of exploration targets. We pursue four Science and Exploration Themes (I – IV) in the context of four areas of Enabling Infrastructure (A – D).



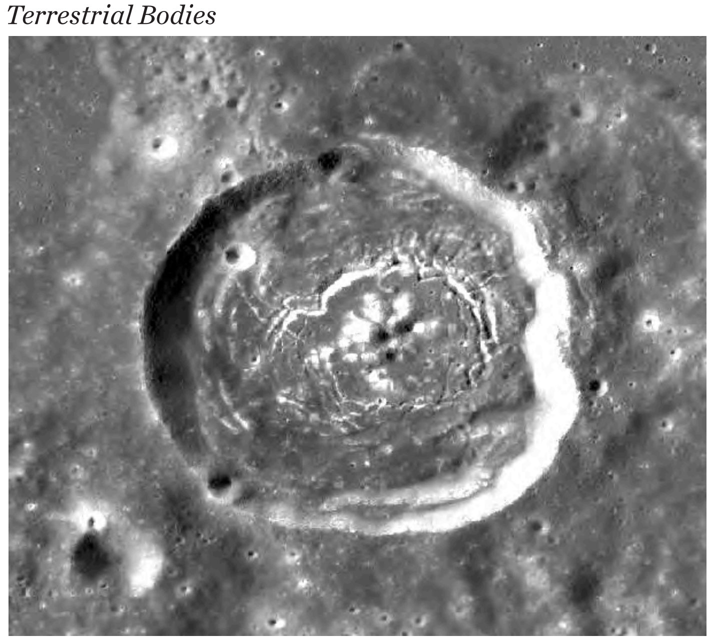
Examples of dike propagation, stall, sill or laccolith formation, uplift, ± volcanic vents that can be associated with an impact crater on a solid body.

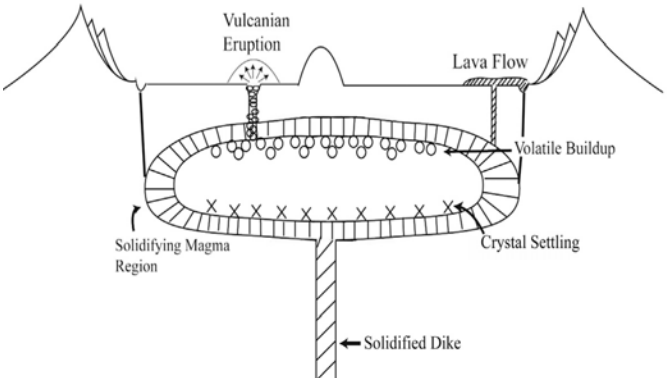
Ongoing SEEED Science and Exploration Themes:

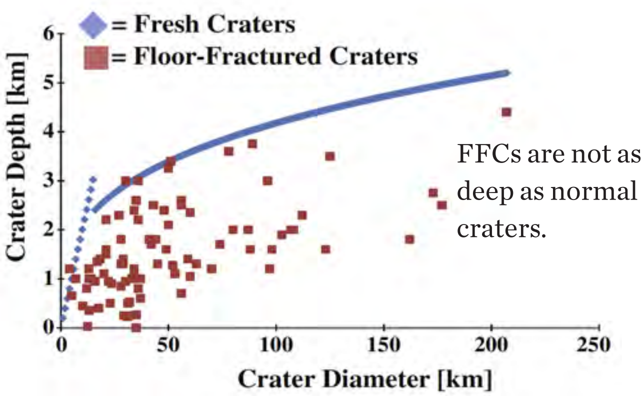
SEEED science and exploration activities encompass four integrated themes with several near- and long-term goals. The active research and academic environment at SEEED institutions along with world-class faculty and research facilities provide core strengths. Involvement with international partners is viewed as an integral and long-term component. This report highlights only a few examples of the accomplishments of the SEEED team during the third year of SSERVI support. These and a more complete summary of SEEED science and exploration products are found in the list of publications and on our SEEED website: http://www.planetary.brown.edu/html_pages/brown-mit_sservi.htm. An overview of the variety of SSERVI related activities performed by SEEED team members can also be found under "EVENTS".

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

Ia. Jozwiak, Lauren, 2016 PhD Thesis: *Shallow Magmatic Intrusions: Comparisons of Formation and Evolution on Terrestrial Bodies*

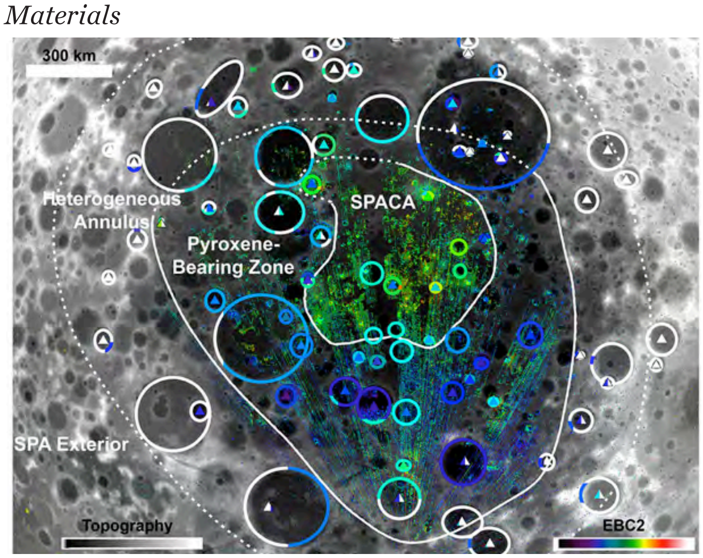






Floor-Fractured Craters (FFC) are found on most rocky bodies as well as rock-water worlds like Ceres. The morphology, location, and physical properties of FFC indicate they are the products of shallow magmatic intrusions. The locations of these features are strongly influenced by both the global tectonic state of the body and by the regional crustal and lithospheric structure.

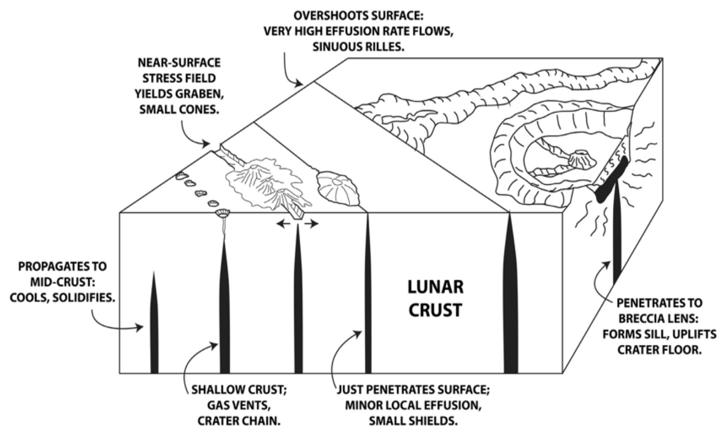
Ib. Moriarty III, Daniel P., 2016 PhD Thesis: *A Compositional Assessment of the Enormous South Pole-Aitken Basin Grounded in Laboratory Spectroscopy of Pyroxene-Bearing Materials*



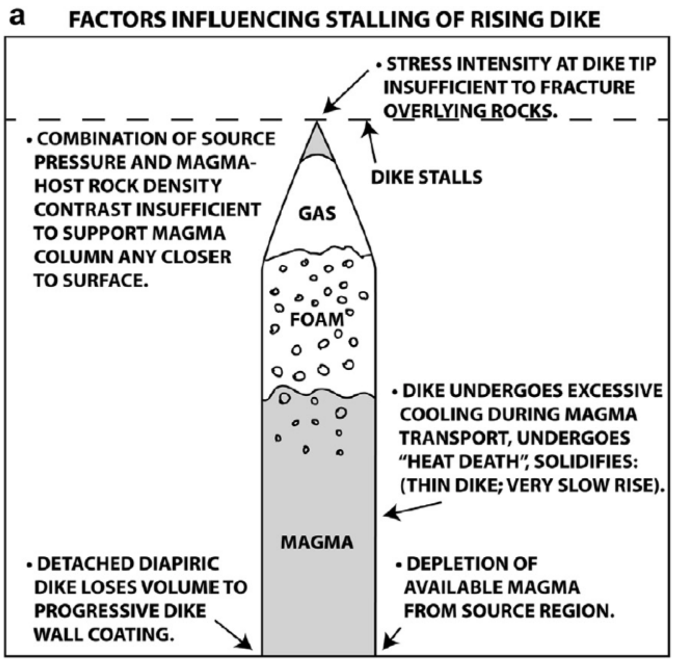
Ic. Head and Wilson (2017); Wilson and Head (2017): *The monumental Generation, ascent and eruption of magma on the Moon (1 & 2)* by the Head & Wilson team of SEEED has been years in the making and combines fundamental physics with geologic processes and observations of planetary surfaces. The physics is described with pages of equations such as

$$K_1 = (\pi\ L)^{1/2}\ [P_d - (g\ \Delta\rho\ L)/\pi\ ].$$

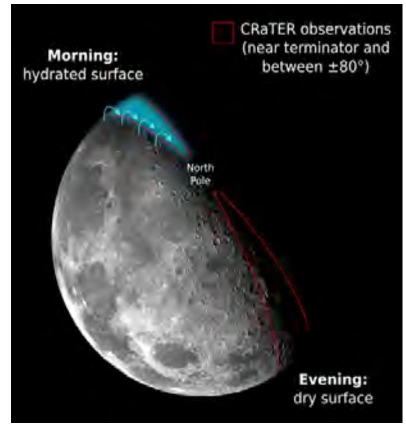
which is the stress intensity at the upper tip of a dike of magma rising to the surface, K_1. Each component is well integrated with observations of planetary surfaces and provides a basis for understanding and testing many physical processes common across the terrestrial planets.



It has long been recognized that the interior of the gigantic 2500 km South Pole-Aitken Basin (SPA) is enriched with iron-bearing materials. A careful mosaicking and analysis of Moon Mineralogy Mapper (M³) near-infrared spectroscopic data across the basin shows that the interior is pyroxene rich (with no trace of olivine), with a clear compositional zoning. Superimposed on a gray-scale image of topography, the distinct innermost compositional anomaly (SPACA) is enriched in Fe, Ca- pyroxenes (green) surrounded by an extensive zone dominated instead by Mg-rich pyroxene (blue). These mineral characterizations are grounded by modern laboratory analyses of pyroxene diagnostic properties. The unusual compositional signature of SPA reflects the evolution of the Moon's largest (and oldest) impact basin.



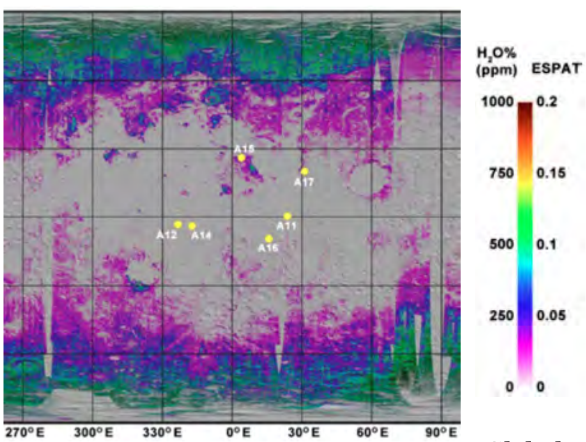
IIb. As a follow-on to Schwadron et al. (2016) Icarus, on-going cross-team analyses seek to evaluate whether diurnal OH/H2O variations are independently observed. It is found that strong enhancement of hydrogenation observed from proton radiation by CRaTER suggests ongoing day-night migration of hydrogenous species (see Schwadron et al., 2017 LPSC abstract). This important integration of diverse data to address a difficult issue continues to be under investigation.

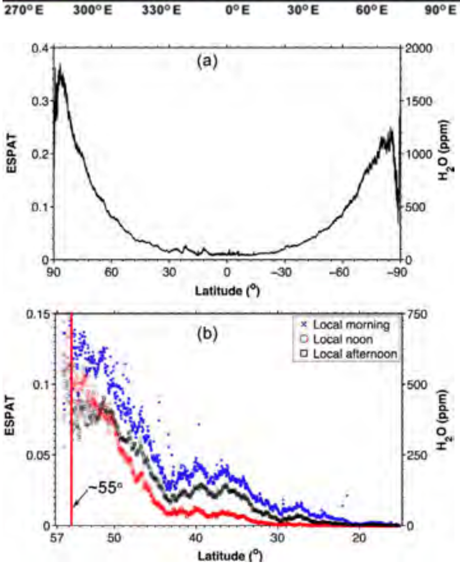


IIc. SEEED investigators were actively involved in the successful SSERVI 2016 Water Workshop and its follow-on. A SEEED Co-I has also instigated a Goldschmidt conference on the "origin, evolution and budget of volatiles in the terrestrial planets" to be held in Paris in 2017. [see Sections 1.C-c, d below]

II. Origin and Evolution of Volatiles in the Solar System

IIa. Li, Shuai, 2016 PhD Thesis: *Water on the Lunar Surface as Seen by the Moon Mineralogy Mapper: Distribution, Abundance, and Origins.*

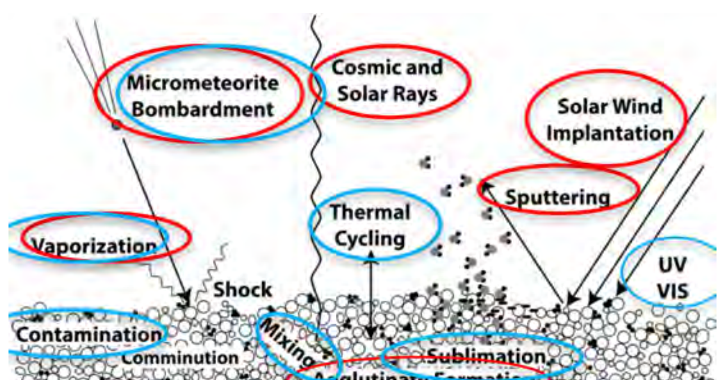




Global analyses of M^3 data, calibrated with a new thermal model, allowed the 3 μm OH/H2O feature to be re-examined. Several pyroclastic areas (yellow dots) are observed to be OH-rich. Latitude (black) and temporal (color) variations of OH are also suggested.

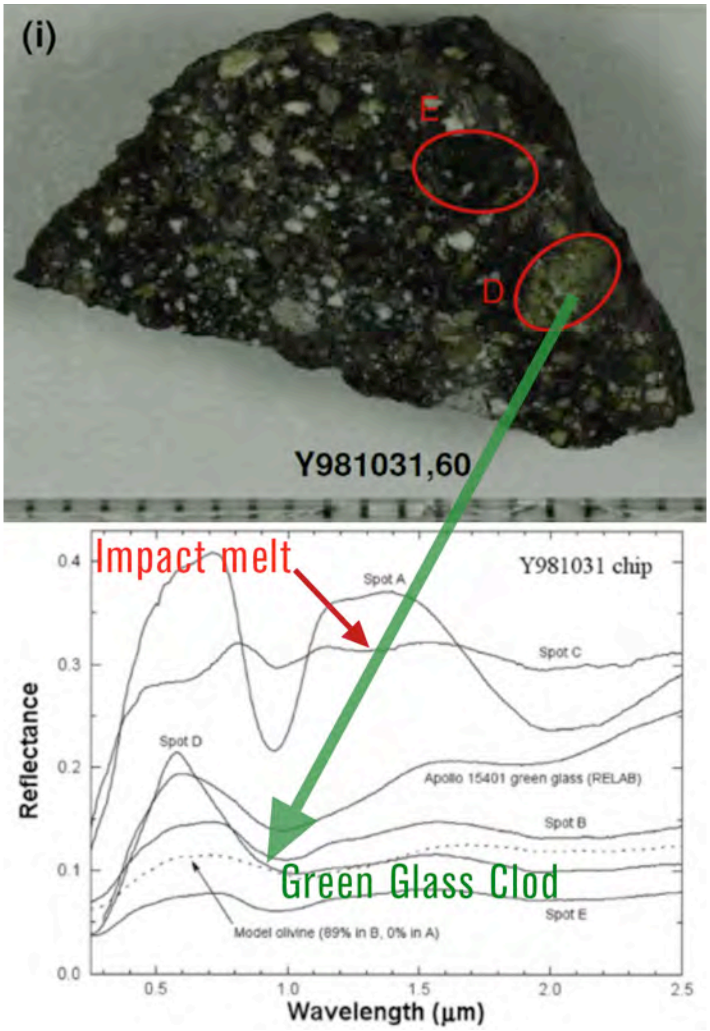
III. Regolith of Airless Bodies (& Space Weathering)

IIIa. Pieters, C. M., and S. K. Noble (2016), *Space weathering on airless bodies* [invited review JGR 25th Anniversary Issue]



Examples of the complex array of processes involved in space weathering of airless bodies. Dominant processes affecting the surface of the Moon at 1 AU are compared to those for the rock-water dwarf planet Ceres at 2.8 AU. Because the surface composition and environments are so different, the dominant processes involved are distinct and do not form the same types of space weathered products.

IIIb. Hiroi et al. (2016): On-going joint activities with Japanese collaborators surveying and analyzing the extensive Japanese collection of lunar meteorites has been highly productive. One example shown here [meteorite Y981031] demonstrates the utility of a visible-near-infrared spectrometer for valuable nondestructive in-situ lunar analyses. In this one lunar sample is found signatures of its complex volcanic and impact evolution.



IV. Science and Engineering Synergism

IVa. SEEED sponsored and led key sessions for Space Horizons, *International City on the Moon* at Brown Univ. (1.C-b & Section 2).

IVb. Pieters, C. M. (2016), *The inspiring 50++ years of lunar exploration* tracks the interplay between science, politics, and technology over 50 years. →

IVc. SEEED continues to actively work with MIT engineering on a course led by former astronaut Jeff Hoffman, addressing engineering constraints for human exploration.

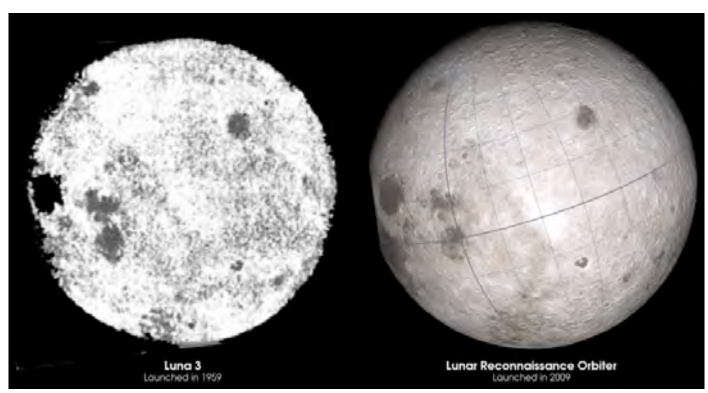
SEEED Enabling Infrastructure

The SEEED academic and research environment provides breadth and fertile ground for leveraging related research within and across teams with long-term NASA activities and goals.

A. Team experience interweaves university – NASA components.

a. SEEED PI and Co-Is provided key insight and experience for the development of several mission concepts involving small bodies, the Moon, Phobos, and Venus proposed to NASA's Discovery Program, including VERITAS and Psyche which were among the five selected for Phase A studies during 2016. ***Psyche*** (led by Co-I L. Elkins-Taunton as PI) is one of the two terrific small bodies missions recently selected for implementation. Co-Is Weiss and Zuber are leads for the Psyche Magnetometer Investigation and Radio Science, respectively. In addition, several experienced SEEED team members are involved with evaluating and planning the next NASA New Frontiers missions to be proposed this spring.

b. The expertise of SEEED PI and Co-Is has resulted in involvement with several internationally led missions to the Moon and small bodies. SEEED Co-I Weiss is a Co-I on a German magnetometer experiment (MasMag) onboard the small MASCOT lander of JAXA's Hayabusa2 mission. PI Pieters and Co-I Milliken are Co-Is on a pending proposal to map OH/H_2O at high lunar latitudes for the



Enhanced first image of the lunar far side from Luna 3 acquired in 1959. Shown for comparison is a comparable view derived from Lunar Reconnaissance Orbiter data obtained 50 years later.

Korean KPLO mission. Co-Is Hiroi and Milliken have independently been invited by JAXA to participate as team members for Hayabusa2 experiments. SEEED Deputy Head works collaboratively with Russian colleagues evaluating potential landing sites for Luna 25.

c. As can be seen in recent LPSC extended abstracts in Section 5, SEEED students and PostDocs continue to gain experience by being involved with planning and analysis of LRO data and integration with data from GRAIL and M3.

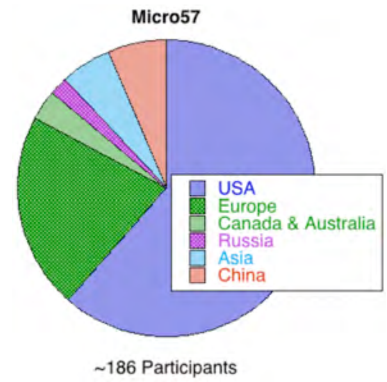
B. Team structure nurtures a new generation of leading scientists and engineers.

The academic environment at SEEED institutions involves direct interaction and mentoring of young scientists with experienced researchers. Several formal courses each year focus on SSERVI topics related to the character and evolution of small bodies and the Moon. In addition to mission involvement mentioned above in (A), SEEED students are encouraged to actively evaluate and think critically about near- and long-term mission issues for exploration and science. One such product is the student led assessment of "Are the moons of Mars in the critical pathway of human Martian exploration?" which stimulated lively discussion at the 2016 SSERVI ESF and later as an invited briefing at NASA HQ for a Technical Integration Forum. Another example is the Stanford-Brown iGEM (International Genetically Engineered Machines) team composed of talented students led by SEEED Colab. L. Rothschild in a hands-on successful competition to produce a balloon for planetary exploration and monitoring, which won an award in 2016 for synthetic biology.

C. International and community involvement is a long-term investment.

SEEED PI and Co-Is are committed to expanding communication and serious discussion about exploration destinations among all planetary scientists and engineers, including international partners. SEEED leads as well as co-sponsors activities that encourage and/or stimulate active communication. Examples are:

a. **Microsymposium57,** "Polar Volatiles on the Moon and Mercury," March 19-20, Houston: http://www.planetary.brown.edu/html_pages/micro57program.htm [SEEED instigated and implemented; informative and intense discussion; strong international participation – see figure on right].



b. **Space Horizons**, Brown Univ., "International City on the Moon," Feb 19-21, at Brown; program: http://www.spacehorizonsworkshop.com/schedules [SEEED co-sponsored; broad participation by industry, NASA, internationals].

c. **SSERVI Lunar Volatiles Workshop**, Nov 15-17, APL; Focused lively, informative, and probing discussion. Summary submitted to EOS. [SEEED PI worked on the planning/organizing committee; Co-Is involved as active participants, and student note-taker assisted greatly in documenting the discussion]

d. **Goldschmidt** session "origin, evolution and budget of volatiles in the terrestrial planets" to be held in Paris (August 13-15, 2017) [SEEED Co-I Saal is Co-Convener].

D. World-class facilities enable broad participation

The ***Reflectance Experiment Laboratory*** (RELAB) continues to serve the community very well by providing (at no cost to users) high quality visible, near-infrared, and mid-infrared spectroscopic data of planetary materials that are fundamentally relevant to NASA science and exploration missions as well as Research & Analysis programs. A separate publication list of research using RELAB data is found at: http://www.planetary.brown.edu/relabdocs/relab.htm.

The bi-directional spectrometer system was upgraded over the past year to allow an appreciable increase in instrument performance that is particularly important for measuring dark materials (e.g., carbonaceous chondrites). Science Manager R. Milliken has sought and received separate funds through the NASA PDART program to overhaul and modernize the RELAB database, including development of an online search tool. Leveraged with operational support through SSERVI, this new tool will increase the accessibility of the laboratory and visibility and utility of the data that are produced.

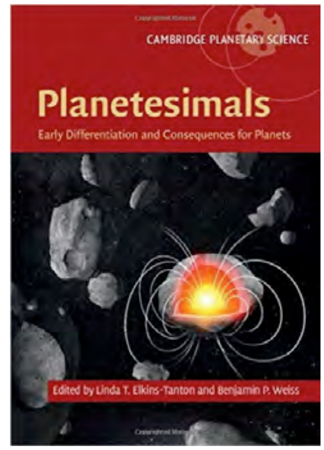
SEEED Inter-team Collaborations

As discussed in Section 1-C, SEEED maintains a long-term commitment to promoting diverse collaborations within the community at large, especially the international component, and across SSERVI teams. In addition to the SEEED activities discussed above, additional relevant information on collaborations is provided here.

Microsymposium57: 'Polar Volatiles on the Moon and Mercury"; Co-Is from 5 SSERVI teams and internationals made oral or poster presentations; for program see 1.C-a above.

Space Horizons: International City on the Moon; http://www.spacehorizonsworkshop.com/#2016 Hosted at Brown University. Lead participants from SSERVI SEEED and CLASS teams; strong international participation; for program see 1.C-b above.

Both the ***SSERVI Water Workshop*** (1.C-c) and **Goldschmidt Water Session** (1.C-d) include substantial SSERVI cross-team and international involvement.



Planetesimals, edited by SEEED Co-Is Elkins-Tanton and Weiss has just been published by Cambridge. This book brings together international experts to discuss processes governing the evolution of planetesimals. Included are topics critical to understanding how rocky planets are formed, how water is delivered to them, the origin of planetary atmospheres, how cores and magnetic dynamos develop, and which planets have the potential to be habitable.

Other Activities with International Partners

In addition to the above international aspects of SEEED activities and those summarized in Section 1 Infrastructure (A-b and C), we highlight several other specific contributions/activities:

Japanese Meteorite analyses have been led by SEEED Co-I Hiroi and involves several JAXA Collaborators. In addition to the peer-reviewed example above (1.III-b), ongoing joint work is summarized in two LPSC abstracts. Several **additional recent publications** have resulted from interactions with colleagues from Russia (Ivanov), India (Kumar), UK (Wilson, Donaldson Hanna). **ISAS-LPL workshop on Planetary Science Enabled by Epsilon Class Missions:** SEEED PI Pieters was invited by JAXA

At the US Embassy in Moscow

Students meeting Russian Scientists

Although SSERVI Site Visits are generally limited to SSERVI Executive Committee (PIs) and the host team, these interactions are stimulating and always develop understanding and productive interactions among SSERVI teams. In 2016 SEEED participated in the highly successful SSERVI site visits hosted by DREAM2 (Goddard) and VORTICES (APL).

to participate and provide a review and perspectives about proposed small missions.

China inroads: Following a visit by Brown President Paxton to academic institutions in China, SEEED Deputy Head was invited to visit in June and lecture at several Chinese Universities and Institutions (lectures supported by Brown Univ.). Two Chinese students (Guo and Qiao) are visiting Brown and participate and contribute substantially in classes and research activities. **EuroMoon:** SEEED PI Pieters was invited to participate in a ISSI (Bern) workshop on *Lunar Surface Composition and Processes* in early March. She also participated in a *Phobos Special Workshop* at the **Italian Embassy** in May. The 7th **International Solar System Symposium**, Moscow (7M-S3) held at IKI Oct 10-14. Information on the program and abstracts can be found at http://ms2016.cosmos.ru/ SEEED presentations included 7 oral and 8 poster. SEEED faculty and student delegation also participated in a **Luna 25 site selection** meeting. SEEED Co-I Head was invited to make a planetary perspective presentation at the **US Embassy in Moscow**.

SEEED Public Engagement (EPO) 2016 Example Highlights

Our EPE team led by C. Runyon has focused on three areas for promoting SSERVI content: 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. Activities have continued in all three areas. As described in Runyon (2016, LPSC #2241), we are committed to making lunar and planetary science accessible to the physically impaired. As an example to accomplishing this, the team has been working with an undergraduate student and a recent graduate who are blind. They develop, review, and test SSERVI-related curricula and activities. The recent publication of the tactile book, Getting a Feel for Eclipses, provides a guide to eclipses for the blind and includes tactile graphics of an illustration of the interaction and alignment of the Sun with the Moon and Earth. It has sparked great interest and the team has been invited to attend and present information at multiple local and international conferences and workshops. This guide is available through the SSERVI website. To access it go to: sservi.nasa.gov –> Public Engagement –> Books - *Getting a Feel for Eclipses*.

Encouraging talented women and any under-represented group to become seriously involved in NASA's science and

A draft of the tactile book, Getting a Feel for Eclipses, is shared with a blind resident of Micronesia during a February solar eclipse in Micronesia.

The SSERVI video conference system has enabled interactions with students who would otherwise have little access to cutting edge developments in planetary science. For example, SEEED Co-I Jim Head led a lecture and discussion with Pedro Munive (UNAM), and students at several Mexico high schools.

engineering activities is a constant endeavor. PI Pieters was invited to participate in a special symposium with such a focus held in conjunction with the 100th anniversary of the Optical Society of America and sponsored by Women in Science, Technology, Engineering and Entrepreneurship [WiSTEE] in Rochester, NY. This was a well-attended all day activity targeting women entering the field and highlighted the accomplishments of of 21 highly active and successful women scientists, engineers, and entrepreneurs across academia, the military, and private sector. The dynamics and excitement within and across such a group was astounding. Although such situations and concentrations are unfortunately rare, it was both inspiring to the younger participants as well as invigorating to all the more experienced scientists and engineers, renewing a strong commitment to living as mentors and leaders.

SEEED Student/Early Career Participants during 2016

*SSERVI cross-team origins or links

SEEED Graduate Students

1. **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.

2. **Caswell, Tess,** *Brown University*

   Evaluating the physical and rheological properties of ices in the solar system.

3. **Deutsch, Ariel***, *Brown University*

   Assessing the nature of polar and circumpolar ice deposits on the Moon and Mercury.

4. **Ermakov, Anton,** *MIT* (defended August 2016; Postdoc: JPL)

   Thesis: "Geophysical Investigation of Vesta, Ceres and the Moon Using Gravity and Topography Data."

5. **Farley, Chris,** *University of Tennessee*

   Assisted in analyzing lunar meteorites.

6. **Hahn, Tim,** *University of Tennessee*

   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 the largest pyroclastic deposit on the Moon, Cobra Head and Schroeter's Valley.

8. **Jozwiak, Lauren***, *Brown University* (defended Spring 2016; Postdoc: APL)

   Thesis: "Shallow Magmatic Intrusions: Comparisons of Formation and Evolution on Terrestrial Bodies."

9. **Kaplan, Hannah**, *Brown University* [through NAI]

   Performing detailed analyses of the spectral signature of organic bearing materials.

10. **Li, Shuai,** *Brown University* (defended Summer 2016; Postdoc 2017: University of Hawaii)

    Thesis: "Water on the Lunar Surface as Seen by the Moon Mineralogy Mapper: Distribution, Abundance, and Origins."

11. **Liu, Boda,** *Brown University*

    Developing a powerful statistical method [called Markov chain Monte Carlo, MCMC] for analysis of geochemical inverse problems related to trace element fractionation during partial melting and magma crystallization.

12. **Lunning, Nicole,** *University of Tennessee* (Postdoc: Smithsonian Museum)

    Analyzed HED meteorites and the evolution of their parent body.

13. **Martin, Audrey C.,** *University of Tennessee*

    Analyzed the petrology of HED meteorites.

14. **McCarty, Lauren,** *University of Tennessee*

    Analyzed the recent Novosibirsk meteorite.

15. **Moriarty, Daniel***, *Brown University* (defended Spring 2016; Postdoc 2017: Goddard)

    Thesis: "A Compositional Assessment of the Enormous South Pole - Aitken Basin Grounded in Laboratory Spectroscopy of Pyroxene-Bearing Materials."

16. **Phillips, Michael,** *University of Tennessee*

    Analyzed the petrology of a NWA howardite.

17. **Roberts, Sarah,** *University of Tennessee*

Analyzed the NWA 10986 meteorite from the lunar highlands.

18. **Tian, ZhenLiang,** *MIT* (defended September 2016)

Modeling orbital and thermal evolution of the Earth-Moon system.

19. **Weiss, David***, *Brown University*

Documenting the nature and characteristics of lunar graben.

20. **Wetteland, Chris J.**, *University of Tennessee*

Studying early nebula irradiation processes.

21. **Wiggins, Sean**, *Brown University*

Evaluating the development of the lunar megaregolith through impact fragmentation modeling.

SEEED Undergraduate Students

1. **Caves, L. R.**, *University of Tennessee*

Analyzing the petrology of HED meteorites.

2. **Eckley, S.**, *University of Tennessee*

Analyzing the petrology of HED meteorites.

3. **Fink, Sam**, *College of Charleston*

Assist with activities and questions from the public at EPE events.

4. **Gladden, T. J.**, *College of Charleston* (underserved)

Helps with accessibility; assists with background research, planning and content presentation at workshops and EPE events.

5. **Hoffer, Quincy**, *College of Charleston*

Assists with content presentation at workshops and EPE events.

6. **Pack, Natalie**, *College of Charleston* (Pre-service teacher)

Helped develop and test SSERVI content-related activities; obtained a position in middle school and is actively integrating curricula into her classroom.

7. **Turner, Ashley**, *College of Charleston*

Evaluates accessibility; assists with background research and content presentation at workshops and EPE events.

8. **Williams, Mariah**, *College of Charleston* (blind)

Addresses accessibility; assists with background research, planning and content presentation at workshops and EPE events.

SEEED Postdocs

1. **Potter, Ross***, *Brown University*

Modeling and evaluating the properties and effects of major lunar basins.

2. **Robertson, Kevin**, *Brown University*

Testing detailed models for characterizing mineral abundance from spectra of mineral mixtures.

3. **Sklute, E. C.***, *Mt. Holyoke College*

Deriving optical constants of mineral and mineral mixtures.

4. **Wang, H.**, *MIT*

Using magnetic measurements of meteorites to derive the lifetime in the solar nebula and hence the condensation history of the early solar system.

William Bottke

Southwest Research Institute, Boulder, CO

Institute for the Science of Exploration Targets (ISET)

Institute for the Science of Exploration Targets

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

The ISET team has deployed their novel accretion and fragmentation code LIPAD to study some fundamental aspects of the "classical" stages of planet growth. In particular the capability of these models to track growth from planetesimals to planets in a single simulation has allowed for an overdue study of how the dissipation of the solar nebula relates to the timing and nature of the onset of the final, giant impact, stage of growth. To this end, a manuscript "Terrestrial Planet Formation from an Annulus" by Walsh & Levison was published in the Astronomical Journal in 2016. This work examined the recent successes found by models of planet formation that start with (or by way of giant planet migration generate) a truncated disk of building block materials for growing terrestrial planets. The end-to-end modeling of planetesimal growth all the way to planets, in the presence of a slowly dissipating gaseous nebula, found a long quiescent period – between the growth of Mars-sized planetary embryos in a few Myr, and the onset of the giant impact stage of growth at 10-15 Myr. This delay amounts to a first generation of small, and closely packed planets, and the final generation of planets built from the remnants of the first.

A larger and more time consuming suite of simulations studied the entire inner disk of the solar system, focusing on the very basic stages of classical growth. This study rapidly evolved into a critical take on the state of the last decade of planet formation modeling – as it finds that the initial conditions typically used, where the same Oligarchic Growth stage is reached across the entire disk at the same time, is very flawed. Here, due to the interaction of collisional fragmentation and the continually evolving gas disk, growth is very inside-out and this condition is never met. A study of very wide interest was submitted to Nature Astronomy in December 2016 titled "Planetesimals to Planets—Revisiting Terrestrial Planet Formation." From this work we also contributed to a Science Advances publication related to timing constraints on giant planet formation and migration by way of the collisionally produced CB chondrite meteorite class (Johnson et al., Science Advances (2016) "Timing of the Formation and Migration of Giant Planets as Constrained by CB Chondrites"). These results have been presented in invited talks by Walsh at a JSPS meeting in Washington DC, a planet formation conference in France, at the Goldschmidt conference in Japan, and various colloquia in 2016.

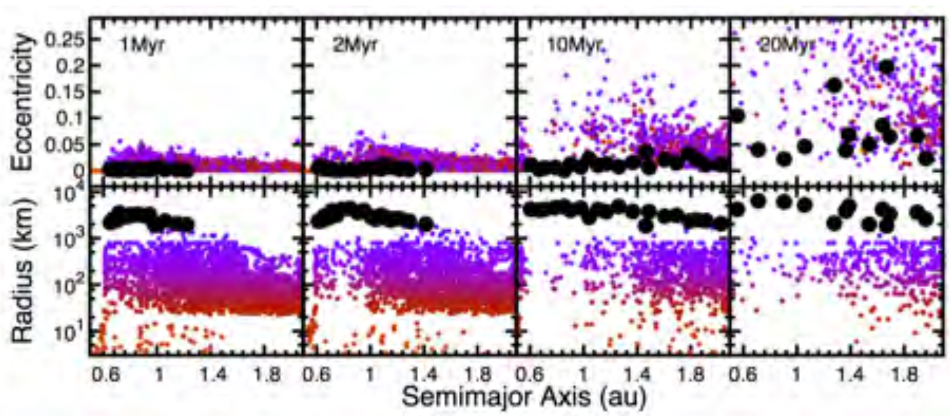


Figure 1: The evolution of the entire inner Solar System during "classical" growth from planetesimals to planets using LIPAD simulations (in review at Nature Astronomy). The growth of planetary embryos (black circles) proceeds in a very inside-out process, where a suite of quasi-stable Mars-mass embryos are formed inside 1au in 1 Myr, and not at 2 au until nearly 20 Myr.

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. As this is the first dynamically self-consistent model for forming the giant planets in our solar system we can, for the first time, investigate how the growth of giant planets will affect the rest of the solar system, particularly the asteroid belt. We have found that the growing giant planets will naturally scatter planetesimals from the region where the giant planets form (5-10 AU) into the modern day asteroid belt. Gas drag will circularize these bodies' orbits, detaching them from the giant planets. A substantial fraction of small bodies originally from the outer solar system are expected to be implanted into the asteroid belt region. Similarly, 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 has been carried out by SSERVI fellow K. Kretke, ISET members H. Levison and W. Bottke with contributions from CLSE member David Kring, and has been presented at DPS and at AGU with the paper in preparation.

Theme 2. Origin of the Moon, Phobos and Deimos

An impact origin for Phobos and Deimos

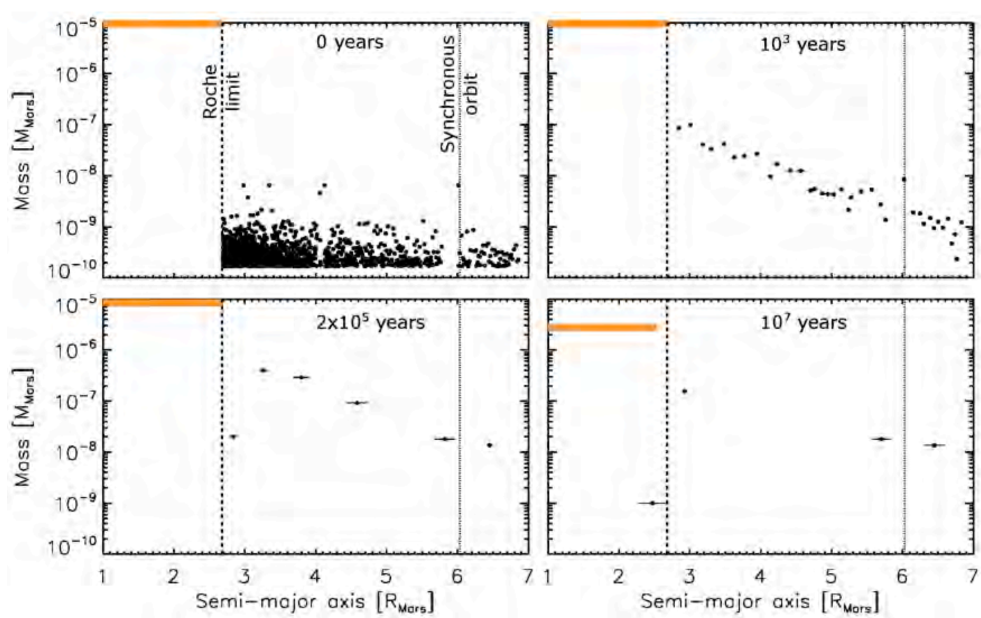


Figure 2: Snapshots of an accretion simulation. Bodies in the outer disk rapidly collide and grow into larger bodies. After ~10^5 years, only a few bodies remain, including two good phobos-Deimos analogs on each side of the synchronous orbit. Inner bodies tidally decay inward, such that only the Phobos and Deimos analogs would remain over long times.

Based on their spectra it has been suggested that Phobos and Deimos are captured asteroids, but intact capture of two bodies in planar and quasi-circular orbits appears unlikely. Such orbits would however be expected from formation from a circum-Mars disk. While Phobos orbits today at ~3 Mars radii (R_M), it has evolved inward significantly due to tides raised on Mars, such that 4 Gyrs ago it was likely just inside the synchronous orbit at ~5.5 R_M. Deimos has evolved little and formed near 6.5 R_M. A disk extending somewhat beyond the synchronous orbit appears to be required.

R. Canup and J. Salmon explored the formation of Phobos and Deimos as remnants from an impact-generated disk. They performed SPH simulations of impacts onto Mars, varying the impactor's mass, and the impact's angle and speed. They found that many impacts lead to the formation of a disk with an outer radius around 7 RM. Disk masses vary largely based on impact parameters, from 10^{-5} to 10^{-3} Mars masses (M_M).

They also studied the evolution of the impact-generated disk using a numerical model developed for the formation of the Moon (Salmon and Canup 2012). They modeled the material within the Roche limit (located at ~2.7R_M) by a continuous disk that spread viscously, and outer material by individual bodies whose orbits are tracked by the N-body integrator SyMBA. They performed a series of about 100 runs, varying the disk's mass, radial extent, as well as the strength of tidal dissipation into Mars. They found that:

- Large disk masses lead to the formation of massive moons that accumulate most of the mass around the synchronous orbit, preventing the survival of Phobos and Deimos analogs.

- For smaller disk masses, Phobos and Deimos analogs can survive. They found that strong tidal dissipation into Mars is required such that large moons inside the orbit of Phobos rapidly tidally decay toward Mars before they can perturb the region around the synchronous orbit and destabilize Phobos-Deimos analogs

Evolution of a protolunar disk in vapor/melt equilibrium

W. Ward has developed a model of the viscous evolution of a two-phase, vapor/melt protolunar disk. Droplets condense from the vapor and "rain-out," forming a stratified structure with a mid-plane magma layer surrounded by a vapor reservoir. The magma layer is gravitationally unstable, but material interior to the Roche distance cannot fragment, and instead develops an effective viscosity. However, magma flowing across the Roche limit can fragment and accrete into moonlets, while magma spreading inward is accreted by Earth. As mass leaves the melt layer, it is replenished by vapor condensation, leading to a quasi-steady state during which the vapor atmosphere steadily decreases. A ~2 lunar mass disk is expected to last for ~50 yrs.

Theme 3. Solar System Bombardment

S. Marchi has focused on expanding the application of his Mercury crater chronology with two major new applications. The first one deals with a revised age determination of the two youngest geological epochs, Mansurian and Kuiperian. Using novel crater counts based on MESSENGER imaging, we find that these epochs date ~1.7 and 0.28 Ga, respectively (Banks et al., submitted). These ages are significantly different than the traditional "assumption" of ~3.5 and 1 Ga (Spudis and Guest 1988). A second application has been crater dating of several lobate scarps associated with impact basins on Mercury. In a first work, we measured terrains associated with 8 basins, and the resulting ages span from 0.6 Ga to 3.7 Ga (Fegan et al., submitted). More recently, Marchi has dated ~20 newly mapped thrust systems on Mercury. A manuscript is in preparation (Giacomini et al.). These research efforts have been carried out in collaboration with several institutes, including Planetary Science Institute, Open University, and Padova University.

S. Marchi has been developing a new model for the early collisional history of the Moon and Mars. The new model builds upon the so-called lunar sawtooth bombardment model, previously developed in a major NLSI/SSERVI collaboration (Morbidelli, Marchi, Bottke, Kring et al., EPSL 2012). The new developments include a revised timeline for the accretion of lunar Highly Siderophile Elements (HSE) and dynamical evolution, which could imply the Moon suffered a much more intense bombardment than previously thought. The ensuing new Martian crater chronology provides the first detailed model of the earliest collisional evolution of Mars, and suggests that the Martian highlands may be significantly older (by 0.5^{-1} Gyr) than previous assumed. A paper has been submitted for publication (Morbidelli et al). This work is in collaboration with Observatoire de la Cote d'Azur and Arizona State University.

S. Marchi and R. Canup have developed, with the partial support of an exobiology grant, a new model to couple the early collisional evolution of the Earth with the accretion of HSE. Furthermore, in collaboration with R. Walker at U. Maryland (SEEED team), we have developed a new tungsten mixing model. The latter result, although preliminary, is very exciting as it provides the first unique opportunity to model terrestrial impact-driven isotopic signatures. Preliminary results have been submitted to LPSC (Canup et al., 2017), and a manuscript is in progress.

W. Bottke, D. Nesvorny, and J. Andrews-Hanna have been working on several issues related to the early bombardment of the Earth, Moon and Mars. First, Bottke and M. Norman (2017) wrote an extensive review of the Late Heavy Bombardment (LHB) for Annual Reviews of Earth and Planetary Science. M. Norman is a member of the CLSE team. In this summary and interpretation of current LHB knowledge, 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 (~3.5-4.0 Ga).

Similarly, in Bottke and Andrews-Hanna (2017), they used insights from numerical models, gravity analysis of Martian basins, and evidence from Martian samples to again argue for two phases of early Martian bombardment. The earliest component was defined by the formation of the gigantic 10,600 × 8,500 km Borealis basin responsible for Mars' north/south dichotomy, which they argue formed >4.5 Ga. The later component, starting near 4.0 Ga, was when 800 < D < 2200 km basins like Hellas, Isidis, and Argyre formed.

In between these times, Mars may have experienced a relative impact lull or "doldrums," an outcome consistent with many other data sets (Bottke and Norman 2017).

In Nesvorny et al. (2016), Vokrouhlicky, Bottke, and Nesvorny (2016) and Nesvorny, Roig, and Bottke (2017), our team examined how the Nice model affected the evolution of the asteroid belt. The Nice model is a family of solutions where the giant planets started in a different configuration, experienced a dynamical instability, and reached their final configuration via interactions with a sea of leftover comet-like planetesimals. The most successful version of this model assumes there were five planets between 5-20 AU: Jupiter, Saturn, Uranus, Neptune, and a Neptune-like body. The extra Neptune-like body was ejected via a Jupiter encounter but not before it helped populate stable niches with disk planetesimals across the solar system. In Vokrouhlicky et al. (2016), they showed this extra Neptune-like body directly interacted with the main belt for several tens of thousands of years, enough to help capture the right proportion of large P- and D-type asteroids in the inner, central, and outer main belt, while also populating the Hilda, Thule, and Trojan populations in Jupiter's 3/2, 4/3, and 1/1 resonances. In Nesvorny et al. (2016; 2017), they showed the Nice model could deplete the primordial asteroid belt of nearly a main belt's mass worth of small bodies while also reproducing the main belt's orbital constraints. Most depletion comes from the inner main belt (a < 2.5 AU); the central main belt is less depleted and the outer main belt is left largely in place. They found that Mars was hit by ~40 [×2, ÷2] D > 10 km bodies while the Moon received ~4. In the paper, they argued that if standard crater scaling laws are used, these values are too small to explain much early bombardment. However, if scaling laws are used that allow the size distribution of NEOs to match craters found on Venus, Mars, and the Moon over the last 3 Gyr, these values reproduce all Martian bombardment and possibly explain Nectarian-era and younger bombardment on the Moon (submitted for LPSC 2017).

M. Kirchoff, S. Robbins and C. Chapman have been working on updating crater analysis techniques. The 2015 Workshop on Issues in Crater Studies highlighted a strong need to update the ~40-year-old techniques still used to analyze crater distributions. Therefore, along with other experts and statisticians in crater studies, they have developed a new system for analyzing crater distributions that produces more robust results. A manuscript detailing the results of this effort is currently submitted to a special issue in Meteoritics and Planetary Science. S. Robbins started work on a global lunar crater database with the goal of a complete census of all impact craters as small as 1 km in diameter (D). Progress on the database was presented at LPSC, where many lunar researchers promoted the usefulness of the database. Currently, 1.8 million craters have been mapped over the entire lunar surface (1.2 million D ≥ 1 km).

Theme 4. Properties and Populations of NEAs

The CU team led by Dan Scheeres has continued its research on the effects and implications of weak cohesive bonds within primitive solar system bodies. This work was extended to cometary bodies this year in an analysis of the physical evolution of comet C-G/67P, target of the Rosetta mission, where they identify a new evolutionary cycle, constrain the strength of the comet, and provide interpretation of its physical morphology. Work also progressed in understanding the details of how thermal forces affect the rotational evolution of asteroids, with papers exploring the tangential YORP effect and the discovery of a new equilibrium state that can exist for

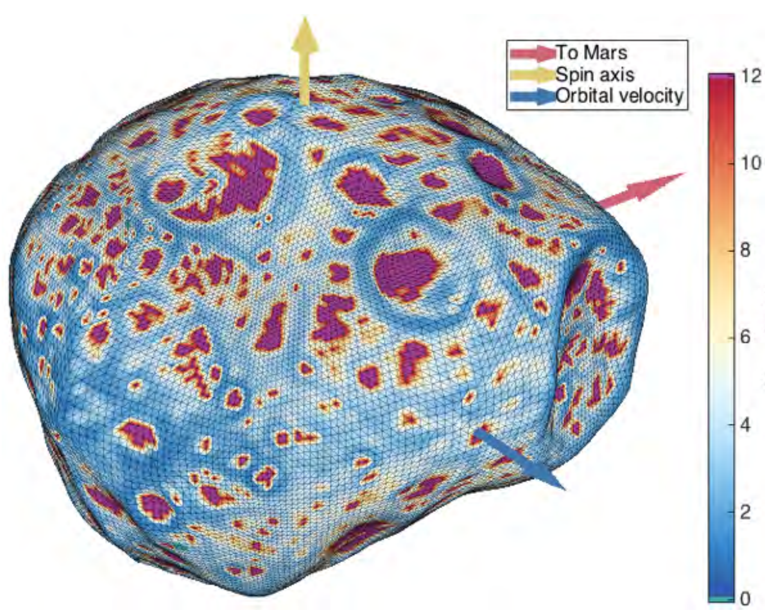


Figure 4: Minimum speeds for achieving orbital liftoff on the surface of Phobos

doubly-synchronous asteroid systems. Work was also continued on the motion of space vehicles and devices over the surface of an asteroid or over the surface of Phobos. This included experimental work to identify the rolling resistance of a sphere across a rocky surface such as regolith. Also, our study of the "speed limit" on a small body surface was continued, in hand with improvements in our simulation methodology. This work has involved support from Senior Research Scientist Paul Sanchez, post-docs Alex Golubov and Simon Tardivel, and graduate student Stefaan Van wal.

R. Jedicke obtained five nights of telescope time in the first half of 2016 on the 8-meter diameter Subaru telescope's Hyper Suprime-Cam (HSC) camera for a survey to detect meter-scale asteroids that are temporarily captured in the Earth-Moon system—minimoons. Four of the nights were under excellent sky conditions with sub-arcsecond seeing, and the fifth still had better seeing conditions than most other astronomical sites in the world. The ~5 TB of image data is currently being processed to identify asteroids. The processing pipeline was developed by a small team of collaborators at the University of Hawaii by combining components of existing image analysis software and the Pan-STARRS Moving Object Processing System. Our original intent was to implement real-time discovery software that would have allowed same-night follow-up of minimoon candidates with HSC but we were not able to do so. Instead, we modified our observing cadence to obtain long enough observational arcs to allow post-processing identification of the nearby minimoons. We estimate that the probability of discovering a minimoon in our survey is about 40%.

Working with Grigori Fedorets and Mikael Granvik we developed an improved model (Fedorets et al., 2016) of the orbital distribution of minimoons relative to the first work of Granvik et al. (2012). The new model begins with an improved orbit distribution for the NEO source population (Granvik et al., 2016), specifically corrects for the limiting behavior of the eccentricity and inclination distributions as they approach zero, and includes the population of objects that are gravitationally bound to Earth but do not make one full revolution about the geocenter (temporarily captured flybys, TCF). The first two issues reduce the expected population relative to the original Granvik et al. (2012) model but the incorporation of the TCFs results in an overall population that is consistent with the earlier estimate.

Finally, the Jedicke team performed a study to compare the asteroid diameter estimates derived from the Near Earth Asteroid Thermal Model (NEATM; Harris 1998) and Fast Rotating Model (FRM; Veeder et al. 1989). The former is generally the preferred method, and has been applied in most recent publications on asteroid diameter estimates, but our concern was that the model might not be appropriate for meter-scale asteroids. Our first step towards determining which model is best shows that NEATM performs better for phase angles of <60° while FRM is best for phase angles >70° (Mommert et al., 2017). Thus, some published diameter values for high phase angles may have large errors.

W. Bottke has been examining the historical properties of the NEO population using several different approaches. In Mazrouei et al. (2017), they used data from LRO's Diviner thermal radiometer to measure rock abundances (RA) on the Moon associated with craters < 1 Ga. An inverse relationship between rock abundance (RA) and crater age was found, and this has allow them to date 111 rocky lunar craters with D ≥ 10 km between 80°N and 80°S. They found the lunar impact flux has increased by 2.3 (-0.3, +0.7) over the past ~0.3 Ga; this means the impact flux is higher today than it has been for the last 1 Gyr. In Vokruhlicky et al. (2017), they examined whether the Flora family could be responsible for this increase. Formed from a catastrophic collision of a 150 km body, the LL-chondrite-like Flora family is located in the inner main belt; objects escaping there have high probabilities (1-2%) of striking the Earth. Using collisional and dynamical models to track the evolution of Flora family members, they found that (i) Flora formed ~1.4 Ga, (ii) it has 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. Finally, in Heck et al. (2017), they reconstructed the background meteorite flux that existed > 466 Myr from an analysis of relict minerals delivered by coarse micrometeorites. They found that the meteorite flux has varied over geological time, with achondrites having higher abundances in the past than the present day contribution from ordinary chondrites.

Inter-team Collaborations

Members of our team have been interacting with David Kring's team (CLSE), Carle Pieters' team (SEEED), Dan Britt's team (CLASS) on a wide range of topics related to the bombardment history of the Earth, Moon, asteroid belt, the origin of Phobos and Deimos, and the evolution/nature of near-Earth and main belt asteroids. We also have had scientific interactions with Mihaly Horanyi's team (IMPACT) and Andy Rivkin's team (VORTICES).

- David Kring (CLSE) and William Bottke are sharing SSERVI postdoc Katherine Kretke on a variety of projects related to linking dynamical models of planet formation with evidence from meteorite samples. Katherine 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 recently led to a breakthrough; she can now show that planetesimals from the Jupiter-formation zone can be implanted across the main asteroid belt via interactions with scattered Jupiter-zone protoplanets. This could potentially provide an alternative non-Grand Tack solution to the origin of many C-complex bodies, including Ceres. It may also lead to insights regarding the mysterious formation of chondrules in carbonaceous chondrites.
- William Bottke worked with Marc Norman (CLSE) on a comprehensive review of the late heavy bombardment for Annual Reviews of Earth and Planetary Science. We argue 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.
- Simone Marchi led a team of scientists that included William Bottke and Lindy Elkins-Tanton (SEEED) on how early terrestrial impacts may have strongly influenced the evolution of Earth's atmosphere and biosphere (i.e., massive release of carbon and sulfur gases). Their work was published in Earth and Planetary Science Letters.
- William Bottke and Simone Marchi are on the Science team for the new Psyche mission led by Lindy Elkins-Tanton (SEEED). It will investigate (16) Psyche, a possible exposed iron core residing in the main asteroid belt.
- William Bottke wrote a chapter for the new "Planetesimals: Early Differentiation and Consequences for Planets" book that was edited by L. Elkins-Tanton (SEEED) and B. Weiss (SEEED).
- William Bottke has been closely interacting with Dan Britt (CLASS), his graduate student Leos Pohl, and Dr. Marco Delbo (Obs. Nice) on calculations regarding how solar heating may have affected near-Earth object 2008 EV5's boulders using a suite of sophisticated dynamical, thermal and crack propagation models. Note that 2008 EV5 is a potential Asteroid Redirect Mission (ARM) target. Bottke and Britt are coordinating their efforts to be involved with the future ARM investigation team if that mission is funded.
- William Bottke has been involved with several on-going projects with Vishnu Reddy of the CLASS team. One such project led to the Icarus paper "Physical Characterization of 2-m Diameter Near-Earth Asteroid 2015 TC25: A Possible Boulder from E-type Asteroid (44) Nysa" in the last year.
- Robin Canup and William Bottke attended and served as discussion leaders for a workshop at APL on the subject of volatiles on the Moon, Mercury, and other bodies. Representatives from many teams (i.e., VORTICES, IMPACT, SEEED, CLSE, DREAM2, etc.) also participated in the three-day workshop.
- Simone Marchi and Robin Canup are working with R. Walker at U. Maryland (SEEED) to develop a new tungsten mixing model. This could provide us with the means to model terrestrial impact-driven isotopic signatures.
- Dan Scheeres has worked extensively with the ISET team to study the mechanics of cohesive asteroids and probe themes of motion on the surfaces of small bodies. This work has also been shared with the CLASS SSERVI team as part of Dan's contribution there as a team member.

- Scheeres and Sanchez (ISET) have had meetings to coordinate research activities with researchers from the Colorado School of Mines as part of the IMPACT SSERVI team.
- The ISET U. Colorado team led by Co-I D. Scheeres has on-going collaborations with the CLASS team led by Britt and with the IMPACT CU team led by Horanyi.

Public Engagement

Summer Science Program.

Kirchoff, Salmon, and Dones served as science lecturers for the Summer Science Program in New Mexico and Colorado in July 2016. This program offers SSERVI-rich participatory science experiences to 36 high-performing high-school students at each session in a continuing partnership with Summer Science Program, Inc. (SSPI). ISET members guided the students through using the numerical integrator Swift to integrate the orbits of their observed asteroids into the future. The students then analyzed and presented their results on the fate of their asteroid to their peers. We also provided scientific lectures to the students on asteroid populations and their dynamical evolutions, including chaos theory. Using feedback from the students, Kirchoff, Kretke, Salmon, and Dones worked on improving the oral lectures.

Helping Librarians and Camps Bring Science to Their Clients.

On April 5, Shupla and Kirchoff gave two webinars on the Explore! Marvel Moon module for librarians, camp and park program facilitators, and other out-of-school time educators, sponsored by ISET and the Lunar and Planetary Institute (LPI). Webinars were of different lengths and content, to provide flexibility in meeting participants' needs. Each included an introduction to the module and implementation discussion. The first included activities "What do you see in the Moon, Earth's Bright Neighbor, and Edible Rocks" (recording is at usra.adobeconnect.com/p6snfjxkcyi). The second included a science presentation by Kirchoff as well as the activities Infant Moon: Moon Mix, Kid Moon: Splat, Teen Moon: Moon Ooze, and Moon Mythbusters (recording is at usra.adobeconnect.com/p3w2yfaf8u8). Evaluations were conducted through online surveys; all (100%) of the attendees indicated they would recommend the webinars to colleagues, with 65% highly

recommending them. Evaluation comments were positive:

- "This was great. It was quick and to the point. It gave me ideas for programming that I can use. The materials are easily obtained and inexpensive. It also taught me great words like "fusion crust" :) Keep up the good work."
- "I love the ideas for programming with kids. I plan on using the pumpkin/grape/peppercorn to show scale at a program in the fall."

In 2016, LPI completed and posted a new ISET activity, Edible Rocks, related to meteorites, and updated the Explore Marvel Moon site with a cleaner look that is accessible to tablets and mobile devices: www.lpi.usra.edu/education/explore/marvelMoon.

On September 6-7, ISET collaborated with LPI and the OSIRIS-REx team to train 31 camp and park program facilitators from across the United States on solar system exploration, particularly related to solar system formation and evolution, asteroids, meteorites, and robotic exploration of the solar system. Kirchoff gave presentations on the current hypothesis on the formation of our solar system and the properties of asteroids. Shaner, Shupla, and Kirchoff led the training of select activities. Evaluation results were extremely positive. When surveyed, all (100%) of the participants felt confident or very confident in their ability to implement some of the activities and their plans to do so; over 87% of participants felt confident or very confident in their ability to implement all of the presented activities. Many attendees have already reported conducting presentations and activities in their communities related to the OSIRIS REx mission and to solar system exploration. Their comments indicated they valued the scientists' presentations:

- "Obviously any connection with scientists is important."
- (The scientists' presentations were valuable because) "they were women - STEM - as the father of a girl who loves science; it was great seeing females leading activities."
- "Learning directly about the mission science and processes will help me to explain it to others."

Sharing Results.

Six ISET scientists participated in the 2016 Denver Comic Con, including SSERVI-related science talks and Kirchoff and Kretke ran a "Superheroes on other planets" activity for elementary children.

Student/Early Career Participation

Senior Research Scientist Paul Sanchez: Dr. 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 SSERVI team.

Research Associate Oleksiy Golubov: Dr. 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.

Research Associate Masatoshi Hirabayashi: Dr. Hirabayashi was initially supported by the SSERVI grant to perform stress and failure analysis of asteroids using commercial and custom continuum mechanics models. He has subsequently taken a post-doc position with Dr. Jay Melosh at Purdue University. Over the last year Scheeres and Hirabayashi collaborated on applying their methods to the Rosetta comet C-G/67P.

Graduate Student Stefaan Van wal: Mr. 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.

Graduate Student Travis Gabriel: Mr 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.

Senior Research Scientist Kevin Walsh: Kevin's ongoing work on planet formation continues to garner invited talks (Primitive Material in the Solar System II in Nice, France, and the Science In Japan Forum in Washington DC) and colloquia (UC Santa Cruz, ELSI in Tokyo), all of which contributed to his promotion to Senior Research Scientist at SwRI and advancement in the field. The on-going series of publications about Terrestrial Planet formation will be presented widely—starting at the ACCRETE meeting in Nice, France in May 2017.

SSERVI Fellow Katherine Kretke: This year Dr. Kretke transitioned from being an ISET post-doc to a SSERVI Fellow, working with David Kring (PI of CLSE) as well as continuing to work with Bill Bottke and Hal Levison, to further develop the planet formation models published last year, applying cosmochemical constraints when available. She gave an invited presentation of her SSERVI work at AGU and has given invited talks at international workshops on planet formation in Germany, the Netherlands, and Japan, including an extended one month stay at the Max Plank Institute for Astronomy in Heidelberg, Germany.

Research Scientist Julien Salmon. Julien Salmon worked with Robin Canup on modeling the accretion of the Phobos and Deimos from a circum-Mars disk. Salmon was in charge of performing the accretion simulations using a code originally developed to study the formation of the Moon from the protolunar disk (Salmon and Canup, 2012). Salmon presented results at several conferences in 2016. Salmon gave a talk on Lunar origin in June as part of the SSERVI Seminar Speaker Series.

Graduate student Ben Boe. University of Hawaii Institute for Astronomy graduate student Ben Boe worked with Jedicke last summer (funded by this grant) on developing a pipeline to determine the minimoon detection efficiency in our Subaru minimoon survey. Ben used a synthetic population of minimoons provided by G. Fedorets to determine which objects would have appeared in our minimoon survey and then generated synthetic detections of these objects for processing through our pipeline.

Postdoc Alex Evans. Alex Evans joined our SSERVI team this spring, working with Jeff Andrews-Hanna. He received support to pursue his on-going work on the early bombardment of the Moon as interpreted using GRAIL data. Jeff and Alex have recently moved to the U. Arizona, but will continue to be part of our SSERVI team.

Daniel Britt

University of Central Florida, Orlando, FL

Center for Lunar and Asteroid Surface Science (CLASS)

Center for Lunar and Asteroid Surface Science (CLASS)

I. CLASS Team Projects:

CLASS Seminar: CLASS sponsors biweekly seminars that are broadcast over AdobeConnect featuring cutting-edge lunar and asteroid exploration science. These seminars have been very popular and in 2016 CLASS hosted a total of 14 speakers who accumulated a total of 816 views from 35 different countries.

CLASS Student Exchange: CLASS provides travel funding for student exchanges between CLASS investigators and for students to attend in-depth workshops lead by CLASS investigators to foster close collaboration between CLASS investigators and CLASS-sponsored students. CLASS supported three exchanges that included:

Peter Tutor: exchanged with Faith Vilas (PSI) and Susan Lederer (JSC) to work on hypervelocity impact experiments.

Wesley Chambers: exchanged with Javier Licandro (IAC, Spain) and attended the IAC's XXVIII Canary Islands 2016 Winter School devoted to solar system exploration.

CLASS Sponsorship of Workshops: CLASS is proactive in creating dynamic intellectual environments that allow the maximum interchange of ideas and approaches across interdisciplinary lines. We helped sponsor several workshops led by our CLASS Co-I's.

CLASS joined Team Members Julia de Leon Cruz and Javier Licandro to sponsor the XXVIII Instituto de Astrofísica de Canarias (IAC) Winter School of Astrophysics on "Solar System Exploration," November 7-16, 2016, Tenerife, Spain. CLASS researchers co-authored more than 10% of the papers and presentations at the conference (only NASA made a larger contribution) at the 15th Biennial ASCE Earth & Space Conference, arguably the world's premier conference on space mining and planetary construction.

CLASS strongly supported AOGS' "The Science of Exploration as Enabled by the Moon, Near Earth Asteroids and the Moons of Mars" Jul 31-Aug 5, Beijing. CLASS researchers gave two oral and five poster presentations. University of Central Florida (UCF) grad student Jenna Jones won best poster award.

CLASS Visiting Scientists: CLASS sponsors a series of visiting Scientists at UCF to foster a deeper collaboration and exchange between CLASS team members. These included Thom Orlando (Georgia Tech), Phil Bland (Curtin University), and Cyril Opiel (Boston College).

CLASS New Tenure-Track Faculty: As part of UCF's commitment to SSERVI and CLASS, two new tenure-track faculty were added: Dr. Adrienne Dove and Dr. Chris Bennett, who were hired as assistant professors in Physics at UCF in August 2015 and 2016, respectively.

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

STRATA 1: CLASS provides most of the science team and the hardware for this JSC ARES Group experiment now on the ISS.

CLASS provides the scientific leadership in partnership with Deep Space Industries to develop a family of asteroid simulants to support NASA exploration goals.

CLASS PI Dan Britt supports the NASA Moons of Mars Human Architecture Team (HAT).

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

CLASS partners with KSC Swampworks to provide scientific support for their ARM-related activities including boulder pull tests, asteroid simulations, radiation stopping power of asteroidal materials, and activities with regolith simulants.

Experiments at NASA-SWAMPWORKS using UCF asteroid regolith simulant. This was to determine the strength of an icy regolith

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

CLASS team members Britt, Campins, Abell, and Scheeres were named to the ARM FAST and supported its report development. Co-I's Durda, Dove, Metzger, and Opiel provided input and data for the FAST report. Opiel measured meteorite thermal properties to support the report.

CLASS is also conducting a range of research programs that will support HEOMD exploration priorities. These are listed below under the individual CLASS scientists.

CLASS Advanced Planetary Science Education: CLASS, SSERVI Central, and SEEED jointly sponsored an advanced graduate seminar on "Science and Exploration of Phobos and Deimos" lead by Dan Britt and Carle Pieters. RISE, VORTICES, ISET, and IMPACT teams also participated.

CLASS Science:

- Dr. Dan Britt (CLASS PI): Dan was named to the ARM FAST and New Horizons science team. On-going research includes: (1) Space weathering products of volatile-rich asteroids; (2) The potential of using asteroidal material for radiation shielding; (3) Measurement of the density and porosity of meteorites; (4) Development and production of simulants for asteroid regoliths, and (5) the ISS Strata-1 experiment.
- Dr. Humberto Campins: Since our last report, we produced five refereed publications and six conference presentations; one has been submitted for publication and two more are in preparation. We have carried out, reduced and analyzed observations from four observatories, NASA's Spitzer Space Telescope and three ground based telescopes.
- Dr. Peter Brown: Currently we are: 1) measuring the flux and pre-impact orbits for meteoroids and meteorites, 2) identifying asteroid and comet parents, particularly those in the late stages of their active-life with individual meteoroid streams/meteorites, and 3) measuring meteoroid physical properties (grain sizes, strength and bulk density) through meteor ablation behavior and correlating their orbits with either comet or asteroid population reservoirs.
- Dr. Josh Colwell: We have carried out a broad experimental program to understand the behavior of asteroid regolith in microgravity conditions, appropriate for asteroids smaller than ~10 km in diameter. We flew the Collisions Into Dust Experiment-3 (COLLIDE-3) on the private New Shepard (Blue Origin) suborbital launch vehicle, observed collisions at 20-30 cm/s into simulated Martian regolith and quartz sand, and performed low temperature studies (130K).
- Drs. Guy Consolmagno and Bob Macke: Dr. Guy Consolmagno is now the director of the Vatican Observatory. Macke continued work on the density and porosity of lunar and Martian materials to aid interpretation of gravity data of the crust of the Moon and Mars. Macke has measured ordinary chondrite heat capacities and modeling of OC heat capacities based on mineral composition.
- Dr. Adrianne Dove: Lead the development of the hardware for the Strata-1 experiment chambers now flying on ISS. Continued work on the SurfSat CubeSat; part of this development includes studies in a plasma chamber at UCF reproducing a variety of plasma environments and will be used to explore spacecraft charging in other environments, and charging of regolith surfaces.
- Dr. Dan Durda: Launched Box-of-Rocks Experiment (BORE) as part of Josh Colwell's MEDEA payload on a suborbital flight launched by Blue Origin's New Shepard rocket on April 2nd.

- Dr. Chris Herd: With PhD student Danielle Simkus, we are 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.
- Dr. Javier Licandro: Analyzed spectroscopic and rotational properties of asteroids in cometary orbits determined using spectroscopic and photometric observations. Developed the Primitive Asteroid Spectroscopic Survey (PRIMASS) to obtain visible and spectroscopic data of primitive families that can produce primitive NEAs.
- Dr. Rob Mueller: The Granular Mechanics and Regolith Operations Laboratory (GMRO Lab) at NASA Kennedy Space Center (KSC) interacted extensively with UCF-CLASS in 2016 to produce 24 kilograms of a carbonaceous chondrite type of asteroid simulant at KSC. This asteroid simulant was based on the known composition of the Orgueil meteorite.
- Dr. Marco Delbo: Continues spectroscopic observations of asteroids with team members Licandro and Campins to obtain mineralogical parameters for asteroid thermal modeling. He is responsible for the Gaia asteroid catalog; the Gaia mission (ESA) will survey the entire sky with a limiting magnitude of about 20, observing ~400,000 asteroids.
- Drs. Tom and Ashley Kehoe: Through detailed dynamical modeling of the structure of a young, still forming, zodiacal dust band, we have shown that such partial dust bands retain significant information about both the size-frequency distribution and cross-sectional area of dust released.
- Dr. Cyril Opeil: Meteoritic investigations focused primarily on CM2 carbonaceous chondrites (Murray, Cold Bokkeveld, etc.) and their majority constituent mineral species (e.g. olivine, diopside). From the heat capacity and thermal conductivity data, thermal diffusivity and thermal inertia were determined. Preliminary analysis of thermal diffusivity indicates volumetric contraction due to abundant hydrous phyllosilicates is present in the meteorite matrix and could have implications to weathering processes on CM parent bodies.
- Dr. Yan Fernandez: Ms. Jenna Crowell is investigating surface properties of S-complex near-Earth asteroids (NEAs), with the goal of understanding the complexity and heterogeneity of NEA surfaces. She presented some of her results at an international conference in Beijing in summer 2016, and was a winner of the Best Student Poster Competition in the planetary science. Mr. Charles Schambeau is studying compositional changes in the surface and subsurface layers of active comets to understand what structure a small-body needs to maintain an icy interior.
- Dr. Phil Metzger: Supported the Resource Prospector (RP) mission: 1) participated as a panelist on the Rover Tiger Team review (JSC); 2) established the mission environmental requirements to address issues likely to be encountered with the lunar soil; 3) performed experiments on how thermal cycling affects soil compaction; 4) these results have been compared to Lunar Reconnaissance Orbiter (LRO) Diviner instrument's measurements (the Diviner data suggest the polar soil is much looser than equatorial soil), and 5) Metzger is helping the NASA Kennedy Space Center perform geotechnical tests using the RP rover wheel as a probe of soil mechanics.
- Dr. Dan Scheeres: 1) The global evolution and dynamics of rubble pile asteroids as they interact and dissipate energy. This resulted in several presentations and publications; 2) Developing models and simulations for the interaction of rigid bodies with a regolith covered surface, and 3) Supported simulation work for the STRATA experiment currently flying on the space station.
- Dr. Patrick Schelling: Two physics PhD students, Abrar Quadery and W. C. Tucker worked on the application of atomic-scale modeling techniques to understand the dissipative and adhesive properties of mineral grains. We model how the addition of surface OH groups to SiO_2 grains affects grain collisions. Preliminary results show conclusively that the bonds formed between the colliding mineral grains, and the interactions responsible for energy dissipation, include the formation of new chemical bonds.
- Dr. Larry Taylor: up-graded the model used by

Starukhina and Shkuratov (2000) with which they stated that the neutron-measurement of hydrogen could be explained entirely by implantation of solar-wind protons.

- Dr. Faith Vilas:_Vilas pursued research with Amanda Hendrix into the spectral effects of space weathering in the UV/blue spectral region for the C-complex asteroids. 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.
- Dr. Chris Bennett: Is constructing a chamber to study space weathering processes.

Inter-team Collaborations

With the Institute for the Science of Exploration Targets (ISET): Thermal Evolution of ARM Targets.

CLASS and ISET are working together to support ARM by investigating the surface thermal evolution of the ARM target 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.

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT): Regolith Processes on Volatile-Rich Small Bodies.

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.

Remote, In-Situ and Synchrotron Studies for Science and Exploration (RIS4E): Shielding Potential of Asteroidal Materials.

RIS4E and CLASS are discussing joint projects and research on the use of asteroidal materials, particularly volatile-rich carbonaceous chondrites for shielding that reduces crew health hazards in long-duration spaceflight.

Center for Lunar Science and Exploration (CLSE): Radar Observations of Asteroids.

CLASS and CLSE are working on an education module to explain the differences between actual pictures and radar "images" of asteroids. Too often even well-trained scientists make the mistake of thinking that radar imaging of an asteroid (which is becoming more frequent) is the same as a picture.

Evolution and Environment of Exploration Destinations: Science and Engineering Synergism (SEEED): Joint Seminar, Joint EPO Activities.

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 node could do on their own.

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

Fernandez is a Collaborator with the VORTICES team.

Australian Planetary Research (APR):

Co-I Brown has an ongoing collaboration with P. Bland in related to his fireball network. CLASS is sponsoring a student exchange with APR for their Australian winter meteorite recovery campaign.

CLASS EPO Report (led by Co-I Cass Runyon)

Throughout the third year of the SSERVI grant, the SEEED and CLASS SSERVI Education Public Engagement (EPE) team was actively engaged in training pre-service and in-service educators from both formal and informal institutions across the country, working with students and engaging the public on SSERVI-related topics, particularly those being focused on by CLASS and SEEED.

Our EPE team is focusing on three areas using SSERVI content: 1) infusing arts into traditional science, technology, engineering and mathematics (STEM) lessons; 2) integrating formal, informal and out-of-school

Event / Activity	Date	Location	# participants	Grades	Underserved*
Charleston STEM Festival	02.06 .2016	Charleston, SC	7500	Public	Yes
Educator Professional Development – small bodies in solar system	02.06.2016	Charleston, SC	30	2 – 12	Yes
Darwin Week	02.08-12.2016	Charleston, SC	600+	Public	Yes
Cougars Basketball STEM Day	02.19.2015	Charleston, SC	1600	4 – 8	Yes
Space Science: Exploring scale and small bodies	03.08.2016	Berkeley County, SC	20	4 – 8	Yes
SC Math Coordinators Workshop	05.06.2016	Columbia, SC	120	K-14	No
SC Science Coordinators Workshop	05.13.2016	Columbia, SC	60	K-14	No
Educator Professional Development – small bodies in solar system	06.01.2016	Dorchester County, SC	30	2 – 12	Yes
Space Science for Teachers Course – hybrid course for pre- and in-service	07.05-08.10.2016	Charleston, SC + online	14	6 - 14	Yes
Camp Happy Days	07.06.2016	Summerton, SC	200 campers	4 – 16	Yes
Science Day at Charleston Battery	09.24.16	Daniel Island, SC	4000+	Public	Yes
Noche de Ciencias	10.15.2016	Berkeley County, SC	400	Public	Yes
SC Science Council	11.03-04.2016	Columbia, SC	300	K-14 informal	Yes
Educator Professional Development Workshop	12.09.2016	St. Louis, MO	35	4 – 12, informal	Yes
NASA Mission Design Course	Fall / Spring 2016	Charleston, SC & Huntsville, AL	120	UG	Yes
Geology of the Moon - Online course for in-service teachers around globe	Fall 2016	10 states + military	14	4 - 16	Yes
CLASS Seminars - hosted WebEx presentations on SSERVI science efforts	Jan – Dec, 2016	Orlando, FL and WebEx	40+	Science Team and public	Yes

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,"

A Tribal Chief (who is blind) 'seeing' an eclipse for the first time!

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.

The OSIRIS-Rex launch was an occasion for a number of planetary scientists to visit CLASS and UCF.

Experiments at NASA-SWAMPWORKS using UCF asteroid regolith simulant. This was to determine the strength of an icy regolith.

COLLIDE team with the New Shepard crew capsule and propulsion module (background) post-flight of the COLLIDE experiment in April 2016. L-R: Julie Brisset, Will Santos, Alexandra Yates, Josh Colwell. Image: Blue Origin.

Undergraduate students, graduate students, postdoctoral fellows:

CLASS had a major influence with 40 undergraduate students, 26 graduate students, 1 visiting scholar, and 1 internship (78 total). Only a partial list is presented here:

Peter Tutor, San Jacinto Junior College, completed a SSERVI CLASS internship at NASA's Johnson Space Center

Abhishek Agrawal, visiting scholar from Delft University, simulations of regolith ejecta launched from the surface of an asteroid.

Sean Wiggins, UCF undergraduate, asteroid regolith simulants

Cody Shultz, UCF undergraduate, asteroid regolith simulants

Z. Landsman, UCF graduate, asteroid Observations

Caroline Gi, Western U, graduate, Modelling bolide infrasound production

Quanzhi Ye, Western U, graduate, Radar detection of meteor streams (completed PhD Aug, 2016)

Abedin Abedin, Western U, graduate, Meteoroid stream modeling (completed PhD Sep, 2016)

Denis Hynen, Western U, undergrad, VLF radiation from meteors

Michael Molliconi, Western U, undergrad, Specular radar and optical simultaneous measurements

William Tucker, UCF graduate, experimental studies of space weathering

Abrar Quadery, UCF graduate, developing variable-charge model to model defect

V. Ali-Lagoa UCF, postdoc, asteroid observations

J. de León, UCF postdoc, asteroid observations

C. Hawley, UCF undergraduate, observation data reduction

C. Lantz, UCF graduate, asteroid observations

D. Morate, UCF graduate, asteroid observations

S. Schreck, UCF undergraduate, asteroid observations

R. Sheikh, UCF undergraduate, asteroid observations

Merritt Robbins, UCF undergraduate, Center for

Microgravity Research labs and Strata

Akbar Whizin, UCF graduate, Center for Microgravity Research labs

Leos Pohl, UCF Graduate, thermal evolution of NEAs

Kristen Brightwell, UCF undergraduate, Center for Microgravity Research labs and Strata

Will Santos, UCF undergraduate, Center for Microgravity Research labs and Strata

Jeffrey Jorges, UCF undergraduate, Center for Microgravity Research labs and Strata

Alexandra Yates UCF undergraduate, Center for Microgravity Research labs and Strata

Meghan Keough, UCF undergraduate, Center for Microgravity Research labs and Strata

Trisha Joseph, UCF undergraduate, Center for Microgravity Research labs and Strata

Mariana Mendonca, UCF undergraduate, Center for Microgravity Research labs and Strata

Seamus Anderson, UCF undergraduate, Center for Microgravity Research labs and Strata

Tom Miletich, UCF undergraduate, Center for Microgravity Research labs and Strata

Emily D'Elia, UCF undergraduate, Center for Microgravity Research labs and Strata

Michael Fraser, UCF undergraduate, Center for Microgravity Research labs and Strata

Sumayya Abukhalil, UCF undergraduate, Center for Microgravity Research labs and Strata

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.

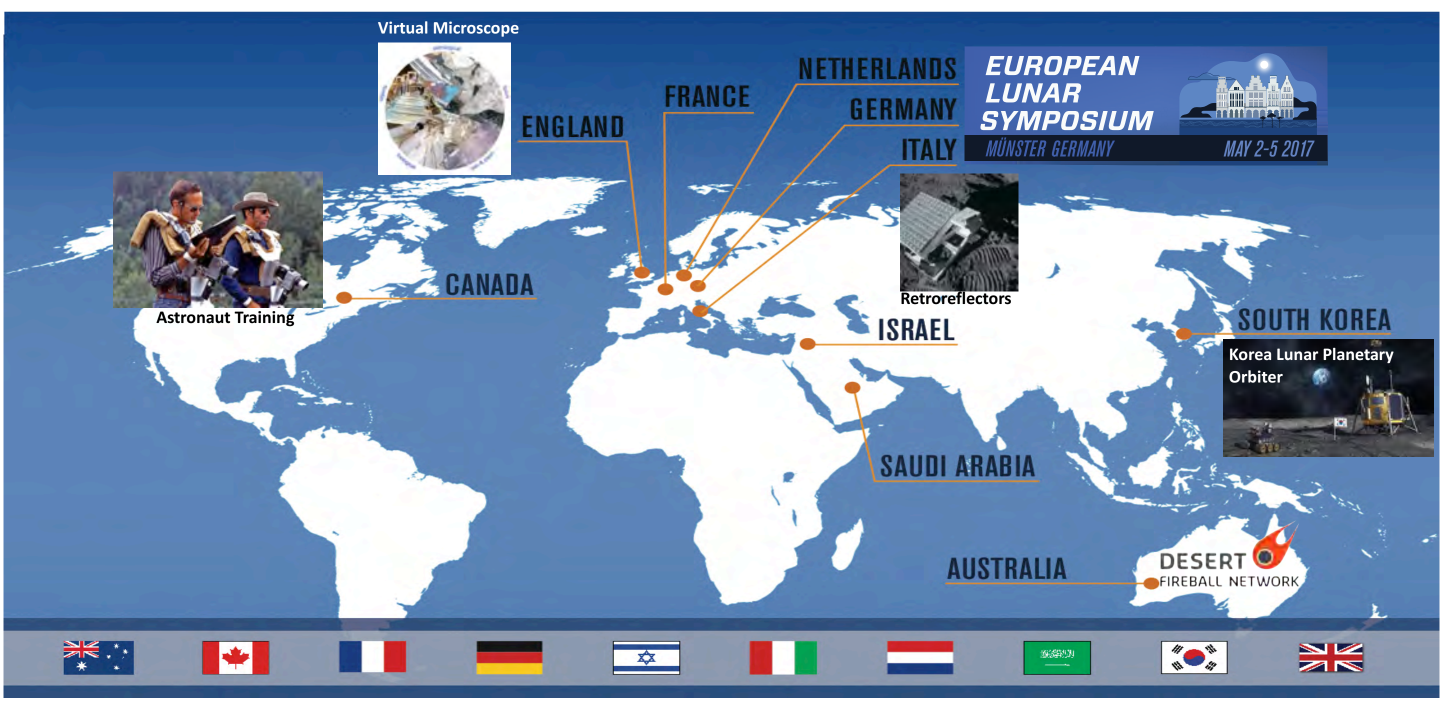
Presently, SSERVI International Partners include: Australia, Canada, France, Germany, Israel, Italy, the Netherlands, Saudi Arabia, South Korea, and the United Kingdom.

Non-U.S. science organizations can propose to become either Associate or Affiliate partners of SSERVI. Affiliate partnerships are with non-government institutions (e.g., universities and other research institutions). Associate partnerships are government-to-government agreements including those between NASA and international space agencies.

During 2016, the SSERVI Central Office participated in the following international activities.

France

SSERVI welcomed its 10th partner by signing an affiliated partnership agreement with France in May 2016. The Principal Investigator is Dr. Patrick Pinet, from University of Toulouse and Research Institute in Astrophysics and Planetology (IRAP). The partnership is based on three scientific aims: 1) the study of the Moon and Mercury, with a special emphasis on the interpretation of multi-mission and instrument datasets, available from Lunar Reconnaissance Orbiter, M3 Chandrayaan, Smart-1, Clementine, Lunar Prospector, Selene, on the one hand, and Messenger, on the other hand, in preparation to Bepi-Colombo, 2) the study of asteroids, with a main focus on Vesta and Ceres, in the



context of the ongoing Dawn mission, and 3) the study of comets, with a main focus on Churuymov-Gerasimenko (67P), in the context of the highly successful Rosetta mission.

United Kingdom/Netherlands

SSERVI attended and supported the planning efforts of the European Lunar Symposium (ELS) held in Amsterdam, Netherlands from May 18 - 19, 2016. SSERVI Central Office staff assisted with the logistical planning, communication within the United States and developing and hosting the ELS website as well as serving on the Science Organizing Committee (SOC). This SOC is led by SSERVI's European partners on a rotating basis.

Canada

SSERVI participated in a Programmatic Interchange Meeting in November 2016 with the Canadian Space Agency (CSA) Planetary Exploration Division and the SSERVI Canadian Affiliate Partner, Dr. Gordon Osinski from the Canadian Lunar Research Network (CLRN). The exchange included sharing of the virtual institute model and scientific research foci with CSA representatives. As a result of this meeting, consideration is being given to the development of an Associate partnership between CSA and SSERVI.

South Korea

SSERVI presented an overview of the virtual institute at the Korean Lunar Symposium on November 15, 2016 in support of the Associated Partnership with the Korean Aerospace Research Institute (KARI). In addition, Programmatic Interchange Meetings were held with KARI and the Korean Institute of Geoscience and Mineral Resource (KIGAM) to discuss opportunities for future collaboration as well with as the Korean Institute for Construction Technology (KICT). The KICT is investigating opportunities and technology in the field of In-Situ Resource Utilization (ISRU) on the Moon and Mars, and is in the process of designing a very large "dirty" vacuum chamber suitable for both science and technology development relevant to airless bodies.

SSERVI gave a remote presentation of Moon Trek to the KARI Lunar Site Selection and Analysis Workshop in December 2016 which resulted in an invitation from KARI and KIGAM for an in-person demonstration in Korea in January 2017. KARI is considering utilizing the Moon Trek system for landing site selection for their eventual Lunar Landing mission.

ESA

SSERVI presented a demonstration of the Solar System Treks at the European Space Agency (ESA) Lunar Village Workshop at ESTEC in May 2016. As a result, they requested a second presentation be made in 2017 to facilitate the integration of Moon Trek into Lunar Village Site Selection and Analysis.

Italy

SSERVI worked with INFN to facilitate their use of Moon Trek in LOLA applications studies. In addition, SSERVI received an application from the Italian Space Agency (ASI) for Associate partnership with SSERVI; anticipated completion is mid 2017.

Australia

SSERVI is working with Professor Phil Bland, PI for the Australian partnership, on strategies to help the global expansion of the Desert Fireball Network (DFN). DFN Collaboration with partners in the U.S. and other international partners is being classified into three components: Research, Camera Hosting, and Citizen Science.

In 2016, SSERVI supported efforts to broaden exposure of the DFN with oral and poster presentations in various conferences and forums. Meetings were conducted with the NASA Meteoroid Environments Office, University of New Mexico, Navajo Technical University, Chaco Canyon National Park Observatory, United Arab Emirates Space Agency, Saudi Arabia. SSERVI also gave presentations at Exploration Science Forum, Telescope Science Symposium, Division of Planetary Science / European Planetary Science Conference, NASA Citizen Science Forum, and American Geophysical Union.

SSERVI is working with the NASA Science Mission Directorate in communicating the DFN to a wider audience through involvement with NASA's Citizen Science Forum and by featuring the DFN's citizen science component, Fireballs In the Sky, online at https://science.nasa.gov/citizenscientists.

Saudia Arabia

A member of the SSERVI Central Office met with representatives from the King Abdulaziz City for Science and Technology (KACST) in Riyadh, Saudi Arabia in August, 2016. She provided a briefing on the Desert Fireball Network (DFN), encouraging KACST to consider Saudi Arabia as a partner in the Global DFN.

In addition to these activities directly involving SSERVI Central Office staff, some of SSERVI's international partners detail their accomplishments in the following section.

Greg Schmidt inspects ChemCam instrument hardware while visiting the French space astrophysics laboratory, the Institut de Recherche en Astrophysique et Planetologie (IRAP), in Toulouse, France. The ChemCam instrument is carried by the NASA Curiosity rover which landed on Mars on August 6th 2012.

SSERVI Central Management (Front row: Greg Schmidt, Kristina Gibbs, and Yvonne Pendleton) and International PIs (back row: Dr. Patrick Pinet (France), Gordon Osinski (Canada), Wim van Westrenen (Netherlands), Mahesh Anand (UK), and Simone Dell'Agnello (Italy) get together at the 2016 European Lunar Symposium in the Netherlands.

INTERNATIONAL PARTNER REPORTS

Australia

by Phil Bland, Curtin University

SCIENCE AND TECHNICAL WORK HIGHLIGHTS

Nature publication by SSERVI Australia members (Andy Tomkins, Lara Bowlt, Matthew Genge, Siobhan A. Wilson, Helen E. A. Brand, Jeremy L. Wykes) Ancient micrometeorites suggestive of an oxygen-rich Archaean upper atmosphere.

In early 2016 the Australian Nuclear Science and Technology Organisation (ANSTO) created a Planetary Materials unit (Helen Maynard-Casely, Helen Brand), and published first JPL collaboration determining of the crystal structure of new material that could be on the surface of Saturn's moon, Titan in International Union of Crystallography Journal.

Aus-US collaboration (Aaron Cavosie, Nick Timms, Timmons Erickson) at Meteor Crater "Transformations to granular zircon revealed: Twinning, reidite, and ZrO2 in shocked zircon from Meteor Crater (Arizona, USA)" published in Geological Society of America.

ARC Centre of Excellence for Core to Crust Fluid Systems and Macquarie Planetary Research Centre (Craig O'Neill, Siqi Zhang) published "*A window for plate tectonics in terrestrial planet evolution?*" in Physics of the Earth and Planetary Interiors with US colleagues.

Nanogeochronology opportunities from the Geoscience Atom Probe Facility at Curtin University (Steve Reddy) published in Science Advances.

Two GRAIL papers published about the formation of the lunar Orientale basin took the cover of Science (SSERVI Au member Katarina Miljkovic).

The Desert Fireball Network (DFN, Phil Bland) successfully recovered two meteorites (1st Jan and 31st Oct) from the upgraded, digital camera network. The first meteorite named Murrili, has been classified as an ordinary chondrite (type H5), with Consortia study results presented at the Meteoritical Society in Berlin. The second was recovered within a week with minimum contamination, thanks to swift reports by members of the public from the award-winning Fireballs in the Sky citizen science app and rapid response by the DFN team.

EDUCATION & PUBLIC OUTREACH

Fireballs in the Sky – with over 26,000 app downloads worldwide, the citizen science outreach program received Premier's Science Award for West Australian Science Engagement Initiative of the Year, and the Australian Government Eureka Prize for Innovation in Citizen Science.

Nerding Out with NASA – a panel workshop for secondary students from Ashdale College, Western Australia, meeting SSERVI AU planetary science researchers and discovering career opportunities available.

ANSTO Big Ideas Forum – SSERVI Au collaboration with students and teachers visiting the ANSTO facility to meet world-class researchers and get hands-on with amazing technology.

COLLABORATIONS WITH SSERVI TEAMS

Missions

OSIRIS-REx [Phil Bland, Trevor Ireland]; GRAIL [Katarina Miljkovic]; Cygnus OA6 Re-entry Observation Campaign [Ellie Sansom]

Australian Research Council Grants

Engagement of SSERVI Au and International collaboration across 4 projects, totalling AU$1.86 million

Discovery Projects

Exploring Solar System Origins with the Desert Fireball Network (Phil Bland)

Decoding the Chronology of Mars (Gretchen Benedix)

Using fossil micrometeorites to examine the ancient Earth environment (Andy Tomkins)

Linkage Infrastructure, Equipment and Facilities [LIEF] Grant

A Global Fireball Observatory (Phil Bland)

MAJOR MEETINGS

SSERVI Australia 2-day Workshop: 60 planetary scientists from across the country came together to strengthen the nation's planetary research and collaborations. The conference hashtag #OzPlanet16 trended top 6 on twitter in Australia during the talks and discussions.

Group photo of SSERVI Australia team. Credit: Curtin University.

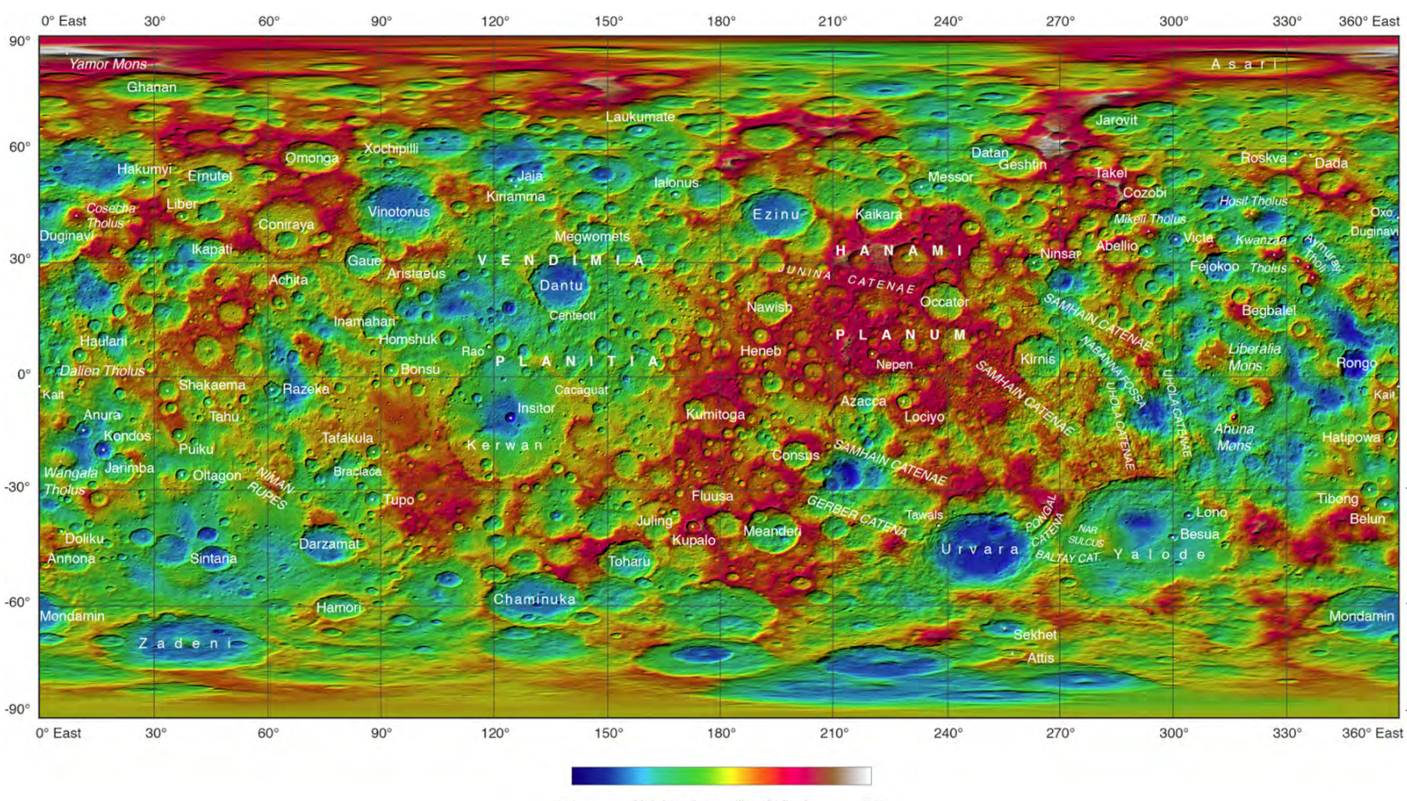
Germany

by Ralf Jaumann, DLR

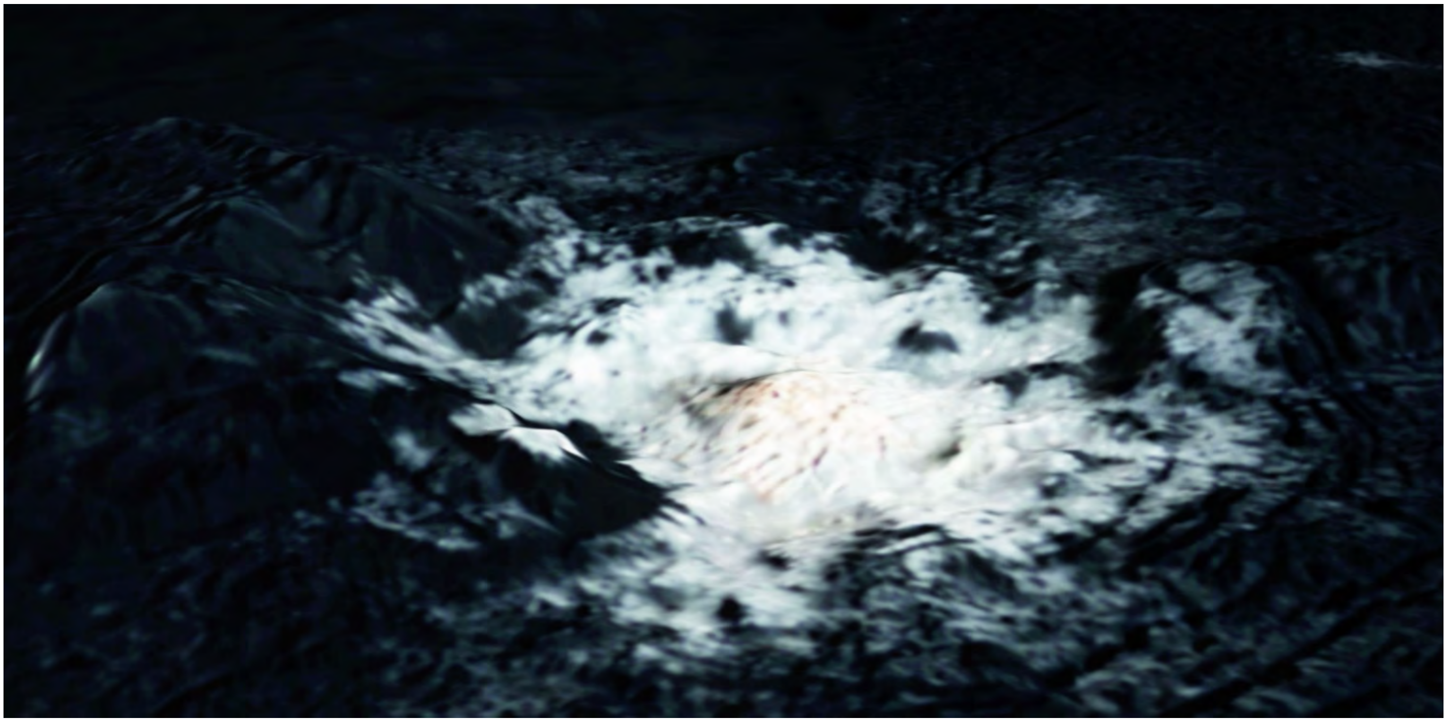
Summary of the German Activities in context with SSERVI in 2016

The German solar system exploration and research activities focus on origins and evolution of our solar system and Earth by investigation of Mars, Mercury, Venus, Jupiter, Saturn, asteroids and comets and Earth analogues 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. 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 small CoI-contributions to full 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. Mars Express orbits at Mars with the High Resolution Stereo Camera (HRSC) as major German contribution. 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 Mars 2020 MastCam-Z by supporting stereo processing. Dawn is a NASA Discovery Mission launched in 2007 to explore the two major asteroids Vesta and Ceres. The 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 topography, cartography and feature naming of Ceres as mapped by Dawn. NASA/JPL-Caltech/UCLA/MPS/DLR/IDA



Oblique view of the Cerealia Facula (bright spot) in Occator crater on Ceres. NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

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. Hayabusa 2 is a JAXA mission launched in 2014 to explore the asteroid (162173) Ryugu and return samples. The MASCOT lander including a camera, a radiometer, a magnetometer and a French spectrometer for surface characterization and sample context is provided by DLR in cooperation with CNES. 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 M-mission PLATO will search for exoplanets with focus on rocky planets with the telescope and camera contributed by Germany. In addition, Germany is contributing to ESA in context with the lunar Prospect activities and also studying additional lunar lander possibilities. In 2016 we also carried out two field campaigns; one for three month to Antarctica to study dry valleys as Mars analogous and for testing ExoMars lander instrumentation and to South Africa for impact studies.

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.

France

by Patrick Pinet, Astrophysics and Planetology Research Institute (IRAP)

The year 2016 has been a particular moment for IRAP, with the official signing on May, 24th of its affiliation to SSERVI, in the presence of Gregory Schmidt (SSERVI Deputy Director, Director or International Partnerships) and Doris Daou (Associate Director), and representatives of the US consulate in Toulouse (Delaissez-Forstall, A. and Crevel, Public Affairs department), as the result of the submission of the proposal 'SSMMAC-France' (Space Studies of the Moon, Mercury, Asteroids and Comets in France) by the Principal Investigator Patrick Pinet (IRAP, Toulouse). The proposal relies on the support of the National Institute for Study of the Universe (INSU) of the French National Research Council (CNRS), of the University of Toulouse, of the French Space Agency CNES) and close interactions with its Toulouse-based part. It is organized within three main scientific threads of participation and potential collaboration with other SSERVI members:

i) the study of the Moon and Mercury, with a special emphasis on the interpretation of multi-mission and instrument datasets, available from Lunar Reconnaissance Orbiter, M3, Chandrayaan, Smart-1, Clementine, Lunar Prospector, Selene, and Messenger.

ii) the study of asteroids, with a main focus on Vesta and Ceres, in the context of the ongoing Dawn mission.

iii) the study of comets, with a main focus on Churuymov-Gerasimenko (67P), in the context of the Rosetta mission.

Major events and facts:

Among a number of actions, one can mention the participation to a brainstorming workshop held at ISSI in Bern focused on lunar surface composition and processes, and preparing for the future exploration of the Moon (02/29-03/04/2016). 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. IRAP interacted with various partners, including SSERVI ones such as C. Pieters, D. Lawrence (USA), H. Hiesinger (Germany) and M. Anand (UK). Also, IRAP attended the European Lunar Symposium 4th held in Amsterdam (Pinet et al., 2016; Chevrel at al., 2016) on May, 17th-19th and met with many SSERVI colleagues. On October 5th, at the request of the US consulate, a tour across the lab and its facilities, highlighting the space-driven technology and space instrumentation under construction and testing, was given to Kirsten SCHULZ, who is a career member of the American Foreign Service, as acts as an Environment, Science, Technology and Health (ESTH) Counselor .

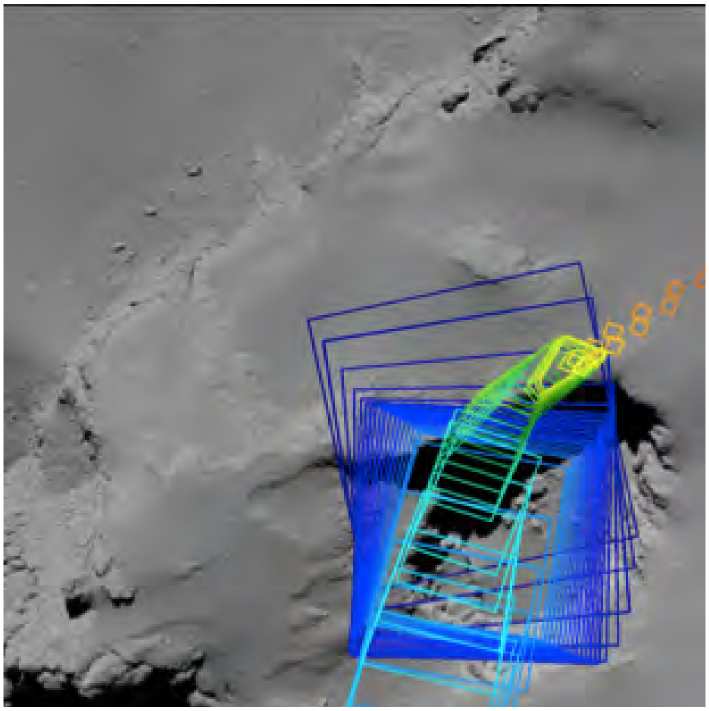
A few science highlights:

2016 has been a major year for the missions Rosetta at 67P/Churyumov-Gerasimenko and Dawn at Ceres.

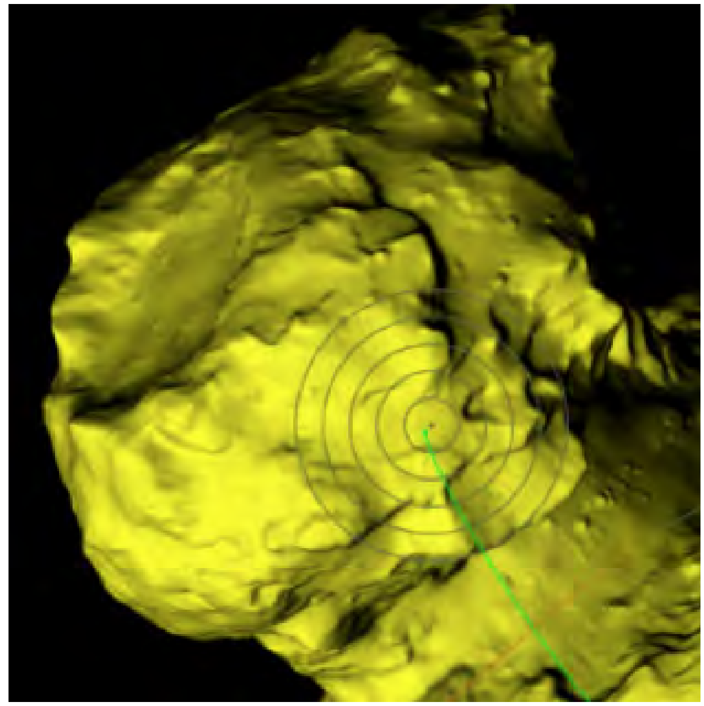
For Rosetta, the Rosina instrument detected for the first time in-situ an amino-acids -the simplest one, glycine- in the tenuous atmosphere of the comet (Altwegg et al. 2016). The mass spectrometer also gave a complete high-time resolution map of the species ejected by the comet during its orbit (Mall et al. 2016). The coma interaction with the solar wind was further described over the 2 years of the space mission with a better description of the plasma boundary and its variations (Fuselier et al. 2016, Mandt et al. 2016). The radar CONSERT measurements analysis has further constrained the fact that cometesimals inside the comet near where Philae landed are not larger than about 1 m (Ciarletti et al. 2016), and that the dust fraction must be primarily constituted of a high organic compound (Herique et al. 2016).We have also participated in the ground-based telescope campaign for the observations of the comet (Snodgrass et al. 2016).

After the successful end of the mission, the symposium "COMETS, a new vision after Rosetta and Philae" organized by the CNES and IRAP (J. Lasue, C. Mazelle, H. Réme; Université Paul Sabatier of Toulouse & CNRS) with financial support from ESA, was successfully held from 14 to 18 November 2016 at the Musée des Abattoirs in Toulouse. The symposium gave all the highlights of the mission so far, with a special publication in MNRAS associated to it.

One of the highlights of 2016 has also been the interpretation of data from the Dawn mission at Ceres, the largest and most massive of the asteroids in the main belt between Mars and Jupiter. The team at IRAP (M. Toplis



Imaging 'footprints' of Rosetta's OSIRIS camera during the descent to the comet's surface. A primary focus was the pit named Deir el-Medina, as indicated by the number of footprints indicated in blue. The trail of orange and red squares reflect the change in pointing of the camera towards the impact site, subsequently named Sais. The final image was acquired at about 20 m above the surface, and the touchdown point was only 33 m from the centre of the predicted landing ellipse. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA



Rosetta touched down just 33 m away from the target point, as indicated by the green descent trajectory line. The inner circle has a radius of 100 m and the concentric circles around the centre are spaced by increments of 100 m. Credit: ESA

and colleagues) has been involved in many of those studies, ranging from the interpretation of the gravity field in terms of internal structure (Park et al., Nature, 2016), piercing the mystery of the mineralogy of the bright spots in Occator crater (DeSanctis et al., Nature, 2016), quantifying the distribution of aqueously altered materials at the surface of the asteroid (Ammannito et al., Science 2016) and the first quantification of the concentrations of hydrogen and iron in the near-surface materials (Prettyman et al., Science, 2017). All of this work is providing unprecedented constraints on the origins and evolution of Ceres over geological time, in turn providing new insights into planet formation in the solar system.

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Mall, U., Altwegg, K., Balsiger, H., Bar-Nun, A., Berthelier, J. J., Bieler, A., ... & Dabrowski, b. (2016). high-time resolution in-situ investigation of major cometary volatiles around 67p/c–g at 3.1–2.3 au measured with rosina-rtof. The Astrophysical Journal, 819(2), 126.

References (Dawn)

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Ammannito et al., Science 2016

United Kingdom

by Mahesh Anand, Open University

Executive Summary

The UK-node of SSERVI is a voluntary group of individuals drawn from academia, industry and government departments in the UK who are passionate about lunar science and exploration. At present the group has just over 100 members representing 25 institutions from across the UK. UK-SSERVI members are involved in a multitude of lunar science and exploration activities ranging from world-leading research on Apollo lunar samples to remote sensing studies of the Moon to actively contributing to various upcoming lunar missions by providing payload instruments and scientific expertise. Another important activity of UK-SSERVI node involves dissemination of information and engagement of wider stakeholders (e.g. students, public, policy makers) in sharing the excitement of lunar science and exploration through various means (e.g., European Lunar Symposia, Virtual Microscope, Moons MOOC, media interviews etc.).

Below are a selection of highlights from the UK-SSERVI node for the year 2016.

https://www.facebook.com/uksservinode/UK-SSERVI-NODE@JISCMAIL.AC.UK

Birkbeck, University of London

Key staff: Prof Ian Crawford, Dr Louise Alexander, Dr Abigail Calzada-Diaz, Ms Indhu Varatharajan

Over the past year, the Department of Earth and Planetary Sciences at Birkbeck, University of London, is currently involved in the following lunar science activities:

1. The Moon as a recorder of galactic history

We are currently in receipt of funding from the Leverhulme Trust to examine the galactic cosmic ray (GCR) record that may be retained in the lunar regolith. The lunar surface has been directly exposed to space since its formation ~ 4.5 billion years ago. During this time the Solar System has been subjected to a wide range of galactic environments as it orbits the galaxy. The lunar surface may preserve a record of enhanced GCR fluxes as a result of supernova explosions and associated supernova remnants occurring in close proximity to the Solar System during these orbits [1]. Changes in Solar activity could also be preserved in the lunar surface as a result of Solar Energetic Particle (SEP) fluxes. We are measuring concentrations of Argon, Neon

Current membersip includes ~100 individuals from 25 institutions across the UK.

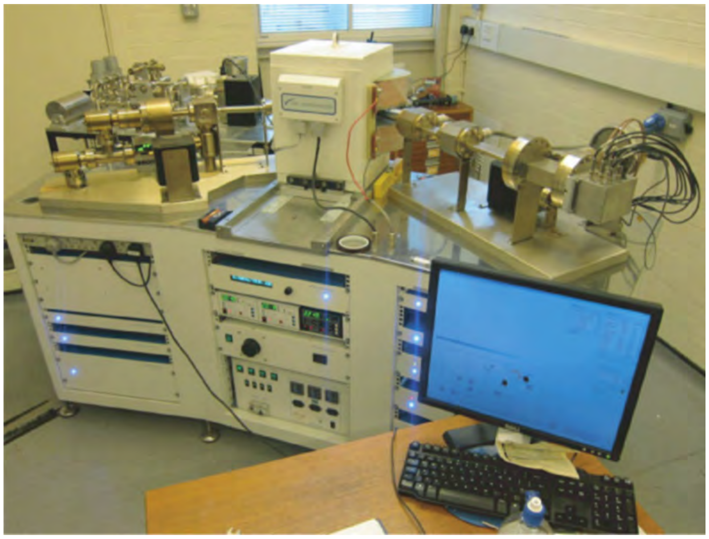

Figure 1. A Nu Noblesse multi-collector mass spectrometer at UCL is used to measure 3He, 21Ne and 38Ar isotopes with additional data collected at the University of Manchester.

and Helium isotopes produced by GCR and SEP interaction with the lunar surface in order to examine variations in these fluxes through time (Figure 1). We are also conducting a thorough literature review with colleagues at the University of Manchester to test hypotheses that enhanced activity is preserved in the lunar regolith and to examine whether signatures of long exposure can be separated from spikes in the lunar record.

Results from this project will be used to develop criteria for selecting future lunar samples which may be able to produce a detailed galactic record, providing that they are extracted from different dateable horizons. We are therefore examining regions on the Moon that have evidence of layered deposits (Figure 2).

2. Source localities of lunar meteorites

We have continued our studies of lunar meteorites and lunar remote sensing to try to constrain the source regions of the former. Abigail Calzada-Diaz successfully defended her PhD thesis on this topic in 2016 and the latest results are given in [2].

3. Mineralogy of far-side mare basalts.

We have used M3 data to study the mineralogy of far-side mare basalts. Preliminary results are given in [3] and a full paper is in preparation.

4. Lunar resources

Building on the review given in [4] we continue to investigate the resource potential of the Moon. We led the organisation of an RAS Discussion Meeting devoted to space resources in April 2016 [5] which resulted the publication of a Special Issue of the journal *Space Policy* (Vol. 37, pp. 51-109).

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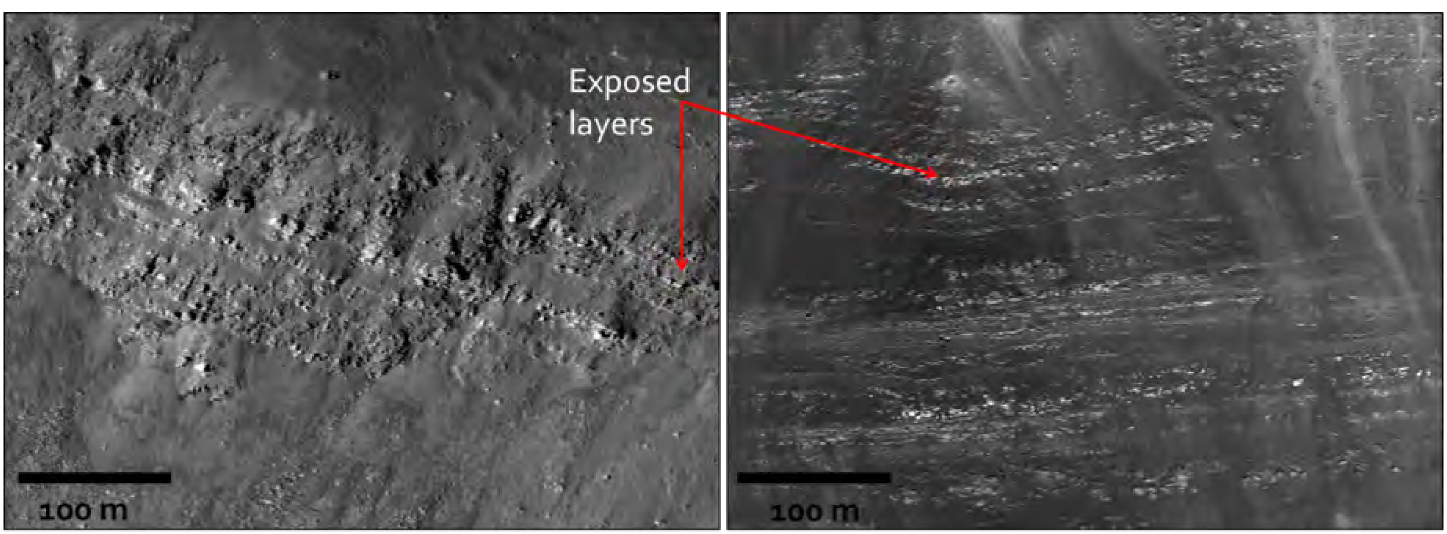

Figure 2. LROC NAC images showing examples of layered deposits in Bessel crater (M135073175R) and Euler crater (M124763045LE). Images NASA/GSFC/Arizona State University.

lunar regolith breccias Miller Range 090036 and 090070: insights into the crustal history of the Moon", Meteoritics and Planetary Science, 52, 3-23, (2017).

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[4] Crawford, I.A., "Lunar Resources: A Review", Progress in Physical Geography, 39, 137-167, (2015).

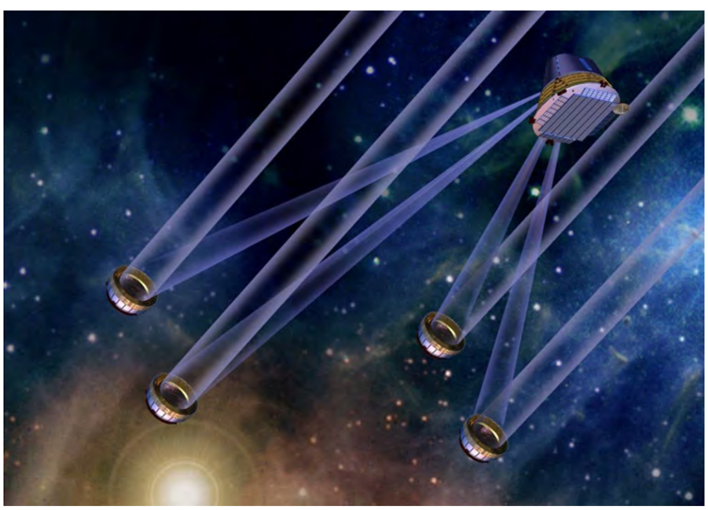
[5] Crawford, I.A., Elvis, M. and Carpenter, J., Using Extraterrestrial Resources for Science, Astronomy and Geophysics, 57, 4.32-4.36 (2016).

5. Community Engagement

Discussion Meeting at the Royal Astronomical Society, London, UK - The use of Extraterrestrial Resources to Facilitate Space Science and Exploration – co-organised by Prof Ian Crawford.

Videos of the talks are available at: https://www.ras.org.uk/events-and-meetings/specialist-discussion-lectures

Meeting report: http://arxiv.org/abs/1605.07691



Lancaster University, Lancaster Environment Centre

Key staff: Prof Lionel Wilson

Lunar research at Lancaster University has continued to involve extensive collaboration with Brown University and has focused on understanding lunar volcanic eruption mechanisms. We have studied (a) the formation and transport of bodies of magma out of the mantle (Wilson & Head, 2017; Head & Wilson, 2017; Rutherford et al., under review), (b) the intrusion of magma in the brecciated zones of impact craters to create floor-fractured craters (Jozwiak et al., 2017), and (c) low-effusion rate eruptions that avoid explosive disruption of magma to create magmatic foams (Wilson and Head, in press), the properties of which explain the anomalously young ages of some volcanic deposits (Head et al., in press; Qiao et al., under review).

Journal papers published

Jozwiak, L. M., Head, J. W., Neumann, G. A. & Wilson, L. (2017) Observational constraints on the identification of shallow lunar magmatism: insights from floor-fractured craters. Icarus, 283, 224-231.

Wilson, L. & Head, J. W. (2017) Generation, ascent and eruption of magma on the Moon: new insights into source depths, magma supply, intrusions and effusive/explosive eruptions (Part 1: Theory). Icarus, 283, 146-175.

Head, J. W. & Wilson, L. (2017) Generation, ascent and eruption of magma on the Moon: new insights into source depths, magma supply, intrusions and effusive/explosive eruptions (Part 2: Observations). Icarus, 283, 176-223.

Head, J. W., Qiao , L., Wilson, L., Xiao, L. & Dufek, J. Ina pit crater on the Moon: extrusion of waning-stage lava lake magmatic foam results in extremely young crater retention ages. Geology doi:10.1130/G38594.1

Wilson, L. & Head, J. W. Eruption of magmatic foams on the Moon: formation in the waning stages of dike emplacement events as an explanation of "Irregular Mare Patches". Journal of Volcanology and Geothermal Research doi:10.1016/j.volgeores.2017.02.009

LPSC abstracts - 2016

Head, J. W. & Wilson, L. (2016) Mare basalt volcanism: generation, ascent, eruption and history of emplacement of secondary crust on the Moon. Lunar and Planetary Science XLVII, #1189.

Jawin, E. R., Head, J. W. & Wilson, L. (2016) Huge pyroclastic cones surrounding Cobra Head, Aristarchus Plateau: relation to Vallis Schröteri. Lunar and Planetary Science XLVII, #1505.

Jozwiak, L. M., Head, J. W. & Wilson, L. (2016) Pyroclastic eruptions on Mercury: insights into eruption mechanisms from vent morphology. Lunar and Planetary Science XLVII, #1178.

Jozwiak, L. M., Head, J. W. & Wilson, L. (2016) An analysis of eruption styles in lunar floor-fractured craters. Lunar and Planetary Science XLVII, #1169.

Qiao, L., Head, J. W., Wilson, L., Kreslavsky, M. A. & Xiao, L. (2016) Compound flow fields in southwest Mare Imbrium: geomorphology, source regions and implications for lunar basin filling. Lunar and Planetary Science XLVII, #2038.

Qiao, L., Head, J. W., Xiao, L., Wilson, L. & Dufek, J. (2016) Sosigenes lunar irregular mare patch (IMP): morphology, sub-resolution roughness and implications for origin. Lunar and Planetary Science XLVII, #2002.

Wilson, L. & Head, J. W. (2016) Explosive volcanism associated with the silicic Compton-Belkovich volcanic complex: implications for magma water content. Lunar and Planetary Science XLVII, #1564.

The Open University

Key staff: Dr Mahesh Anand, Dr Ian Franchi, Dr Jessica Barnes, Dr Romain Tartese, Dr James Mortimer, Ms Nicci Potts, Dr Sasha Verchovsky, Prof Ian Wright, Dr Simon Sheridan, Dr Andrew Morse, Dr Feargus Abernathy, Prof David Rothery, Dr Andrew Tindle, Prof Simon Kelley, Dr Phillipa Smith, Ms Samantha Faircloth, Dr Helen Ashcroft, Dr Thomas Hopkinson, Dr Ana Cernok, Ms Vibha Srivastava, Dr Sungwoo Lim

Members of the Open University lunar group are currently involved in the following lunar activities:

1. PROSPECT package on ESA-Roscosmos Luna 27 mission

The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) is in development by Leonardo S.p.A. (Italy) under contract to the European Space Agency (ESA) for application at the lunar surface as part of international lunar exploration missions in the coming decade, including the Russian Luna-27 mission planned for 2021. PROSPECT will search for and characterize volatiles in the lunar polar regions to answer science questions and investigate the viability of these volatiles as resources.

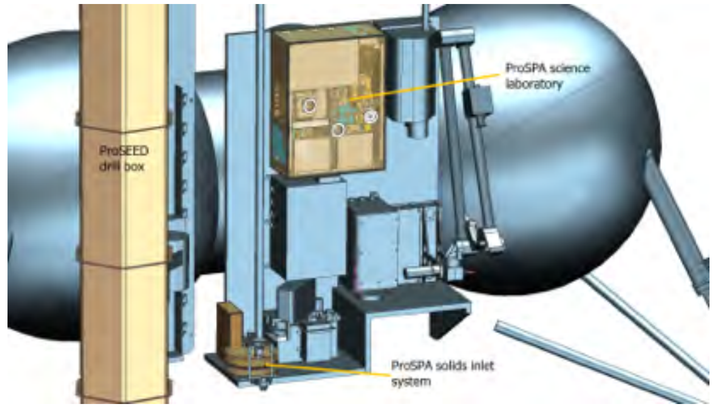


Figure 1: Location of ProSPA units and ProSEED drill box on Luna-27 lander (credit IKI/Roscosmos)

The Open University is leading the development of ProSPA, the Sample Processing and Analysis element of PROSPECT, supported by RAL Space and Airbus Defence and Space (UK), Max Planck Institute for Solar System Research and Technical University of Munich (Germany) and Media Lario Technologies (Italy). ProSPA will receive samples extracted from the lunar sub-surface by the ProSEED drill, and perform a suite of analytical experiments aimed at understanding the nature, source, evolution and utility of the volatiles therein. These functions are distributed across two physical units – a Solids Inlet System (SIS) comprising a series of single-use sample ovens on a rotary carousel together with a sample imager, and a miniature chemical analysis laboratory incorporating two mass spectrometers and associated ancillary and control systems (Figure 1). The science output is anticipated to be the identity, quantity and isotopic composition of volatiles as a function of depth within the first 1.2 m of the lunar surface.

2. Lunar volatiles

Several papers published on this topic including some that received attention beyond the lunar community.

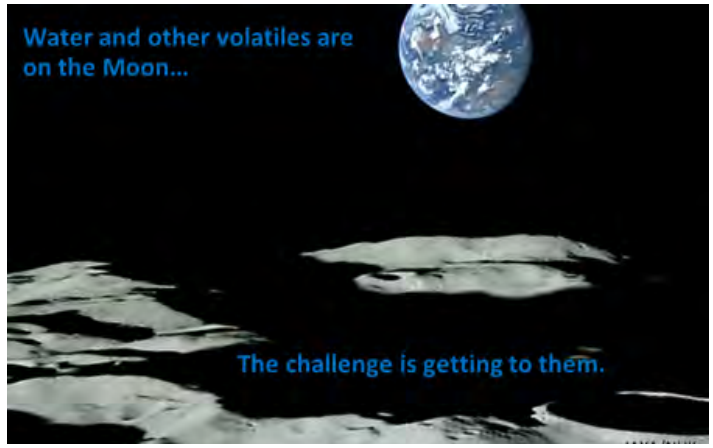
Barnes, J.J, Kring, D.A., Tartèse, R., Franchi, I.A., Anand, M and Russell, S.S. (2016). An asteroidal origin for water in the Moon. Nature Comm., 7, # no. 11684.

This work was a result of collaboration between the

members of the UK-node and the US-based SSERVI team at LPI. Our work revealed that most of the water inside the Moon was delivered by wet asteroids during the early evolution of the Moon, ~4.5-4.3 billion years ago, while comets contributed only a small proportion of volatiles to the interior of the Moon.

3. Scientific community engagement

Dr. Mahesh Anand Co-chaired the 4th European Lunar Symposium in Amsterdam that was attended by over 100 delegates.



4. Public education and dissemination of knowledge

The Open University Moons MOOC, presented in partnership with FutureLearn https://www.futurelearn.com/courses/moons was presented for the 4th and 5th times in 2016, with start dates in February and October. A similar pattern is being followed in 2017. This offers free online learning spread over 8 weeks at a notional 3 hours of study per week. A few thousand learners participate in each presentation, and the keenest have formed a Facebook

Dr Simeon Barber and Dr Mahesh Anand contributed to ISECG Virtual Workshops on Exploring and Using Lunar Polar Volatiles group https://www.facebook.com/groups/flmoons/ that has 700 members.

5. Virtual Microscope

A collaborative project between SSERVI and Open University: Dr Everett Gibson, JSC; Prof Simon Kelley, OU; Dr Andy Tindle, OU.

http://www.virtualmicroscope.org/collections/apollo

Peer-reviewed publications:

- Barnes, Jessica J.; Tartèse, Romain; Anand, Mahesh; McCubbin, Francis M.; Neal, Clive R. and Franchi, Ian A. (2016). Early degassing of lunar urKREEP by crust-breaching impact(s). Earth and Planetary Science Letters, 447 pp. 84–94.
- Barnes, Jessica; Kring, David A.; Tartèse, Romain; Franchi, Ian A.; Anand, Mahesh and Russell, Sara S. (2016). An asteroidal origin for water in the Moon. Nature Communications, 7, article no. 11684.
- Mortimer, J.; Verchovsky, S. and Anand, M. (2016). Predominantly Non-Solar Origin of Nitrogen in Lunar Soils. Geochimica et Cosmochimica Acta, 193 pp. 36–53.
- Potts, Nicola J.; Tartèse, Romain; Anand, Mahesh; van Westrenen, Wim; Griffiths, Alexandra A.; Barrett, Thomas J. and Franchi, Ian A. (2016). Characterization of mesostasis regions in lunar basalts: Understanding late-stage melt evolution and its influence on apatite formation. Meteoritics & Planetary Science (Early Access).
- 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.
- Snape J. F., Nemchin A. A., Bellucci J. J., Whitehouse M. J., Tartèse R., Barnes J.J., Anand M., Crawford I. A. and Joy K. H. (2016) Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon. Earth and Planetary Science Letters DOI:10.1016/j.epsl.2016.07.026
- Srivastava, Vibha; Lim, Sungwoo and Anand, Mahesh (2016). Microwave processing of lunar soil for supporting longer-term surface exploration on the Moon. Space Policy, 37(2) pp. 92–96.

Lunar Mission One (A crowd-sourced lunar mission concept – contributions from several UK-node members)

LM1 now has an international network of over 60 scientists and engineers who have been confirming the mission profile and its science aims. We have identified as the key technology challenge the secure lining of the borehole by in-situ additive manufacturing, and are addressing it.

The educational public engagement is now underway via Chapters of enthusiastic volunteers and pilot schools with representation in 43 countries (see flags). Activities cover all ages and, in addition, we have established long term relationships for student projects with six universities – in the US, UK, Germany, France, Australia.

All this activity has been unfunded, but sponsorship is expected to regain the project's funding momentum.

Meanwhile we see continuing progress by space agencies towards internationalising their programmes, exploiting private sector resources and engaging their citizens – all key features of LM1.

University of Manchester

Key staff: Dr Katherine Joy, Prof Ray Burgess, Dr Trish Clay, Ms Natalie Curran, Dr. J Pernet-Fisher, Ms Fran McDonald, Mr Dyl Martin

Ongoing activities: Cosmogenic noble gas analysis of lunar meteorites and Apollo regolith samples are currently taking place at the University of Manchester to investigate surface residence times and space weathering effects on lunar samples. Halogen concentrations of melt inclusions are being analysed using NI-NGMS (neutron irradiation noble gas mass spectrometry) techniques to investigate the volatile abundances of volcanic source regions. Plumbing system processes of mare volcanics are being investigated through analysis of crystal size distributions, textures and compositions. Chemical studies of lunar meteorites have shed new light on current lunar crust formation hypotheses. Analysis of zircons using xenon isotopes are helping to understand impact processing of ancient magmatic deposits. Shock studies of lunar samples are being investigated using integrated ESEM, FTIR, and CL imaging techniques. Group members involved with the PROSPECT user group have been undertaking studies of regolith simulant analysis.

Recent outputs and collaborations: Collaborations with Birkbeck College and the Natural History Museum has resulted in a publication investigating the source locations of lunar meteorites and the history of the lunar crust. Another publication in collaboration with Birkbeck College, LPI, ARES (JSC), and Western Carolina University details the identification and characterisation of types of impactors bombarding the lunar surface.

Public Engagement: Group members publicise their research outputs on the group blog at https://earthandsolarsystem.wordpress.com/ and have been involved with public engagement events discussing lunar science at the Museum of Manchester, Jodrell Bank radio telescope visitor centre at the Bluedot music festival and the Museum of Science and Industry.

Publications

Alexander L., Snape J. F., Joy K. H., Downes H. and Crawford I. A (2016). An analysis of Apollo lunar soil samples 12070,889, 12030,187 and 12070,891: Basaltic diversity at the Apollo 12 landing site and implications for classification of small sized lunar samples. Meteoritics and Planetary Science. Vol. 51: pp. 1654–1677 DOI: 10.1111/maps.12689

Bugiolacchi R., Bamford S., Tar P., Joy K. H., Crawford I. A., Grindrod P. M., Thacker N. and Lintott C. J. (2016) The Moon Zoo citizen science project: Scientific objectives and preliminary results for the Apollo 17 landing site. Icarus Vol. 271, pp. 30–48

Joy K. H., Crawford I. A., Curran N. A., Zolensky M. E., Fagan A. L., and Kring D. A. (2016) The Moon As An Archive Of Small Body Migration In The Solar System. Earth Moon and Planets 118: 133.DOI: 10.1007/s11038-016-9495-0

Matthewman R., Crawford I. A., Jones A. P., Joy K. H. and Sephton M. A. (2016) Organic Matter Responses to Radiation under Lunar Conditions. Astrobiology. Vol. 16, No.11. DOI: 10.1089/ast.2015.1442

McDonald F., Martin D., Curran N. and Calzada-Diaz A. (2015) Exploring the Moon on Earth. Astronomy and Geophysics. 56, 6.31-6.32 doi: 10.1093/astrogeo/atv199

Pernet-Fisher J. R. and Joy K. H. (2016) The lunar highlands: old crust, new ideas Astronomy and Geophysics 57 (1): 1.26-1.30 DOI: 10.1093/astrogeo/atw039

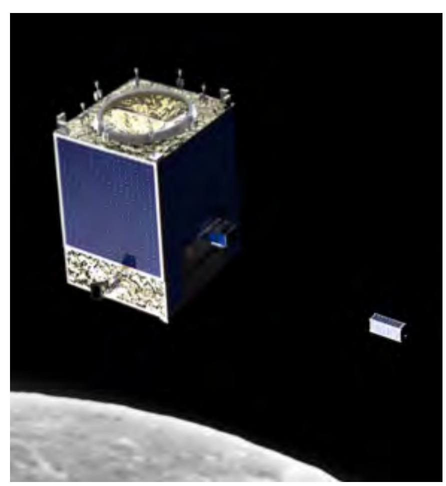
Snape J. F., Nemchin A. A., Bellucci J. J., Whitehouse M. J., Tartèse R., Barnes J.J., Anand M., Crawford I. A. and Joy K. H. (2016) Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon. Earth and Planetary Science Letters DOI:10.1016/j.epsl.2016.07.026

Steenstra E. S., D. J. P. M. Martin, F. E. McDonald, S. Paisarnsombat, C. Venturino, S. O'Hara, A. Calzada-Diaz, S. Bottoms, M. K. Leader, K. K. Klaus, W. van Westrenen, D. Hurwitz-Needham, and D. A. Kring. (2016) Analyses of robotic traverses and sample sites in the Schrödinger basin for the HERACLES human-assisted sample return mission concept. Advances in Space Research, Vol. 15, 1050–1065. doi:10.1016/j.asr.2016.05.041

Surrey Satellite Technology Limited (SSTL) and Goonhilly Earth Station (GES)

Key staff: Susan Jason

Surrey Satellite Technology Limited (SSTL) and Goonhilly Earth Station (GES) and the European Space Agency (ESA) are working together on a pilot phase as part of ESA's Commercial Partnerships for Exploration activity. The vision is to lower the cost of missions to the moon and beyond and open up space exploration to broad participation, through provision of affordable core infrastructure such as communications and navigation services. The first planned mission in the series is the Lunar Communications Pathfinder Mission, which comprises a 600kg class Mothership built by SSTL, which will deliver a small fleet of Customer CubeSats to lunar orbit and then provide communications services with Earth via the GES ground segment. There are also hosted payload opportunities on the data relay orbiter. The business model is based upon customers paying for their ticket to lunar orbit. For early bird customers, the first 6 months of data relay is included as part of the ticket price. Further details are available at www.goonhilly.org/lunar.



South Korea

by Gwanghyeok Ju, Korea Aerospace Research Institute (KARI)

Lunar science research activities in Korea are mainly focused on system architectural design and lunar sciences associated with scientific instruments for Korea Pathfinder Lunar Orbiter (KPLO).

KARI is leading all phases of KPLO mission from design through flight operation after launch and the pre-phase A study for planned lunar surface mission.

Moreover, Korea Astronomy and Space Science Institute (KASI) has led a variety of space sciences including cosmic infrared background experiment and star formation history with in-house designed near-infrared imaging spectrometer.

Korea Institute of Geoscience and Mineral Resources (KIGAM's) planetary research group has main focus on cosmochemistry and remote sensing in order to study planetary surfaces of the solar system, and education for young scientists and students for its lunar missions in order to build a promising planetary surface exploration program in the future.

The space construction research center at Korea Institute of Civil Engineering and Building Technology (KICT), newly established in 2016, initiated research activities for ISRU instruments and lunar soil analysis based on international collaboration and has been building a large scale dirty vacuum chamber and analog test facility.

The department of astronomy and space science at Kyung Hee University (KHU) has worked on theory and modeling of the solar-terrestrial space environments including distribution of heavy ions in the magnetotail near the lunar orbit and interaction of plasmas with the Moon.

The cosmic ray research group at CHU have been searching for the lunar caves using LRO/NAC data and evaluated feasibility and scientific values of recently identified lunar caves. They found ground level enhancement (GLE)-like events observed by the LRO/CRaTER.

The KPLO project officially started as of January 2016 as the first phase of the Korean Lunar Exploration Program (KLEP). The design phase of four selected scientific instruments as part of its primary mission was initiated after the official contract in early 2016: a lunar terrain imager (LUTI, PI: Dr. H. Heo, KARI), a KPLO gamma-ray spectrometer (KGRS, PI: Dr. K. Kim, KIGAM), a wide-field polarimetric camera (PolCam, PI: Dr. Y. Choi, KASI), and a KPLO magnetometer (KMAG, PI: prof. H. Jin, KHU).

In December 2016, KARI and NASA signed a MOU for KPLO collaboration with NASA including navigation, Deep Space Network (DSN) support and NASA science instruments.

The NASA HEOMD Advance Explorations Systems (AES) is currently under final evaluation for proposed U.S. instruments for the KPLO mission as Ride Share Payloads since AO released in September 2016. When deployed on the KPLO mission, these spaceflight instruments will be used to conduct innovative, integrated, hypothesis- or question-driven investigations addressing the lunar strategic knowledge associated with lunar volatiles.

The KARI optical instrument division led the system architectural design of a Lunar Terrain Imager (LUTI) in 2016. The LUTI is a high resolution camera designed to capture regions of interest of the moon surface with a high spatial resolution of 5m or less and take topographical measurements to provide appropriate information on prospective landing sites for future robotic missions.

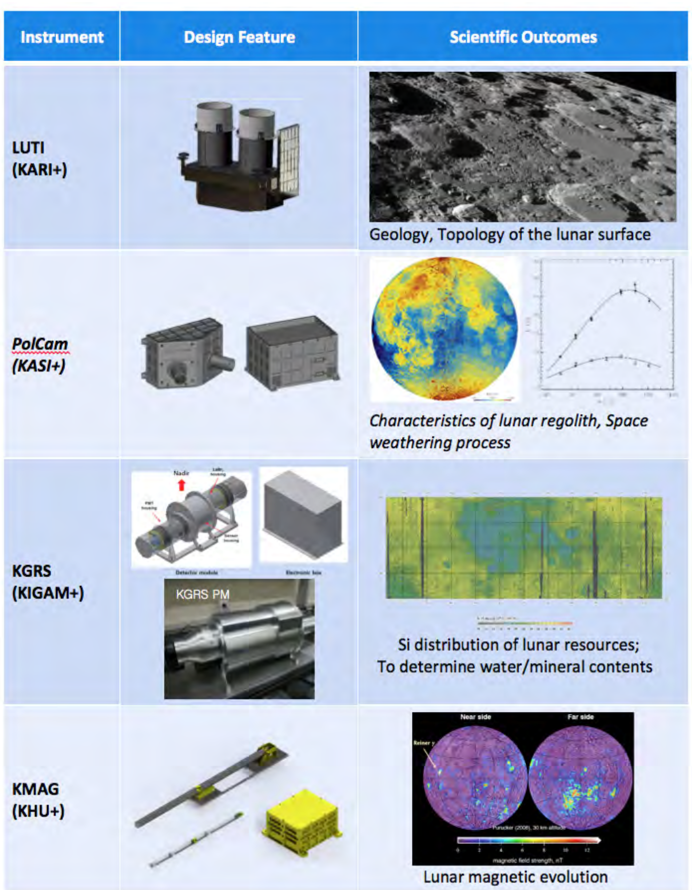
The KGRS by KIGAM's planetary research group is a compact low-weight instrument with the main $LaBr_3$ detector for the chemical analysis of lunar surface materials within a gamma-ray energy range from 10s keV to 10 MeV. Its scientific objectives include lunar resources (water and volatile measurements, rare earth elements and precious metals, energy resources, major elemental distributions for prospective in-situ utilizations), investigation of the lunar geology and studies of the lunar environment (mapping of the global radiation environment from keV to 10 MeV, high energy cosmic ray flux using the plastic scintillator). The KGRS will map major elements (Mg, Ca, Al, Ti(He-3), Fe, Si, O, and etc.), natural radioactive elements (U, Th, K) and water over the Moon.

The PolCam will perform polarimetric obseravtions of the whole surface of the Moon at wavelengths of 430 nm and 650 nm for phase angles between 0 and 120 degs with a spatial resolution of ~80m. This is intended to characterize lunar regolith and space weathering processes by investigating grain size of the lunar regolith, surface roughness and the fairy castle structure, internal composition of regolith grains.

The KMAG will provide a 3-D map of lunar magnetism, and additional magnetic science of lunar swirls and will seek the origin of crustal magnetism in Earth-moon system

Those instruments will adopt PDS4 format in order to generate their own scientific data.

KIGAM's team has also kept collaborating with SSERVI's FINESSE team to conduct an integrated research program focused on scientifically-driven field exploration aimed at generating strategic knowledge in preparation for the human and robotic exploration of the Moon, near-Earth asteroids (NEAs) and Phobos & Deimos. KIGAM organized special sessions on lunar spectroscopy at the fall meeting of Korean Society of Aeronautical & Space Sciences



KPLO Domestic Science Instruments

KIGAM's GeoEduCamp

in November 2016 as well as planetary explorations at the international symposium on Remote Sensing focusing on investigations of future lunar and martian satellites explorations by nuclear science payload in Jeju island in April 22-23. A series of classes for planetary geology exploration (Mars exploration) were provided at GeoEduCamp for primary and secondary level public school (K1-K12) teachers during summer and winter breaks with approx. 100 teachers in August 2016 and January 2017.

KARI hosted 7th Korean Lunar Exploration Symposium with over 150 domestic and international attendees in Jeju Island in November 2016. In the internationally invited session, SSERVI activities were introduced to Korean scientists and engineers by Greg Schmidt, deputy director of SSERVI.

7th Korean Lunar Exploration Symposium in Jeju Island

Selected Presentations and Publications

[1] Jin, H. et al. (2016) Small-scale Magnetic Anomalies: Northeast Region of Lunar Near Side, *47th Lunar and Planetary Science Conference*.

[2] Choi, Y.-J. (2016), Lunar Geophysics Using Sound and Vision and Serious Moonlight, *47th Lunar and Planetary Science Conference*.

[3] Choi, Y.-J. et al. (2016), Polarimetric Characteristics of the Reiner Gamma Swirl, *47th Lunar and Planetary Science Conference*.

[4] Kim, K.J., Ju, G. et al. (2016), Korean Lunar Lander – Concept Study for Landing-Site Selection for Lunar Resource Exploration, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B4, XXIII ISPRS Congress*, 12–19 July 2016, Prague, Czech Republic.

[5] Ju, G. (2016), Prospective Lunar Science Activities in Korean Lunar Mission, *SSERVI Exploration Science Forum*.

[6] Kim, K.J. (2016), Silicon Variation on the Moon as Observed by the Kaguya GRS and Chandrayaan-1 Moon Mineralogy Mapper (M^3) Calibration, SSERVI Exploration Science Forum.

[7] Choi, Y., Kim, K.J. et al. (2016), Development of an optimized Compton suppressed gamma-ray spectrometric system using Monte Carlo simulation, *Applied Radiation and Isotopes 109*, 558-562.

[8] Kim, K.J. et al. (2016), Development of a Gamma-Ray Spectrometer for Korean Pathfinder Lunar Orbiter, *48th Annual DPS Meeting, Pasadena*, CA, USA.

The Netherlands

by Wim van Westrenen, VU University Amsterdam

The Netherlands SSERVI team is characterised by expertise in radio-astronomy from the Moon, and in high-pressure experimental simulations of conditions and processes in the interior of the Moon.

In 2016, the Netherlands team, together with the leads of the other European SSERVI teams and supported by both SSERVI and ESA, organised the 2016 European Lunar Symposium that took place in Amsterdam on May 18 and 19. Over 110 participants from Europe, the US, Russia, Canada and China attended, with a high proportion of junior scientists.

In terms of exploration, a major highlight was the signing of a partnership agreement between the Netherlands Space Office (NSO) and the Chinese National Space Agency (CNSA) in Beijing in June. Led by PI Heino Falcke who is an international member of the SSERVI LUNAR team, researchers at Radboud University, ASTRON, and the Delft company Innovative Solutions in Space (ISIS) are developing a radio antenna instrument that will be on board the Chinese Chang'e 4 communications relay satellite that will be placed in an orbit around the L2 Point in June 2018. With the instrument, astronomers want to start measuring radio waves originating from the period directly after the Big Bang, before the first stars and galaxies were formed, and test technology in preparation for a possible low frequency array placed on the far side of the Moon. The partnership agreement follows a Memorandum of Understanding between the Netherlands and China signed in 2015, and constitutes a major step forwards for Dutch lunar exploration.

Members of the Dutch SSERVI team, in collaboration with partners from US and UK SSERVI teams, published a range of peer-reviewed scientific papers covering a broad range of SSERVI related topics in 2016, ranging from possible robotic traverses through the Schrodinger basin, to assessments of the chemical environment characterising the formation of the mineral apatite in lunar rocks, to a new experimental study of the solidification of the lunar magma ocean, and to new geochemical constraints on core formation in the Moon and Vesta.

One paper, published by Lin et al. in Nature Geoscience, provides the first fully experimental study of lunar magma ocean solidification in both dry and water-bearing conditions. The paper presents new measurements of the mineralogy and phase compositions that characterised the Moon after its initial magma ocean solidified, which in turn provides a starting point for models of subsequent interior and surface evolution. The study suggests that the lunar magma ocean must have contained several 100s of milligrams water per kilogram of magma – if the magma ocean had been dry, its solidification would have led to the production of a far thicker crust than actually observed on the Moon today. Because the magma ocean stage is the first stage of the Moon after it formed, this suggests the lunar interior was water-bearing from the start.

Italy

by Simone Dell'Agnello, Frascati National Labs

Solar System Exploration Research Virtual Institute Affiliate Member Cooperation

INFN Activity Report Jan. 1 – Dec. 31, 2016

The Istituto Nazionale di Fisica Nucleare (INFN) of the Italian Republic is an Affiliate level partner with the NASA Solar System Exploration Research Virtual Institute (SSERVI) since September 15, 2014, as the first formal representative of Italy's Solar System science community.

In 2016 INFN has continued on goals of common interest, exploiting its unique expertise with Laser Retroreflector Arrays (LRAs). LRA technology and applications promise to provide great support for future exploration missions to the Moon, Mars, Phobos, Deimos, as well as other planets and their moons in the Solar System. The affiliation will allow INFN and SSERVI to collaborate to improve future scientific undertakings and support the next generation of space scientists.

Highlights of the INFN activities in 2016 were:

Continued development of the next-generation lunar laser retroreflectors (large size and microreflectors) for new US lunar landing mission opportunities, in cooperation with D. Currie of the Univ. of Maryland (this Univ. was PI of the Apollo laser retroreflectors).

Formal letter of Interest by the President of INFN to SSERVI concerning the provision of next-generation lunar laser retroreflectors for NASA's Resource Prospector Mission.

Deployment of the INFN-ASI microreflector payload (INRRI, see Annex 1) onboard the ESA mission ExoMars-EDM 2016. INRRI was one of the science experiments onboard the Schiaparelli lander.

INFN – NASA/SSERVI Italy-USA projects: the research proposal SPRINGLETS (Solar system Payloads and laser Retroreflectors of Infn and Nasa-sservi for GeneraL relativity, Exploration and gravitational asTrophysicS), was approved by the Italian Ministry of Foreign Affairs and International Cooperation (MAECI) for the years 2016 and 2017. In May 2016 INFN SSERVI and MAECI organized a Mini-Workshop at the Embassy of Italy in Washington DC (see Annex 2).

Participation in the organization of the ELS 2016 symposium held in Amsterdam, Holland in May 2016. S. Dell'Agnello chaired one of the ELS sessions.

Within the Italian framework, INFN has collaborated with ASI to prepare the proposal for the ASI Association to NASA-SSERVI, in which INFN itself is included.

Formal letter by NASA-HQ to ASI concerning the interest in the deployment of an INFN-ASI microreflector onboard the NASA Mars 2020 Rover (see Annex 3).

The 5-year research proposal NESS (Network for Exploration and Space Science) was submitted to NASA in 2016 by Prof. J. Burns as PI for the SSERVI CAN-2 Solicitation n. NNH16ZDA009C. S. Dell'Agnello is Co-I and Key Project Lead for Co-lead for Lunar Laser Ranging, tests of General Relativity and lunar core. G. Delle Monache is Co-I for tests of General Relativity and lunar core models using Lunar Laser Ranging. This proposal has been selected by NASA in March 2017.

Refereed publications

Probing gravity with next generation lunar laser ranging, M. Martini and S. Dell'Agnello, Chapter in the book: R. Peron et al. (eds.), *Gravity: Where Do We Stand?* DOI 10.1007/978-3-319- 20224-2_5, Springer International Publishing, Switzerland (2016).

Thermo-optical vacuum testing of Galileo In-Orbit Validation laser retroreflectors, S. Dell'Agnello, et al, Advances in Space Research, 57 (2016) 2347–2358.

INRRI-EDM/2016: the first laser retroreflector on the surface of Mars, Advances in Space Research, available online 22 October 2016 (published as Advances in Space Research 59 (2017) 645–655.

Prepared for INFN by Simone Dell'Agnello

INFN-Laboratori Nazionali di Frascati, Italy

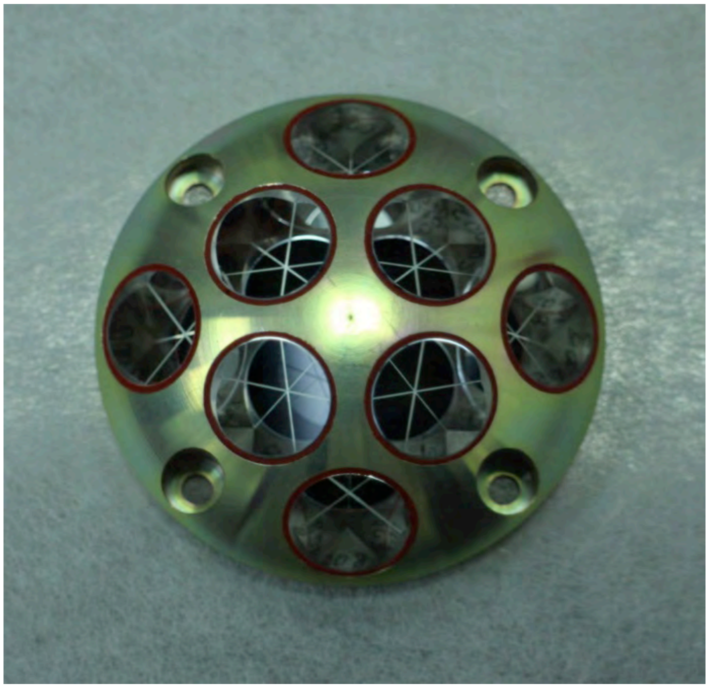
PI of the INFN Affiliation to NASA-SSERVI

Annex 1: Highlights of the INFN-ASI microreflector deployed on ExoMars Schiaparelli

INRRI is attached to the zenith-facing surface of Schiaparelli and has an unobstructed view to the Martian sky, which is essential since it will enable Schiaparelli to be located, using laser ranging, from Mars orbiters.

INRRI is a very compact and lightweight Corner Cube laser Retroreflector (CCR) in the form of a dome of diameter about 54mm and a total mass of 25g. The aluminium body has eight Suprasil1 (fused silica) CCR's mounted within it using silicone rubber.

INRRI was designed and built by the SCF_Lab (http://www.lnf.infn.it/esperimenti/etrusco/) of the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF) in Italy for ESA. It is provided to the ExoMars mission by the Italian space agency, ASI.



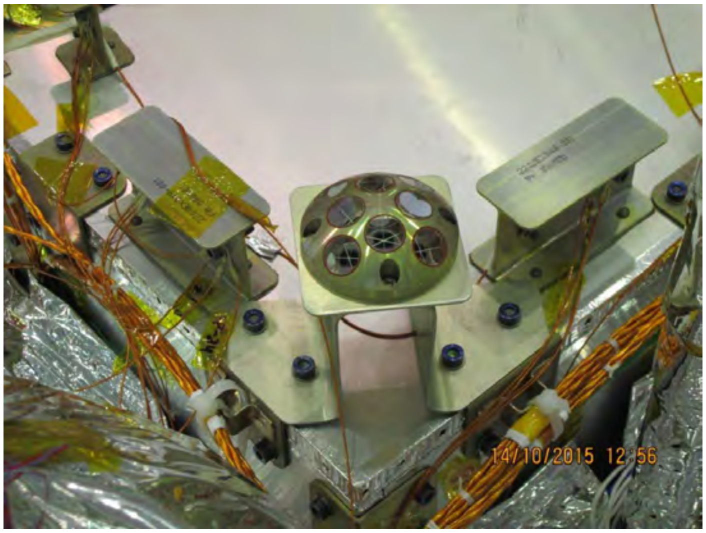
This is a photo of the INstrument for landing - Roving laser Retroreflector Investigations (INRRI) carried on the ExoMars 2016 Schiaparelli entry, descent and landing demonstrator module. Credit: [INFN]

INRRI Integrated On-board ExoMars Schiaparelli

INRRI is attached to the zenith-facing surface of Schiaparelli and has an unobstructed view to the Martian sky, which is essential since it will enable Schiaparelli to be located, using laser ranging, from Mars orbiters.

INRRI is a very compact and lightweight Corner Cube laser Retroreflector (CCR) in the form of a dome of diameter about 54mm and a total mass of 25g. The aluminium body has eight Suprasil1 (fused silica) CCR's mounted within it using silicone rubber.

INRRI was designed and built by the SCF_Lab (http://www.lnf.infn.it/esperimenti/etrusco/) of the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF) in Italy for ESA. It is provided to the ExoMars mission by the Italian space agency, ASI.



This is a photo of the INstrument for landing - Roving laser Retroreflector Investigations (INRRI) taken at TAS-F, Cannes, France, right after the integration of INRRI on the ExoMars 2016 Schiaparelli entry, descent and landing demonstrator module. Credit: [ESA - TAS]

Thursday, May 5th at 2:00 p.m.

Embassy of Italy
3000 Whitehaven Street, NW
Washington, DC

NASA-SSERVI & INFN Mini-Workshop

Theme: Asteroids and Phobos/Deimos: review of science and exploration goals and of applications of lasercom and laser telemetry

The Meeting is intended to discuss main goals in the science and the exploration of Phobos, Deimos and asteroids, as well as lasercom and laser telemetry as key technologies enabling some of those goals. Concerning asteroids, the AIM-DART mission under consideration by ESA-NASA is taken as a reference.

Preliminary Agenda

1:45pm Registration & coffee

2:00 ▷ Welcome, S. Lami (5min)

▷ *Introduction to workshop topics* (planetary science, exploration, defense, laser telemetry/lasercom and missions), G. Schmidt & S. Dell'Agnello, 20min

▷ *The ESA Asteroid Impact Mission (AIM) to Didymos*, I. Carnelli (ESA), 10min

▷ *Introduction to laser telemetry and the International Laser Ranging Service (ILRS)*, G. Bianco (ASI), 10min

▷ *AIM and DART*, A. Rivkin (JHU/APL), 15min

▷ *Thoughts on the origin of Phobos, its surface mineralogy, and reasonable compositional analogues*, D. Britt (U. Central Florida), 15min. *The regolith of Phobos,* C. Pieters (Bown U.), 15min

3:15 ▷ Coffee Break

3:30 ▷ *NASA laser transponder experiments*, J. McGarry, NASA-GSFC, 20min

▷ *Lidar and telemetry applications: the experience of SigmaSpace*, J.Degnan, SigmaSpace, 20min

▷ *Lasercom and laser retroreflector applications*, S. Dell'Agnello (INFN), 20 min

▷ *Outlook and link with next workshops and potential AOs*, Y. Pendleton, S. Dell'Agnello

If you didn't register yet, please R.S.V.P.: here

A PHOTO ID is required to enter the Embassy of Italy

Organizers:
Dr. Simone Dell'Agnello (INFN-Frascati) simone.dellagnello@lnf.infn.it
Dr. Stefano Lami (Embassy of Italy) stefano.lami@esteri.it
Dr. Gregory K. Schmidt (NASA-SSERVI) gregory.schmidt@nasa.gov

Italy in US.org

Annex 3: NASA Letter on deployment of INFN-ASI microreflector onboard Mars 2020.

National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

July 14, 2016

Reply to Attn of: SMD/Mars Exploration Program

Dr. Enrico Flamini
Chief Scientist
Agenzia Spaziale Italiana
Via del Politecnico snc
00133 Rome
Italy

Dear Dr. Flamini:

NASA is agreeable to hosting the Agenzia Spaziale Italiana (ASI) Laser Retroreflector Array (LRA) on the Mars 2020 rover, as we see the instrument to be of mutual benefit, holding the potential to improve the accuracy of geospatial maps that the scientific community has been building for the last several decades. We are also exploring the possibility of including an ASI LRA on NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission.

NASA and ASI have a distinguished history of Mars exploration, notably with the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on the European Space Agency's Mars Express orbiter, and the ASI-contributed Shallow Radar (SHARAD) instrument on NASA's Mars Reconnaissance Orbiter (MRO). Both instruments have contributed to our understanding of the Red Planet, and I look forward to continued discoveries resulting from our further collaboration.

Our technical teams should continue their dialogue. If NASA and ASI identify a mutually agreed plan forward, the next step would be for our teams to draft the respective responsibilities required for this activity. Once those are agreed upon, NASA's Office of International and Interagency Relations will work with your team to complete the necessary international agreement.

I look forward to this natural continuation of our successful cooperation in the exploration of Mars by building on our activities from Mars Express and MRO.

Sincerely,

Jim Watzin

James G. Watzin
Director, Mars Exploration Program

Canada

by Gordon Osinski, University of Western Ontario

Canadian Lunar Research Network 2016 Summary

The Canadian Lunar Research Network (CLRN) is comprised of approximately a dozen universities from across Canada. Researchers from CLRN focused on a number of research topics related to the Moon and asteroids. A highlight of the year for the Canadian space community was the launch of the OSIRIS-Rex mission with the Canadian-led and made OSIRIS-REx Laser Altimeter (OLA) instrument on board. Several CLRN researchers are involved in this instrument (Cloutis, Daly, Johnson, Tait) and a substantial research focus has been on the analysis of "analogue" materials (e.g., carbonaceous chondrites), understanding the spectroscopic properties of OSIRIS-REx target asteroid Bennu, and simulations related to making and evaluating shape models for Bennu in preparation for the arrival of the OSIRIS-Rex spacecraft.

In other research, CLRN scientists led by the University of British Columbia have revisited the subsurface density structure of Taurus Littrow valley using Apollo 17 gravity data and recent high resolution LOLA and LROC DEMs (Urbancic et al., 2016). At the University of Alberta, the ongoing, active use of the cold curation facility continues as well as the development of curation methods for cometary nucleus materials. The facility and its commissioning are described in Herd et al. (2016). At the University of Winnipeg, in addition to OSIRIS-Rex activities, Cloutis worked with colleagues in the US and China on analysis of Chang'e-3 Yutu rover spectroscopic data and with colleagues in Germany and Italy on analysis of Dawn data for asteroid Ceres

At the lead node at the University of Western Ontario, Flemming, Osinski and Tornabene have continued their work on impact cratering processes, including cratering mechanics, impact ejecta emplacement, shock metamorphism, and the potential for sampling deep lunar lithologies. Osinski was a co-author on a Science paper detailing the first results of the ICDP-IODP drilling of the Chicxulub impact crater. This article focused on the formation of peak rings in large impact craters, which is an ongoing discussion in lunar science. Banerjee, Bouvier, Moser, and Osinski continued research on radiometric and isotopic systematics of lunar meteorites and Apollo samples. A highlight was Bouvier's paper in Nature demonstrating that Earth and other planetary objects formed in the early years of the Solar System share similar chemical origins (Bouvier and Boyet, 2016).

In addition to the aforementioned scientific activities, 2016 was an active year in terms of updating Canadian priorities for space exploration. This process is being led by Topical Teams created in response to a Canadian Space Agancy Announcement of Opportunity in 2015. The CLRN PI, Osinski, is Chair of the Planetary Geology, Geophysics, and Prospecting Topical Team. Following the Canadian Space Exploration Workshop, held in Montreal in November 2016, this team has formulated 6 draft objectives:

- Document the geological record and processes that have shaped the surface of the terrestrial planets and their moons, icy satellites and asteroids;
- Determine the interior structure and properties of the terrestrial planets and their moons, icy satellites and asteroids;
- Determine the resource potential of the Moon, Mars, and asteroids;
- Understand surface modification processes on airless bodies;
- Understand the origin and distribution of volatiles on the terrestrial planets and their moons, asteroids, and comets;
- Understand the impact threat and hazards posed by impact events on the Earth and other solar system bodies.

Comments and input on these objectives is welcome (contact the CLRN PI).

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PUBLICATIONS

The following list of 177 publications was compiled from all SSERVI teams for 2016, bringing the total for years 1-3 to 478. Publications previously not included in the SSERVI Years 1 and 2 annual reports have been included here for completeness.

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