YEAR ONE ANNUAL REPORT

National Aeronautics and
Space Administration

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

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

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Timothy Glotch, Stony Brook University, Stony Brook, NY

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William Farrell, NASA Goddard Space Flight Center, Greenbelt, MD

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Andy Rivkin, Johns Hopkins Univ. Applied Physics Laboratory, Laurel, MD

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Daniel Britt, University of Central Florida, Orlando, FL

Institute for the Science of Exploration Targets: Origin, Evolution and Discovery (ISET)
William Bottke, Southwest Research Institute, Boulder, CO

INTRODUCTION

NASA's Solar System Exploration Research Virtual Institute (SSERVI) is pleased to present the following summary of scientific and technical accomplishments from its first year of operation. This report contains executive annual reports prepared by each of the nine U.S. teams, highlighting accomplishments in their first year of funding, March 2014-February 2015.

A bibliography of peer-reviewed SSERVI scientific publications can be found at http://sservi.nasa.gov/science-library/

NASA's Solar System Exploration Research Virtual Institute (SSERVI) was established in 2013 through joint funding from the NASA Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD), and is focused largely on science at the intersection of these two NASA enterprises. Expanding upon the scope of the successful NASA Lunar Science Institute (2008-2013), NASA created a new virtual institute to study not only the Moon, but also Near-Earth Asteroids, and the moons of Mars (Phobos and Deimos). SSERVI research teams address basic and applied scientific questions fundamental to these target bodies and their near space environments, providing scientific, technical and mission-defining analyses for relevant NASA programs and space missions.

The institute currently has nine Principal Investigators, who each lead a team of 30-50 researchers. Of the 318 co-Investigators and collaborators, 33% are students (undergraduate, graduate and/or postdoctoral fellows), representing a substantial investment in the next generation of planetary and exploration scientists. In the initial year of operation, SSERVI teams published 195 peer-reviewed papers and presented over 400 conference papers and presentations. SSERVI fosters collaborations between its competitively selected domestic teams, and at least 93 peer-reviewed papers have resulted from such cross-team collaborations. This represents research that was uniquely enabled by the sharing of ideas and data, often ahead of publication, within the institute framework.

The SSERVI central office is located at NASA Ames Research Center, Mountain View, CA, in the heart of Silicon Valley. Surrounded by innovation and cutting-edge information technology solutions, interactions occur easily in the virtual environment enabled by SSERVI's Central Office, among the geographically dispersed SSERVI teams, the greater research communities across the U.S., and several global partners.

In 2014, the Central Office held the first annual Exploration Science Forum (ESF), which featured scientific discussions of exploration targets of interest, recent mission results, and in-depth analyses of science and exploration studies. Dedicated side-conferences for graduate students and young professionals coincided with the ESF, and citizen science and public outreach discussions were interwoven among science topics as well. SSERVI also supports grass roots-driven Focus Groups on a wide variety of topics of interest to the broad community; Focus Group meetings are held annually at the ESF. In addition to hosting the Exploration Science Forum at NASA's Ames Research Center, SSERVI participates in, and often organizes special sessions at, scientific meetings such as the Lunar and Planetary Science Conference (LPSC), the European Planetary Science Conference (EPSC), the European Lunar Symposium (ELS), the Committee on Space Research (COSPAR), the American Geophysical Union (AGU) and others.

SSERVI also has an international partnership program that provides global collaborative opportunities. Proposals that demonstrate collaborative intentions and clear goals aligned with the U.S. teams can be accepted for partnership, allowing participation in SSERVI programs on a no-exchange-of-funds basis. Italy joined SSERVI in 2014, bringing the international partnership total to eight, including Canada, Korea, Germany, Israel, the Netherlands, Saudi Arabia and the United Kingdom.

NASA builds its virtual network of researchers to address complex, multi-faceted questions and uses Cooperative Agreement Notices (CANs) as the mechanism through which teams are funded. SSERVI and NASA Headquarters are currently developing a second CAN in anticipation of additional team selections in 2016. SSERVI teams are funded for five years, with CANs issued every 2-3 years to allow for both overlap between institute teams, as well as responsiveness to changes in NASA direction.

The first year of SSERVI operations saw many new collaborations and partnerships that resulted in new knowledge and scientific advancements. We hope you enjoy these first-year highlights focused on the intersection of science and exploration!

For more information, please visit us online at sservi.nasa.gov where you will find an archive of SSERVI seminars and scientific highlights of current space exploration activities.

Yvonne Pendleton, Director
Greg Schmidt, Deputy Director

CARLE PIETERS

Evolution and Environment of Exploration Destinations: Science and Engineering Synergism (SEEED)

Brown University, Providence, RI

Solar System Exploration Research Virtual Institute
Hosted at Brown University

Prof. Carlé M. Pieters, PI
http://www.planetary.brown.edu/html_pages/brown-mit_sservi.htm

SSERVI
Evolution and Environment of Exploration Destinations
[SEEED]

Co-Investigators at
MIT
Carnegie
AZ State Univ.
Mt. Holyoke
Univ. Tennessee
College of Charleston

Collaborators from
UC Santa Cruz
APL
Case Western
Consultants

Collaborators from
Russia
Germany, UK
Canada, France
Ukraine, Japan

First SSERVI Annual Report: January 2014 – February 2015

Overview:

The SSERVI Evolution and Environment of Exploration Destinations (SEEED) team is hosted by Brown University with major contributions from Co-Investigators at MIT and five additional institutions. We partner with collaborators from another four institutions as well as seven foreign countries. Altogether, SEEED participants include 24 CoIs and 19 Collaborators. 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

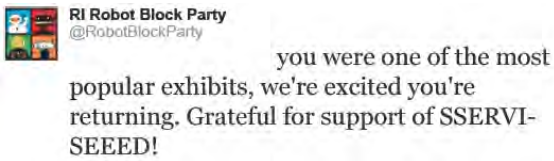
Our principal objective is to *create a virtual center of excellence focused on the science and environment of exploration targets,* including asteroids, the Moon, and the moons of Mars. Our implementation includes robotic and human exploration synergy and is structured to not only a) build bridges within the community and b) produce the next generation of knowledgeable and qualified planetary scientists and engineers, but also to c) attract some of the best minds into the field and keep them involved.

In addition to integrating SSERVI focused activities into the academic and research environment at institutions of our SEEED team, we actively sponsor workshops on cutting-edge topics that are well attended by the community and promote a strong element of discussion. Examples shown below include the Microsymposia (March: Houston) and Space Horizons (February: Brown) which are attended by scientists, astronauts, engineers, students, and NASA officials (programs available on our SEEED website - see cover). SEEED also participates extensively in local events that build a foundation for science and engineering synergy.

2014

2015

Grateful Tweet!



SSERVI Teams Collaboration:

SEEED and CLASS are in the process of jointly developing a graduate-level course on Phobos using the recently published PSS Book (see next page). The weekly lectures are planned to be open and available through Webex. Course credit involves additional activities and is arranged separately through a home institution.

During the regular SSERVI interactions (EC virtual and face-to-face meetings, site visits, ES Forum), many components of cutting edge research being carried out by different SSERVI teams have served as inspiration for SEEED activities (and visa-versa). This is a significant value-added core component of SSERVI. For example, our space weathering analyses have benefitted enormously from physical insights by DREAM2 and IMPACT. SEEED models for crustal evolution and the composition of small bodies are guided by cratering insights discussed by LPI-CLSE and dynamical history developed by ISET. We share a commitment to understanding the character and history of volatiles with VORTICES and understanding the evolution of regolith with CLASS. Such connections are of immeasurable value across SSERVI teams.

SEEED welcomed international collaborators Sasha Basilevsky, Misha Ivanov, and Lionel Wilson to Brown for extended visits and scientific discussions.

Special SEEED programs

In addition to our normal planetary science courses, a special graduate seminar is being held this term at Brown entitled "The Crater to Basin Transition on the Moon and Mercury"

During summer 2014 we hosted held a series of intensive seminars for SEEED faculty CoI's to exchange research insights and ideas at a high level. Topics included timescale of planetary evolution, diversity of lunar volatiles, and character and evolution of the crust. These extended detailed discussions were invigorating and strengthened ongoing collaborations and productivity.

Other SEEED Activities

Three new SKG were presented by PI Pieters at the LEAG meeting in October 2014. These SKGs address fundamental unknowns concerning time/space variations of surficial water and its potential value as a resource. The new SKGs were recommended by LEAG for inclusion.

SEEED collaborator Garrick-Bethell arranged for PI Pieters, IMPACT PI Horianyi, and DREAM2 CoI Halekas to be the core invited speakers at the Lunar Science Workshop at Hyung Hee University in Korea (May, 2014). As a group we also made visits to and presentations at KASI and KARI. The week-long visit resulted in very informative and productive interactions.

In October 2014, a Brown delegation of two faculty, and four students/staff traveled to the 5th International Moscow Solar System Symposium (5MS3), an outgrowth of the Moscow Microsympsosium. While there, they delivered eight oral presentations and posters on SSERVI topics (Phobos, asteroids, the Moon, Science and Engineering Synergism).

Research:

SEEED research activities encompass a number of integrated science themes with several near- and long-term goals: thermal/chemical evolution of rocky bodies (surface and interior); origin and evolution of volatiles in the Solar System; regolith of airless bodies (including space weathering). The active research and academic environment at SEEED institutions along with world-class research facilities enable broad participation in accomplishing SEEED goals. In this context, international involvement is viewed as an integral and long-term investment.

This report can highlight only a few of the many accomplishments of the SEEED team during the first year of SSERVI participation. In the examples below the institution or country of SEEED investigators are shown *(in italics).* A more complete overview of SEEED activities is found in the attached Appendix of Publication for SEEED peer-reviewed manuscripts and extended reports (not reviewed) produced during this first year. As shown in the publication summary, SEEED activities span all of the exploration targets, including significant integrated solar system topics (such as impact cratering, meteorite analyses, and early solar system modeling) and also include discussion of future opportunities or directions. Note: Although relevant to SSERVI, publications by SEEED CoIs that were funded entirely by missions (Dawn, GRAIL, LRO) are excluded from these SSERVI lists, but are also made available on our SEEED website : <http://www.planetary.brown.edu/html_pages/brown-mit_sservi_pubs.htm

D.R. Scott and J.W. Head *(Brown)*
50 years of Russian-US-International Lunar Exploration: A Roadmap for the Future.
Akademiai Nauk, in press (2015)

The Earth's Moon holds fundamental clues to the earliest history of the Solar System and the formative years of planetary geological and geodynamic evolution. Exploration of the Moon has revealed significant information about Earth's origin and evolution, from the earliest years of our Home Planet to clues about what it will be like in the future. Due to its relative proximity to the Earth, the Moon has served as a test bed to formulate global scientific questions, design scientific experiments to address these questions, develop engineering exploration capabilities to obtain the critical data, construct exploration strategies to undertake integrated exploration programs, undertake off-Earth human exploration capabilities and strategies, and formulate the bottom-up Science and Engineering Synergism (SES) that provides optimal scientific return. We review the steps in the development of these scientific exploration capabilities, show their optimization in the Apollo Lunar Exploration Program, and outline how Science and Engineering Synergism can lead to fundamental new engineering capabilities and scientific discoveries for future human and robotic exploration of the Moon.

Apollo 15 Commander Dave R Scott collecting rock samples at the edge of Hadley Rille.

Three SEEED papers in **Special Phobos book: Planetary and Space Science, Vol 102 (2014)**
[Pieters, Head, Ramsley *(Brown);* Britt *(CLASS, UCF);* Basilevsky *(Russia)*]

Composition of Surface Materials on the Moons of Mars

Carle M. Pieters [a,*], Scott Murchie [b], Nicolas Thomas [c], Daniel Britt [d]

[a] Dept. Geological Sciences, Brown University, Providence, RI 02912, USA
[b] Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA
[c] Universitaet Bern, Bern, Switzerland
[d] University of Central Florida, Orlando, FL 32816, USA

The value of Phobos sample return

Scott L. Murchie [a,*], Daniel T. Britt [b], Carle M. Pieters [c]

[a] Applied Physics Laboratory, Room 200-W216, 11101 Johns Hopkins Road, Laurel, MD 20723, USA
[b] Department of Physics, University of Central Florida, Building 12 Room 310, Orlando, FL 32816, USA
[c] Department of Geological Sciences, Brown University, Box 1846, 324 Brook St., Providence, RI 02912, USA

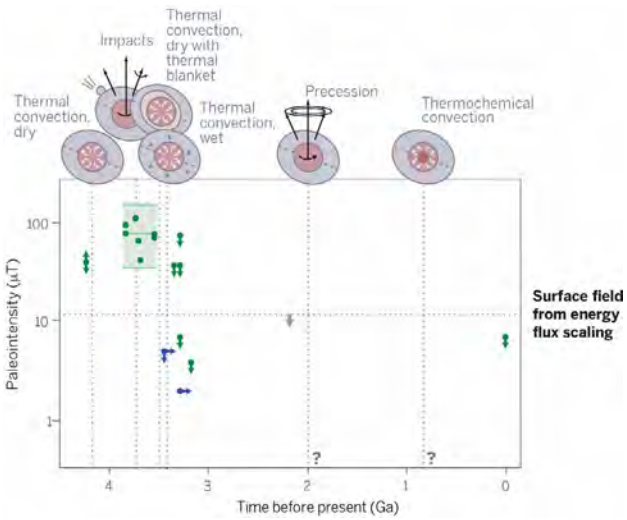
The surface geology and geomorphology of Phobos

A.T. Basilevsky [a,*], C.A. Lorenz [a], T.V. Shingareva [a], J.W. Head [b], K.R. Ramsley [b,c], A.E. Zubarev [d]

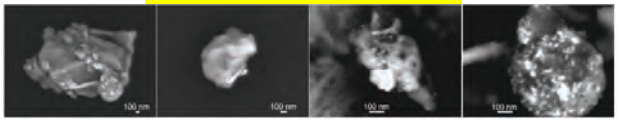
[a] Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, Russia
[b] Department of Geological Sciences, Brown University, Box 1846, Providence, RI, USA
[c] School of Engineering, Brown University, Box D, Providence, RI, USA
[d] Moscow State University of Geodesy and Cartography (MIIGAiK), 105064 Moscow, Russia

Lunar Dynamo

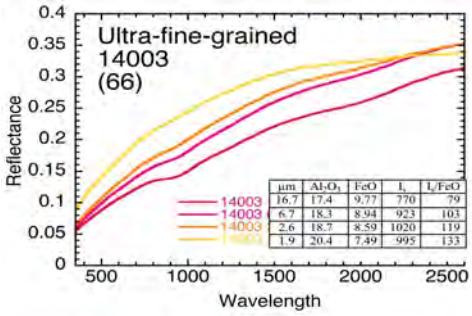
Benjamin P. Weiss (*MIT*) and Sonia M. Tikoo (2014) *Science* 346, 1198, 1-10.
=> The dynamo field persisted from at least 4.25 to 3.56 billion years ago (Ga), with an intensity reaching that of the present Earth. The field then declined by at least an order of magnitude by *~3.3 Ga.*



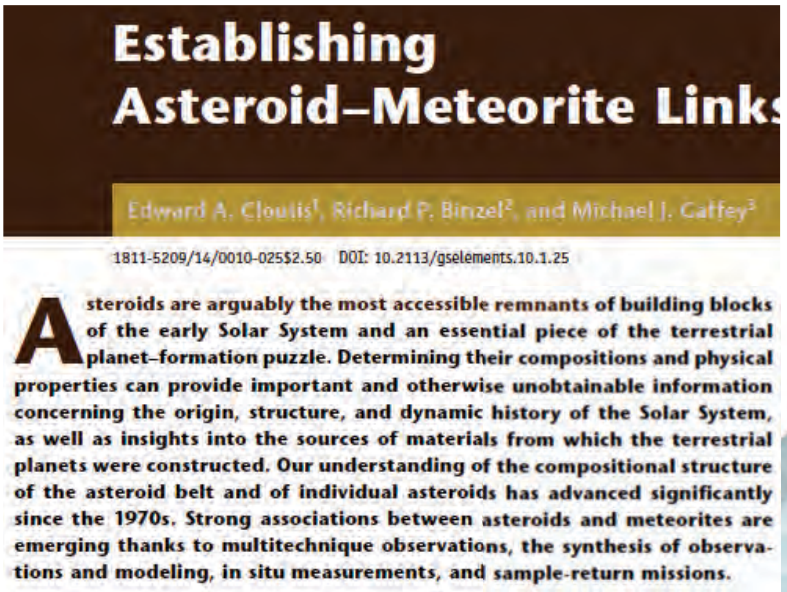
Ultra-fine Regolith



D.S. McKay, B.L. Cooper, L.A. Taylor (*U TN*), J.T. James, K. Thomas-Keprta, C.M. Pieters (*Brown*), et al. (2015) Physicochemical properties of respirable-size lunar dust, *Acta Astronautica* 107, 163-176
=> These ultra-fine lunar soil particles follow the compositional trends seen with larger soil particles. They are less toxic than crystalline fine particles.



μm	Al_2O_3	FeO	I_s	I_s/FeO
16.7	17.4	9.77	770	79
6.7	18.3	8.94	923	103
2.6	18.7	8.59	1020	119
1.9	20.4	7.49	995	133



Establishing Asteroid–Meteorite Links

Edward A. Cloutis[1], Richard P. Binzel[2], and Michael J. Gaffey[3]

1811-5209/14/0010-025$2.50 DOI: 10.2113/gselements.10.1.25

Asteroids are arguably the most accessible remnants of building blocks of the early Solar System and an essential piece of the terrestrial planet–formation puzzle. Determining their compositions and physical properties can provide important and otherwise unobtainable information concerning the origin, structure, and dynamic history of the Solar System, as well as insights into the sources of materials from which the terrestrial planets were constructed. Our understanding of the compositional structure of the asteroid belt and of individual asteroids has advanced significantly since the 1970s. Strong associations between asteroids and meteorites are emerging thanks to multitechnique observations, the synthesis of observations and modeling, in situ measurements, and sample-return missions.

E. Cloutis (*Canada*)
R. Binzel (*MIT*)
***2014, ELEMENTS*, VOL. 10, PP. 25–30**

Asteroid (and planetary) exploration analogy. At the wide base is the discovery of the broad population, largely through telescopic surveys. Physical measurements are carried out on many, but not all, discovered objects. A still fewer number of objects are found to be particularly interesting. Significant science questions are posed for those which can be subjected to additional observational and theoretical study. The capstone (uncompleted) represents spacecraft missions to the few objects whose study has the potential to deliver the highest level of understanding.

Education / Public Engagement Report

SEEED and our sister SSERVI team, CLASS (Center for Lunar and Asteroid Surface Science hosted at Univ. Central FL), have developed an integrated public engagement program that is jointly sponsored by both SSERVI teams. Throughout the first year of the SSERVI cooperative agreement, the SEEED and CLASS SSERVI Education Public Engagement (EPE) team was very productive in training pre-service and in-service educators from both formal and informal institutions as well as working with students and engaging the public on SSERVI-related topics such as how our broader teams are exploring and working to understand the formation and evolution of the Moon and small bodies in our solar system.

To facilitate inspiring and engaging both students and the public, we have brought together a dynamic team of science educators, authors, artists and storytellers from around the country – all of whom are committed to working on the project through its 5-year entirety. Our EPE team is focusing on three areas: 1) infusing arts into traditional science, technology, engineering and mathematics (STEM) lessons; 2) integrating formal, informal and out-of-school experiences to foster content retention; and 3) broaden audience reach to include ALL learners, especially those with physical limitations. After the initial highly successful workshop, we continue to work closely with the core group of educators who actively participated. During this process, we identify gaps and redundancy in curricula and activities related to SSERVI science and technology that would benefit from future effort.

Our Education and Public Engagement group is also working with two students and one part-time staff member who are blind. They are helping to review existing SSERVI – related curricula and activities vetted by our EPE Core Team that may become part of the final educator guide. As we progress, we are building a list of modifications and / or adaptations needed to ensure that we address Universal or Inclusive Design.

Summarized below are some of the activities and events of our SEEED/CLASS EPE team.

Educator Professional Development Events that included SSERVI STEM content

Event / Activity	Date	Location	# Educators	Grades	Underserved*
Space Science for Teachers Course	06.05-07.03.2014	Charleston, SC + online	10	6 - 14	Yes
SSERVI Workshop – Core TEAM	09.05-07.2014	Columbia, SC	20	4 -16 / informal	Yes
National Federation of the Blind Workshop for Educators of the Blind	10.14-17.2014	Baltimore, MD	40	4 – 16	Yes
Geology of the Moon - Online course for in-service teachers	Fall 2014	18 states + military	20	4 - 16	Yes

*Underserved participants include Deaf/Hearing Impaired, Blind / Visually impaired and underserved populations

Student- and Public - Centered Events

Event / Activity	Date	Location	# Participants	Grades / Public	Underserved*
Charleston STEM Festival	02.08 2014	Charleston, SC	1500	Public	Yes
Cougars Basketball STEM Day	02.18.14	Charleston, SC	1600	4 – 8	Yes
Grand Opening – SC State Museum	08.13-14.2014	Columbia, SC	5000+	Public	Yes
InOMN	09.06.2014	Columbia, SC	6000	Public	Yes
Riverdogs	04.09.14	Charleston, SC	5000	K-12	Yes

Upcoming EPE activities

- Quarterly telecon with the Core EPE Team; planning for upcoming Summer 2015 workshop
- Participation in and Poster presentations at LPSC46 in Houston, TX

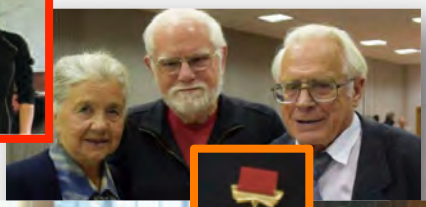
SSERVI Evolution and Environment of Exploration Destinations

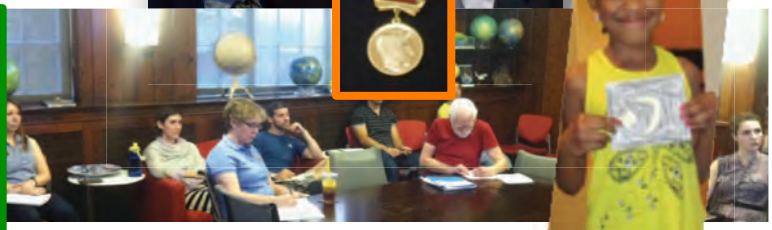
SEEED

Annual Report Appendices:

1. SEEED snapshots of 2014 Page 7
2. List of students actively participating in SEEED activities Page 8
3. Conferences, workshops and meetings where SEEED presentations were made [other than LPSC, etc.] Page 9
4. SEEED Publications: January 2014 to February 2015
   - Peer Reviewed Manuscripts Page 10
   - Extended Reports/Abstracts (not peer-reviewed) Page 15

SEEED 2014





SEEED Students and Postdocs
2014, 2015

SSERVI Graduate Students at Brown or MIT who have been a lead author on a SEEED publication are listed below. Students who graduated in 2014 are indicated as a recent graduate.

Bruck Syal, Megan (recent graduate)
Cannon, Kevin
Chan, Nicholas (undergraduate student)
Cheek, Leah (recent graduate)
Cournède, Cécile (a student in France working with B. Weiss of MIT)
Dhingra, Deepak (recent graduate)
Dygert, Nicholas
Ermakov, Anton
Evans, Alexander
Fu, Roger
Goudge, Timothy
Greenberger, Rebecca
Jackson, Colin R.M. (recent graduate)
Jansen, Johanna
Jawin, Erica
Jozwiak, Lauren
Li, Shuai
Moriarty III, Daniel
Prissel, Tabb
Scheinberg, Aaron
Sun, Chenguang (recent graduate)
Tikoo, Sonia (recent graduate)
Vaughan, William
Whitten, Jennifer (recent graduate)

Summer Undergraduate Intern:
Reed Mershon from the University of Chicago

SSERVI Postdoctoral Researchers:
Baker, David M. H. (partial)
Potter, Ross
Wiseman, Sandra (partial)

Conferences, Workshops and Meetings

For which SEEED presentations were made

(LPSC and similar conference presentations that include Extended Reports/Abstracts are identified under Publications)

Space Horizons, Brown Univ. February 2014
1 talk, numerous posters

Brown-Vernadsky Microsymposium 55 Houston, March 2014
4

ESLAB New Insights into Volcanism across the Solar System, Noordwijk June 2014
4 (1 invited talk)

Goldschmidt Conference
1 (invited talk)

SSERVI Exploration Science Forum, AMES July, 2014
16 (1 invited talk)
[Note: this in the minimum number; Only 1st authors are identified.]

COSPAR, Moscow August, 2014
1

Meteoritical Society Meeting, Morocco, September, 2014
1

Annual Meeting of the Lunar Exploration Analysis Group, APL, October, 2014
2

The Fifth Moscow Solar System Symposium, Moscow, October, 2014
8

Hayabusa Symposium, Japan, December 2014
1

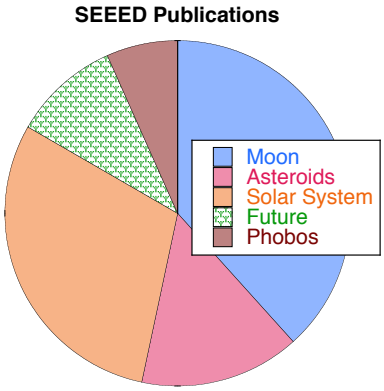
American Geophysical Union, San Francisco, December 2014
28 (1 invited talk)

Publications Involving SEEED Participation
January 2014 to February 2015

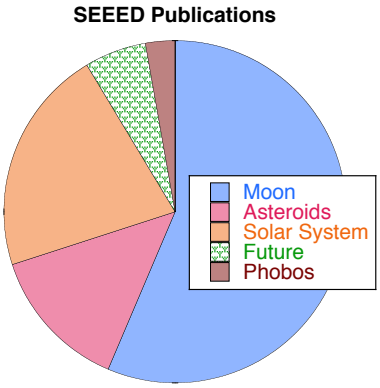
For all SEEED publications listed below any student lead author is underlined. When more than one SSERVI team was involved in the collaboration it is indicated with ** by the SSERVI number. We also indicate when International participation was involved after the SSERVI number. Active mission publications are *not* included unless led by a student of a CoI.

SEEED contributions span all of the SSERVI exploration targets, including significant integrated solar system topics (such as impact cratering, meteorite analyses, and early solar system modeling) as well as discussion of future opportunities or directions. We have organized our SSERVI publications alphabetically into two lists and provide a graphical summary below according to general target.

a. **Peer-reviewed manuscripts** that have been published in peer-reviewed professional journals (or will after review is successfully completed).
b. **Extended reports** that are ≥ 2 pages but are not peer reviewed. Most of these are comparable to extended abstracts linked to presentations made at the *Lunar and Planetary Science Conference*. Both 2014 and 2015 LPSC reports are included here because of the timing between submission and presentation.



Peer-Reviewed 2014-15 [60]



Extended Reports/Abstracts [103]

SEEED Peer-reviewed Publications
January 2014-February 2015

Alibay, F., V. R. Desaraju, J. E. Duda, and J. A. Hoffman (2014), Fractionated robotic architectures for planetary surface mobility systems, *Acta. Astronaut.*, *95*, 15-29. Doi: 10.1016/J.Actaastro.2013.10.014. SSERVI-2014-291.

Basilevsky, A. T., M. A. Kreslavsky, I. P. Karachevtseva, and E. N. Gusakova (2014), Morphometry of small impact craters in the Lunokhod-1 and Lunokhod-2 study areas, *Planet. Space Sci.*, *92*, 77-87. Doi: 10.1016/J.Pss.2013.12.016. SSERVI-2014-296; International.

Basilevsky, A. T., C. A. Lorenz, T. V. Shingareva, J. W. Head III, K. R. Ramsley, and A. E. Zubarev (2014), The surface geology and geomorphology of Phobos, *Planet. Space Sci.*, *102*, 95-118. Doi:

10.1016/j.pss.2014.04.013. SSERVI-2014-297; International.

Bauch, K. E., H. Hiesinger, J. Helbert, M. S. Robinson, and F. Scholten (2014), Estimation of lunar surface temperatures and thermophysical properties: test of a thermal model in preparation of the MERTIS experiment onboard BepiColombo, *Planet. Space Sci.*, *101*, 27-36. Doi: 10.1016/J.Pss.2014.06.004. SSERVI-2014-298; International.

Cheek, L. C., and C. M. Pieters (2014), Reflectance spectroscopy of plagioclase-dominated mineral mixtures: Implications for characterizing lunar anorthosites remotely, *American Mineralogist*, *99*, 1871-1892. Doi: 10.2138/am-2014-4785. SSERVI-2014-308.

Cloutis, E. A., R. P. Binzel, and M. J. Gaffey (2014), Establishing Asteroid-Meteorite Links, *Elements*, *10*(1), 25-30. SSERVI-2014-309; **, International.

Cole, D. M., M. A. Hopkins, and L. A. Taylor (2014), Contact behavior of lunar materials and their simulants: Experimental observations and model developments, *American Society of Civil Engineers, Earth and Space 2014*, 1-8. SSERVI-2014-xxx; **.

Cournède, C., J. Gattacceca, M. Gounelle, P. Rochette, B. P. Weiss, and B. Zanda (2014), An early solar system magnetic field recorded in CM chondrites, *Earth Planet. Sci. Lett.*, *410*, 62-74. SSERVI-2014-460. SSERVI-2014-xxx; International.

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SSERVI YEAR ONE
ANNUAL REPORT

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Lunar and Planetary Institute, Houston, TX

Annual Report – Year 1 **PI David A. Kring**

1. Team Project Science, Exploration, & Related Training Activities

Our team is in the first year of an intensive investigation of (i) the consequences of near-Earth object (NEO) impacts in the Earth-Moon system, (ii) the sources of those impactors as a function of time, (iii) implications those sources have for the past evolution of the Solar System, and (iv) implications those results have for the hazards of future impacts on Earth.

There is nothing like a real near-Earth asteroid (NEA) impact event to rivet attention on the problem. Such an event occurred unexpectedly February 15, 2013, near Chelyabinsk, Russia, and required our immediate attention. With the talent and resources assembled for NLSI (final year) and SSERVI (first year), we were able to quickly react and provide an assessment of the size of the impactor, predict its composition and structural properties, confirm those properties once samples were recovered, and then determine the collisional history of the impactor over the past 4.5 billion years (Fig. 1).

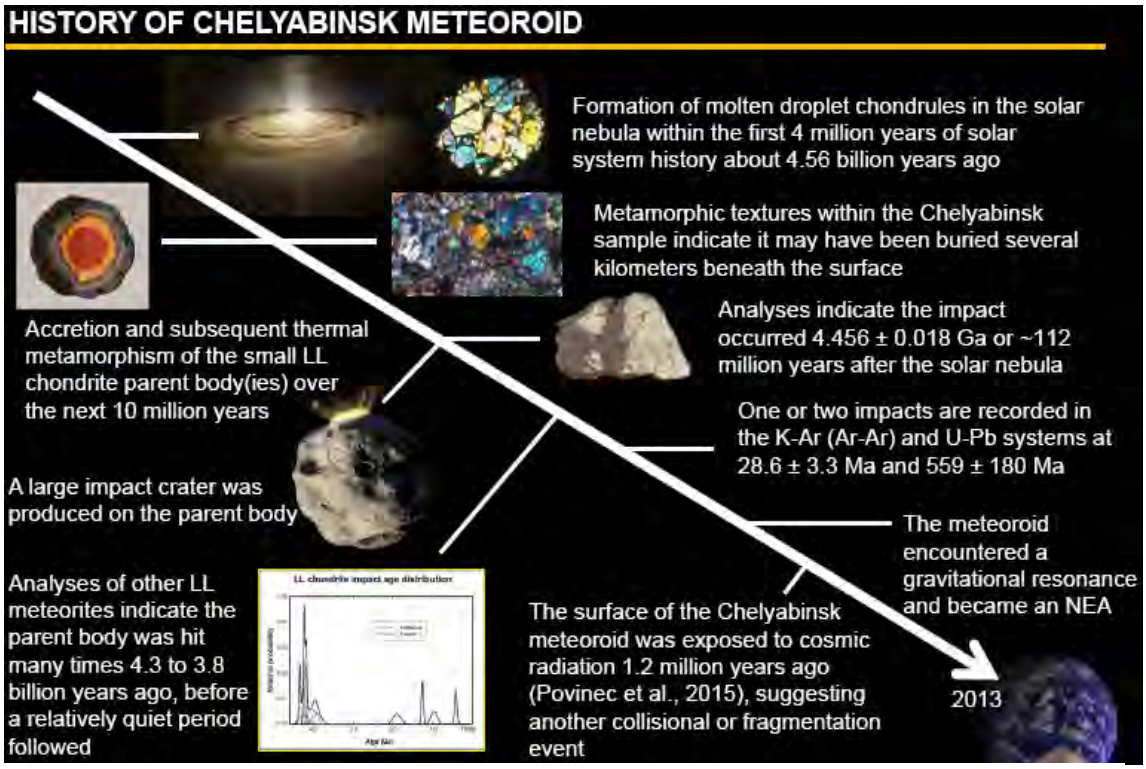

Fig. 1. *Summary graphic with the history of the Chelyabinsk near-Earth asteroid (Kring et al. 2013a,b; Beard et al. 2014; Lapen et al. 2014).*

Because there was broad interest in the Chelyabinsk event, the editors of *Physics Today* asked PI Kring to write a feature summary article (Fig. 2). He teamed up with Mark Boslough (Sandia National Laboratories) to integrate the analytical results represented in Fig. 1 with the impact dynamics that occurred in the atmosphere and created havoc on the ground (Kring and Boslough, 2014).

The Chelyabinsk NEA was a fragment of one of the ordinary chondrite parent bodies that our team is studying to unravel the collisional evolution of the Solar System. In a project led by Co-I Swindle, we published an article that summarized ~100 Ar-Ar impact ages (Swindle et al., 2014), the cadence of which is an essential input parameter for dynamical models of the processes that led to the impacts.

Those analyses are part of our broader effort to understand the impact flux in early Solar System history and how it was shaped by the accretion and orbital evolution of planets. We teamed up with international partners to identify appropriate lunar samples for U-Pb radiometric analyses (Norman and Nemchin, 2014; Merle et al., in press) and are using LROC imagery to better understand the geologic context of the samples (e.g., Hurwitz and Kring, 2015), which is needed to link those samples to specific basin-forming impact events.

Fig. 2. *Cover of Physics Today showing a three-dimensional simulation of the 20-m diameter Chelyabinsk asteroid's half-megaton impact in Earth's atmosphere (Kring and Boslough, 2014).*

In parallel with those sample analyses, we have been using computer hydrocodes to simulate basin-forming impact events in early Earth-Moon history. We compiled a large series of individual simulations to generate analytical scaling relationships (Potter et al., in press) that can be used by future investigators to easily calculate the outcome of a basin-forming impact event. While those scaling relationships were derived from studies of lunar basins, the results are applicable to the Hadean Earth. One important outcome of the work is that the basins produced on the Hadean Earth were far larger than previously suspected, because of the consequences of hotter target conditions. (See, also, an inter-team study of the Hadean Earth in Section 2.) As always, we work very hard to translate our research results into formats that can be used by the broader planetary science and exploration communities, particularly for training purposes. Thus, we ran a specific set of hydrocode simulations that can be used to teach the principles involved and posted them on-line with the title *Video Simulations of Impact Cratering Processes*.

As noted above, it is essential to understand the sources of impactors and how those sources may have changed with time as the Solar System evolved. In Year 1, we attacked that problem in two ways. We began by determining the ages of 250 lunar regolith samples in both the Apollo collection and our lunar meteorite collection (Fagan et al., 2014). Those ages represent the time when each regolith sample was closed to additional material. We can then use a sequence of those time-calibrated samples to see if impactor relics change as a function of time. To begin the second step of that process, we selected a group of regolith breccias that were closed at ~2 Ga. We have independent evidence that the Earth-Moon system may have been hit by a spike of impactors at that time, so we wanted to determine if that spike was generated by a single type of impactor (or not) that might reflect the break-up of a larger asteroid or cometary body. Preliminary results (Fagan et al., 2015) reveal a diversity of impactors at that time, rather than a dominant type of impactor.

We also used highly siderophile elements (HSE) to fingerprint remnants of impactors that are entrained in Apollo melt samples. In a huge effort, nine Apollo 16 impact melt rock samples were split to produce over 110 individual HSE and Re-Os isotope analyses (Liu et al., in press). We are seeing a hint in this data of two trends that could be interpreted as follows (Fig. 3): resonances swept through the asteroid belt delivering outer-belt carbonaceous chondrite-type impactors circa 4.2 Ga; followed by inner-belt ordinary and enstatite chondrite-type impactors circa 4.0-3.7 Ga; on top of which are iron-core fragments that may have originally formed in the vicinity of Earth, been randomly scattered into the asteroid belt, and then re-delivered to the vicinity of Earth by sweeping resonances. It will be fascinating to see if this initial picture survives further work. We have to be cautious of mis-directions that can be created in a data-poor environment.

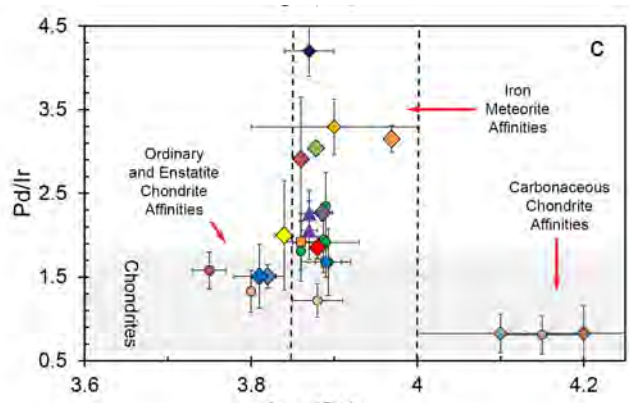

Fig. 3. *HSE signatures of impactors that hit the Moon.*

Those accretional and impact cratering processes delivered volatiles to the Moon. In Year 1, we initiated a multi-task study of those volatiles, including their origin, their cycling in the lunar interior, and eventual venting and processing at the lunar surface. This work has strong elements of both science and future exploration of the Moon. We calculated the production of volatiles (H_2O, CO_2, CO, F, S, and Cl) at pyroclastic vents as a function of vent size (Kring et al., 2014a) and for a specific vent in Schrödinger basin (Kring et al., 2014b) that is a proposed target for a human-assisted sample return mission involving the Orion crew vehicle (e.g., Potts et al., as described further below). With that input, our SSERVI colleagues on the APL team (Hurley and Bussey, then a SSERVI team PI and now HEOMD's Chief Exploration Scientist) modeled the transport of those volatiles and the masses that would be trapped in permanently shadowed regions. We also described a fragment of magnetite (oxidized iron) found in an Apollo sample and how it may have formed in reactions involving molecular species like H_2O (Joy et al., submitted). Finally, in a another (and, as yet, preliminary) study of Apollo samples, we utilized the D/H isotopic ratio in Apollo samples to infer that the ultimate source of water in the lunar interior was dominated by material with carbonaceous chondrite affinities, rather than comets or other types of chondrites (Barnes et al., 2015). Work on all three of those efforts will continue in Year 2.

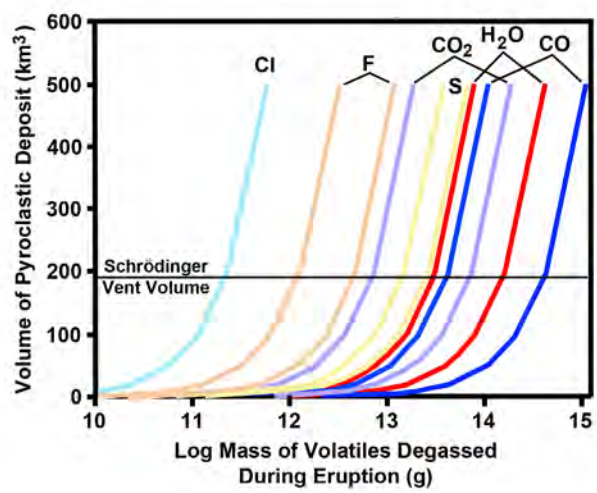

Fig. 4. *Production of volatiles by lunar pyroclastic vents.*

To further enhance our assessment of the sources of material delivered to the Moon and how the volatiles were cycled through the lunar interior, we began developing two new analytical techniques. To quantify the trace volatile elements Zn, Cd, Se, Rb, Ag, In, Sb, Tl, Bi, and Mo in Apollo samples, new ICP-MS protocols and standards needed for calibration of the results are being developed at Co-I Neal's lab. While those techniques are in development, Neal and Co-I Taylor prepared and submitted Apollo sample requests that were approved for application of the new techniques. In addition, Co-I Walker's group is developing a new negative thermal ionization mass spectrometry (N-TIMS) technique for analyzing Ru isotopes as a new tool for genetic identification of the asteroidal sources of material hitting the Earth and Moon. Application of these pioneering methods will occur in Year 2 and beyond.

Our assessment of near-Earth asteroids and comets proceeded along two paths. We analyzed the properties of meteoritic samples of asteroids (e.g., Farsang et al., 2015; Gregory et al., 2015; Zolensky et al., 2015) that contain evidence of the collisional and surface-altering properties that may affect an assessment of their hazards and an assessment of future exploration of them by crew. Moreover, with our Co-I's Nolan and Howell at Arecibo Observatory, we made a number of radar observations that are now being analyzed. Those observations include 209P/LINEAR (comet nucleus), 2014 HQ124 (Fig. 5), 2006 SX217, and 2004 BL86, the latter of which was the tenth asteroid observed by our Arecibo colleagues during SSERVI. There are nearly two dozen opportunities to observe NEO Human Space Flight Accessible Targets (NHATS) at Arecibo in the remainder of 2015.

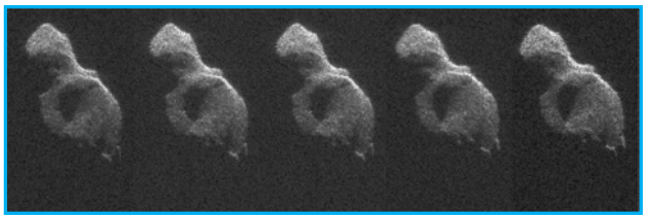

Fig. 5. *Near-Earth asteroid 2014 HQ124 using Goldstone to transmit and Arecibo to receive, which produced results with a 3.75 m spatial resolution and a signal-to-noise value about 20 times higher than that possible with Goldstone alone.*

A particularly rich component of our team's work is application of our scientific expertise to exploration issues. In Year 1, we made several significant contributions to those efforts. Building on a previous NLSI-sponsored 5-year study (e.g., Kring and Durda, 2012) that had identified Amundsen crater as an excellent landing site to meet the exploration objectives of a NRC (2007) report, we published as part of Year 1 SSERVI activities a detailed analysis of Amundsen crater, including its permanently shadowed regions (PSRs), and proposed two traverses for robotic rovers (Lemelin et al., 2014). That rover could either be commanded from Earth (because Amundsen is on the limb of the Moon) or by crew in an orbiting Orion vehicle. The global lunar landing site study (Kring and Durda, 2012) also identified Schrödinger basin as the scientifically-richest location on the Moon. As part of our Year 1 SSERVI activities, we published a detailed analysis of Schrödinger basin, including several robotic traverse options (Potts et al., 2015) that could be coordinated with crew in an orbiting Orion vehicle. That input was forwarded to a LEAG Strategic Action Team evaluating potential targets for lunar volatile missions. We are very proud to report that two of our team's students participated on that Strategic Action Team.

In evaluating the robotic rover traverses with colleagues at Boeing (who provided two student engineers to supplement our science and exploration summer intern program), we identified several rover parameters that affect trafficability, traverse speed, and, thus, traverse distance during a mission with a limited duration (such as a single lunar day). That prompted us to begin a study to size rovers for those types of activities; the goal is to provide better scope for future architectural assessments.

In support of Orion and the development of Exploration Missions (e.g., Fig. 6), we briefed the Orion team and also generated white papers about the stability of distant retrograde orbits (DROs) and orbital communication relays. Important elements of that work were led by former NLSI PI Jack Burns and our partners on the Lockheed Orion team. At the very end of SSERVI Year 1, we began to expand our efforts with assessments of a shorter Orion mission (e.g., 21 vs. 31 days), daily schedule options for crew on Orion involved in a human-assisted robotic and sample return mission, and imaging requirements from Orion.

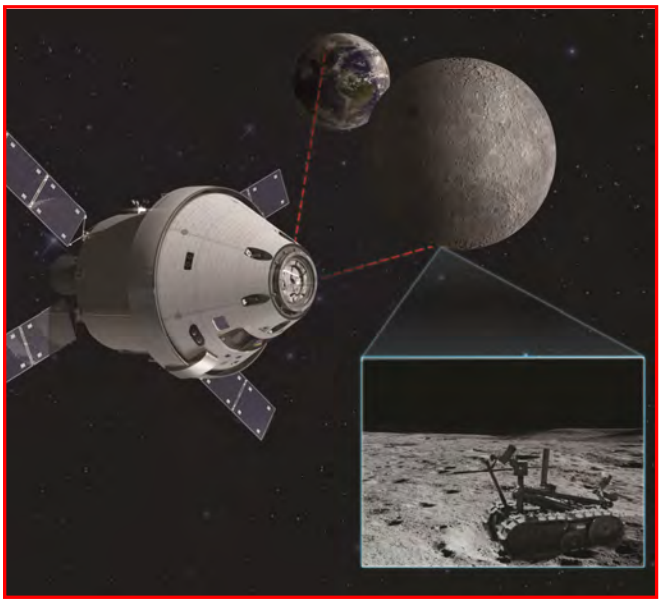

Fig. 6. *In an Exploration Mission scenario being investigated, crew within Orion in an DRO or L2 halo orbit would coordinate activities with a robotic asset within the Schrödinger basin on the lunar farside. An ascent vehicle on the robotic lander would then deliver samples to Orion for return to Earth.*

PI Kring, Co-I's Eppler, Abell, Zolensky, and others were involved in the training of the latest class of astronauts. We expanded the previously developed lunar and planetary surface curriculum with new presentations, tools, and exercises to assist this class with anticipated work on the ISS and in the vicinity of asteroids. Geologic training of the new class of astronauts began in February 2014 and was completed in November 2014.

Throughout the year, PI Kring continued his work as the U.S. representative on an ESA Lunar Sample Return Science Definition Team. In the midst of Year 1, those activities received a big boost when the Human Spaceflight and Operations Directorate within ESA was tasked to set up a formal lunar program. We also continued to support the Global Exploration Roadmap (GER) process, providing input and attending meetings organized by Kathy Laurini, Roland Martinez, and others.

See Sections 4 and 5 for a complete list of our published results. As the Lemelin et al. (2014) and Potts et al. (2015) papers illustrate, we try to publish as many of our exploration results as possible, but it is important to note that much of our exploration work goes into briefings and is absorbed by mission architects, rather than appearing in peer-reviewed research journals.

We want to close this section of the report with a few remarks about our training activities, which are important derivatives of our science and exploration program that help ensure a credible workforce will be in place when human exploration once again extends beyond low-Earth orbit.

One of the highlights is our *Field Training and Research Program at Meteor Crater*. We hosted 16 of the world's brightest graduate students at the crater in October 2014 (Fig. 7). In addition to learning about impact cratering processes and the demands of exploring that type of terrain (whether it be on the Moon, Mars, or an asteroid), the students were immediately asked to apply their skills to a research project. They mapped deposits of impact ejecta far beyond those in the classic map of Gene Shoemaker; results are being presented at the 2015 Lunar and Planetary Science Conference.

Fig. 7. *PI Kring with two students at Meteor Crater.*

We also worked with International Space Station (ISS) Expedition 38 and 39 crews to obtain new images of NEA impact sites on Earth (e.g., Fig. 8). One of those ISS images (Fig. 9) was used to generate an on-line laboratory exercise to Measure the Depth of Meteor Crater and the Height of its Rim, which was used in our training programs and made available for universities everywhere.

Fig. 8. *Image of the Manicouagan impact crater in Canada. ISS structure is evident in the left side of the image. NASA Image ISS-038-E-25460*

Fig. 9. *Image of Meteor Crater taken by ISS crew to assist with our 2014 astronaut training program and subsequent student training programs. This spectacular shot was taken with a 1000 mm lens with a very low sun angle, so that it would be suitable for the training exercise. Detail from NASA image ISS-038-E-067508.*

Finally, we used Lunar Reconnaissance Orbiter Camera (LROC) images and Kaguya Terrain Camera (TC) images to build an on-line Atlas of Lunar Sinuous Rilles that can be used for exploration planning and training purposes.

Closing remarks: This report is a representative subset of our team's productivity and accomplishments. Additional details can be found on the team's website (http://www.lpi.usra.edu/exploration/), in monthly reports that were submitted throughout Year 1, and in the list of publications in Sections 4 and 5.

2. Inter-team Collaborations

We initiated our SSERVI program with a planned collaboration with the team at the Southwest Research Institute. That collaboration has already produced a high-profile paper in *Nature* (Marchi et al., 2014). In that work, we used analyses of the lunar impact record to examine the consequences of early Solar System bombardment on the Hadean Earth (Fig. 10). We argue that the impacts resurfaced the planet, heated the crust and upper mantle of the Earth, and episodically boiled away the oceans. To facilitate the communication of those results to a broader community and to make them accessible to universities, we produced an on-line collection of graphics and videos for download under the title Impact Cratering on the Hadean Earth.

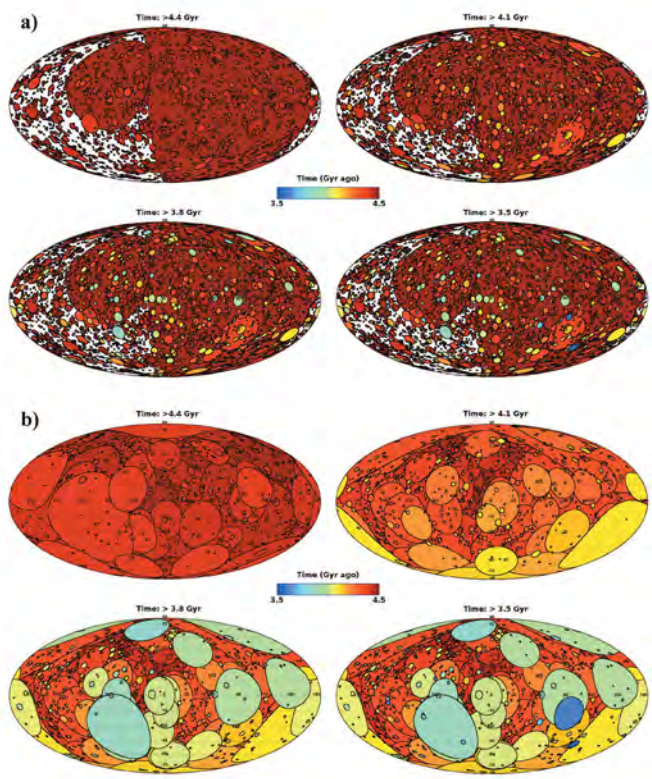

Fig. 10. *Spatial distribution and sizes of craters formed on the early Earth from circa 4.4 Ga (top) to 3.5 Ga (bottom) (Marchi et al., 2014). One cannot interpret the early Earth without taking into account the thoroughly invasive effects of early Solar System bombardment.*

That work fed another collaborative effort with the SwRI team, which was to organize and host the *Workshop on Early Solar System Bombardment III* (meeting banner below) held at the end of Year 1. Although it was a small workshop, the intellectual content and discussion was incredibly rich. Our previous NLSI-sponsored Bombardment II workshop generated several high-profile papers in *EPSL* and *Nature* journals. It already seems clear that the SSERVI-sponsored Bombardment III workshop will have a similar influence on the field.

As noted in Section 1, we have a series of parallel tasks to evaluate the delivery, processing, venting, and transport of volatiles on the Moon, including an evaluation of their ISRU potential. That work has benefited immensely from contributions provided by the APL SSERVI team (Bussey and Hurley). Preliminary results were presented at the *Lunar Exploration Analysis Group* meeting at APL in 2014 and a draft manuscript is in preparation.

Some of our Co-I's (e.g., Bleacher) and international partners (e.g., Osinski) are also assisting other SSERVI teams. It is evident that some of the work being conducted by our team is influencing work by other teams (and vice versa). Because those collaborations were not an integral part of our proposal, we have not yet worked out how they will evolve in subsequent years. Nonetheless, we anticipate several additional inter-team publications as a result of those collaborations.

3. E/PO Report

Our efforts in Year 1 focused on:

1. Research experiences for high school students that emphasize the nature of science and scientific inquiry and inspire STEM career decisions; and
2. Engagement of the public through materials for informal education venues.

Fig 11. *Locations of 2014-15 ExMASS schools.*

Exploration of the Moon and Asteroids by Secondary Students (ExMASS)

Exploration of the Moon and Asteroids by Secondary Students (ExMASS) offers high school student teams from across the country the chance to conduct student-driven research in either lunar or asteroid science, under the guidance of their teacher and a scientist advisor. The 2014-2015 program began in July 2014 with an ExMASS advisory board meeting consisting of past teachers and scientist advisors. This group met to discuss ways to improve ExMASS, which has its heritage in the highly successful, NLSI-funded High School Lunar Research Projects. This meeting was highly productive and discussions produced, among other things, an articulation of (i) topics to be covered in a new Asteroid 101 activity, (ii) the role of the teacher vs. the role of the scientist advisor, and (iii) possible asteroid research topics and available data. Since September 2014, 46 students from 10 schools across the country (Fig. 11) have been participating in ExMASS. Five of the 10 schools serve underserved and underrepresented populations. For six schools, ExMASS represents the first time they have participated in an authentic research experience. At the onset, three of the participating schools piloted a new Asteroid 101 guided-inquiry activity, a modified version of Moon 101 created for ExMASS and its predecessor program. Feedback from both students and teachers regarding Asteroid 101 was very positive; few changes will need to be made to the activity before the 2015-2016 program. Pre-program evaluation data were collected on student knowledge of lunar science and their views of the nature of science. These data will be compared to post-program evaluation data to be collected following completion of student research projects.

Traveling Library Exhibits

CLSE has created a new exhibit designed for display in public libraries. *Protecting Our Home* is currently available for loan, along with supplemental materials available on the CLSE E/PO website. This exhibit discusses the threat of asteroid impacts and airbursts on Earth and the research conducted by CLSE that is assisting the scientific and engineering community in addressing the issue. A second exhibit will be created in Year 2.

CLSE continues to offer seven NLSI-funded exhibits for loan. Between March 2014 and January 2015, 16 unique locations displayed these exhibits, reaching an estimated 40,000 members of the general public. As intended, most institutions reported integrating the exhibits into larger public programming such as International Observe the Moon Night (InOMN) and summer reading programs for children.

4. Peer-Reviewed Publications

Key: Underlines indicate student names
Double-asterisk (**) attached to postdoc names
Triple-asterisk (***) appears at the end of cross-team collaborations

SSERVI-2014-078
P. D. Spudis, D. J. P. Martin, and G. Kramer (2014) Geology and composition of the Orientale Basin impact melt sheet. *Journal of Geophysical Research 119*, 19–29.

SSERVI-2014-079
M. Sharp, I. Gerasimenko, L. C. Loudin, J. Liu**, O. B. James, I. S. Puchtel, and R. J. Walker (2014) Characterization of the dominant impactor signature for Apollo 17 impact melt rocks. *Geochimica et Cosmochimica Acta 131*, 62–80.

SSERVI-2014-133
A.L. Fagan**, K. H. Joy, D. D. Bogard, and D. A. Kring (2014) Ages of globally distributed lunar paleoregoliths and soils from 3.9 Ga to the present. *Earth, Moon, and Planets 112*, 59-71.

SSERVI-2014-134
D. M. Hurwitz** and D. A. Kring (2014) Differentiation of the South Pole-Aitken basin impact melt sheet: Implications for lunar exploration. *Journal of Geophysical Research: Planets 119*, 1110-1133.

SSERVI-2014-135
T. Öhman, G. Y. Kramer, and D. A. Kring (2014) Characterization of Melt and Ejecta Deposits of Kepler Crater from Remote Sensing Data. *Journal of Geophysical Research: Planets 119*, 1238-1258.

SSERVI-2014-136
K. H. Joy, I. A. Crawford, G. R. Huss, K. Nagashima, and G. J. Taylor (2014) An unusual clast in lunar meteorite MacAlpine Hills 88105: A unique lunar sample or projectile debris? *Meteoritics and Planetary Science 49*, 677–695.

SSERVI-2014-164
M. Lemelin, D. M. Blair, C. E. Roberts, K. D. Runyon, D. Nowka, and D. A. Kring (2014) High-priority lunar landing sites for in situ and sample return studies of polar volatiles. *Planetary and Space Science 101*, 149-161.

SSERVI-2014-191
G. J. Taylor and M. A. Wieczorek (2014) Lunar bulk chemical composition: a post-Gravity Recovery and Interior Laboratory assessment. *Philosophical Transactions of the Royal Society A372*, 20130242.

SSERVI-2014-192
I. A. Crawford and K. H. Joy (2014) Lunar exploration: opening a window into the history and evolution of the inner Solar System. *Philosophical Transactions of the Royal Society A372*, 20130315.

SSERVI-2014-193
M. Anand, R. Tartèse, and J. J. Barnes (2014) Understanding the origin and evolution of water in the Moon through lunar sample studies. *Philosophical Transactions of the Royal Society A372*, 20130254.

SSERVI-2014-194
R. J. Walker (2014) Siderophile element constraints on the origin of the Moon. *Philosophical Transactions of the Royal Society A372*, 20130258.

SSERVI-2014-195
S. S. Russell, K. H. Joy, T. E. Jeffries, G. J. Consolmagno, and A. Kearsley (2014) Heterogeneity in lunar anorthosite meteorites: implications for the lunar magma ocean model. *Philosophical Transactions of the Royal Society A372*, 20130241.

SSERVI-2014-196
K. H. Joy, A. Nemchin, M. Grange, T. J. Lapen, A. H. Peslier, D. K. Ross, M. E. Zolensky, and D. A. Kring (2014) Petrography, geochronology and source terrain characteristics of lunar meteorites Dhofar 925, 961 and Sayh al Uhaymir 449. *Geochimica et Cosmochimica Acta 144*, 299-325.

SSERVI-2014-197
C. R. Neal, P. Donohue**, A. L. Fagan**, K. O'Sullivan, J. Oshrin, and S. Roberts (2014) Distinguishing between basalts produced by endogenic volcanism and impact processes: A non-destructive method using quantitative petrography of lunar basalt samples. *Geochimica et Cosmochimica Acta*, in press.

SSERVI-2014-220
D. A. Kring and M. Boslough (2014) Chelyabinsk: Portrait of an asteroid airburst. *Physics Today 67(9)*, pp. 32–37.

SSERVI-2014-246***
S. Marchi**, W. F. Bottke, D. P. O'Brien, P. Schenk, S. Mottola, M. C. De Sanctis, D. A. Kring, D. A. Williams, C. A. Raymond, and C. T. Russell (2014) Small crater populations on Vesta. *Planetary and Space Science 103*, 96-103.

SSERVI-2014-247
M. Sharp, K. Righter, and R. J. Walker (2014) Estimation of trace element concentrations of the lunar magma ocean using mineral- and metal-silicate melt partition coefficients. *Meteoritics and Planetary Science*, in press.

SSERVI-2014-248
R. E. Merle, A. A. Nemchin, M. L. Grange, M. J. Whitehouse, and R. T. Pidgeon (2014) High resolution U-Pb ages of Ca-phosphates in Apollo 14 breccias: implications for the age of the Imbrium impact. *Meteoritics and Planetary Science*, in press.

SSERVI-2014-275
N. J. Potts, A. L. Gullikson, N. M. Curran, J. K. Dhaliwal, M. K. Leader, R. N. Rege, K. K. Klaus, and D. A. Kring (2014) Robotic traverse and sample return strategies for a lunar farside mission to the Schrödinger basin. *Advances in Space Research*, in press.

SSERVI-2015-027
R. W. K. Potter**, D. A. Kring, and G. S. Collins (2015) Scaling of basin-sized impacts and the influence of target temperature. In *Large Meteorite Impacts and Planetary Evolution V*, G. R. Osinski and D. A. Kring (eds.), Special Paper ###, Geological Society of America, in press.

SSERVI-2015-TBD
J. Liu, M. Sharp*, R. D. Ash, D. A. Kring, and R. J. Walker (2015) Diverse impactors in Apollo 15 and 16 impact melt rocks: Evidence from osmium isotopes and highly siderophile elements. *Geochimica et Cosmochimica Acta*, in press.

5. Conference papers, extended abstracts, posters, and presentations

Total number of conference papers, extended abstracts, poster presentations and oral presentations: 85 (with an additional 32 pending). Per instructions, only the extended abstracts are reported by title below.

Extended Lunar and Planetary Science Conference XLV abstracts:

Key: Underlines indicate student names
Double-asterisk (**) attached to postdoc names
Triple-asterisk (***) appears at the end of cross-team collaborations

SSERVI-2014-011
D. M. Hurwitz** and D. A. Kring (2014) Destinations for sampling impact produced by the South Pole-Aitken basin impact event. *Lunar and Planetary Science XLV,* Abstract #1398.

SSERVI-2014-012
R. W. K. Potter** and D. A. Kring (2014) Collisional erosion: Consequences for the Young Earth. *Lunar and Planetary Science XLV,* Abstract #2230.

SSERVI-2014-013
O. Abramov, D. A. Kring, S. J. Mojzsis (2014) Predictions of crustal age-resetting by impact bombardments on Early Earth. *Lunar and Planetary Science XLV,* Abstract #2491.

SSERVI-2014-014
A. L. Gullikson, N. M. Curran, N. J. Potts, J. K. Dhaliwal, M. Leader, R. Rege, and D. A. Kring (2014) Traverse and station options for a robotic sample return to Schrödinger basin. *Lunar and Planetary Science XLV,* Abstract #2082.

SSERVI-2014-015
N. M. Curran, A. L. Gullikson, N. J. Potts, J. K. Dhaliwal, M. Leader, R. Rege, and D. A. Kring (2014) A robotic sample return mission to the northern portion of the Schrödinger basin peak ring. *Lunar and Planetary Science XLV,* Abstract #1475.

SSERVI-2014-016
N. J. Potts, A. Gullikson, N. M. Curran, G. Chang, J. K. Dhaliwal, M. K. Leader, R. N. Rege, and D. A. Kring (2014) Mapping solar irradiance within Schrödinger basin for future robotic sample return missions. *Lunar and Planetary Science XLV,* Abstract #1835.

SSERVI-2014-017
M. K. Leader, R. N. Rege, N. J. Potts, A. L. Gulikson, N. M. Curran, J. K. Dhaliwal, and D. A. Kring (2014) Velocity of a rover as a function of slope of lunar terrain. *Lunar and Planetary Science XLV,* Abstract #2683.

SSERVI-2014-018
C. M. Altomare, A. L. Fagan**, D. A. Kring (2014) Eolian deposits of pyroclastic volcanic debris in Meteor Crater. *Lunar and Planetary Science XLV,* Abstract #1448.

SSERVI-2014-019
S. P. Beard, D. A. Kring, C. E. Isachsen, T. J. Lapen, M. E. Zolensky, and T. D. Swindle (2014) Ar-Ar analysis of Chelyabinsk: Evidence for a recent impact. *Lunar and Planetary Science XLV,* Abstract #1807.

SSERVI-2014-020
T. J. Lapen, D. A. Kring, M. E. Zolensky, R. Andreasen, M. Righter, T. D. Swindle, and S. P. Beard (2014) Uranium-lead isotope evidence in the Chelyabinsk LL5 chondrite meteorite for ancient and recent thermal events. *Lunar and Planetary Science XLV,* Abstract #2561.

SSERVI-2014-021
A. L. Fagan**, K. H. Joy, D. D. Bogard, and D. A. Kring (2014) Investigating a potential impact pulse in the Earth-Moon system ~2 Ga. *Lunar and Planetary Science XLV,* Abstract #1907.

SSERVI-2014-038
T. Haber, M. D. Norman, V. C. Bennett, and F. Jourdan (2014) Formation Ages, Cogenetic Relations and Formation Processes of a Set of Apollo 16 Impact Melt Rocks. *Lunar and Planetary Science XLV,* Abstract #1693.

SSERVI-2014-039
M. D. Norman, T. R. Ireland, and L. Cousins (2014) U-Pb Ages and Chemical Compositions of Apollo 11 Regolith Glasses. *Lunar and Planetary Science XLV,* Abstract #1756.

SSERVI-2014-081
D. J. P. Martin and P. D. Spudis (2014) New Geological Map of the Lunar Orientale Basin. *Lunar and Planetary Science XLV,* Abstract #1368.

SSERVI-2014-082
P. D. Spudis and D. J. P. Martin (2014) Composition of the Deposits of the Lunar Orientale Basin. *Lunar and Planetary Science XLV,* Abstract #1469.

SSERVI-2014-083
J. A. Skinner Jr., D. B. Eppler, J. E. Bleacher, W. Feng, J. Gruener, D. M. Hurwitz**, B. Janoiko, and P. Whitson (2014) Comparing and reconciling traditional field and photogeologic mappig techniques: Lessons from the San Francisco Volcanic Field, Arizona. *Lunar and Planetary Science XLV,* Abstract #2913.

SSERVI-2014-084***
W. S. Kiefer, P. J. McGovern, R. W. K. Potter, J. C. Andrews-Hanna, J. Besserer, G. S. Collins, J. W. Head III, D. M. Hurwitz**, K. Miljkovic, F. Nimmo, R. J. Phillips, D. E. Smith, J. M. Soderblom, G. J. Taylor, M. A. Wieczorek, and M. T. Zuber (2014) The contribution of impact melt sheets to lunar impact basin gravity anomalies. *Lunar and Planetary Science XLV,* Abstract #2831.

SSERVI-2014-085
Y. Sonzogni** and A. H. Treiman (2014) Petrology of a very-low titanium basalt (or picrite) clast in lunar highland regolith breccia 15295. *Lunar and Planetary Science XLV,* Abstract #1030.

SSERVI-2014-086
J. W. Boyce, F. M. McCubbin, S. Tomlinson, A. H. Treiman, and J. P. Greenwood (2014) Equilibrium-exchange hygrometry and a solution to the lunar apatite paradox. *Lunar and Planetary Science XLV,* Abstract #2096.

SSERVI-2014-087
J. E. Bleacher, D. B. Eppler, J. A. Skinner, C. A. Evans, W. Feng, J. E. Gruener, D. M. Hurwitz**, P. Whitson, and B. Janoiko (2014) Mapping planetary volcanic deposits: Identifying vents and distinguishing between effects of eruption conditions and local lava storage and release on flow field morphology. *Lunar and Planetary Science XLV,* Abstract #2504.

SSERVI-2014-088
D. E. Eppler, J. Bleacher, C. Evans, W. Feng, J. Gruender, D. Hurwitz**, B. Janoiko, J. Skinner, and P. Whitson (2014) Comparing geologic data sets collected by planetary analog traverses and by standard geologic field mapping: Implications for planetary exploration planning. *Lunar and Planetary Science XLV,* Abstract #2078.

Other extended abstracts:

SSERVI-2014-122
D. A. Kring (2014) Exploring the Lunar South Polar Region and far side with human and human-assisted sample return missions. *European Lunar Symposium 2014,* 50-51.

SSERVI-2014-123
F. E. McDonald, K. H. Joy, P. L. Clay, R. Burgess (2014) The origin and evolution of volatiles in the earth-moon system: A halogen perspective. *European Lunar Symposium 2014,* 85–86.

SSERVI-2014-124
C. R. Neal, G. Schmidt, I. A. Crawford, P. Ehrenfreund (2014) Developing the global exploration roadmap: Expanding the "lunar vicinity" scenario. *European Lunar Symposium 2014,* 67–68.

SSERVI-2014-125
A. A. Nemchin, M. J. Whitehouse (2014) Zircon from the moon, Earth and Mars. *European Lunar Symposium 2014,* 43–44.

SSERVI-2014-126
K. G. Weilding, R. Bugiolacchi, I. A. Crawford (2014) Identification (and misidentification) of dark-halo craters within the Taurus-Littrow region of the Moon from MoonZoo Data. *European Lunar Symposium 2014,* 101–102.

SSERVI-2015-028***
S. Marchi, W. F. Bottke, L. T. Elkins-Tanton, K. Wuennemann, A. Morbidelli, and D. A. Kring (2015) The Bombardment of the Earth during the Hadean and Early Archean eras. *Workshop on Early Solar System Bombardment III*, Abstract #3008.

SSERVI-2015-029
D. A. Kring, P. J. McGovern, R. W. K. Potter**, G. S. Collins, M. L. Grange, and A. A. Nemchin (2015) Was an epoch of lunar magmatism triggered by the South Pole-Aitken basin impact? *Workshop on Early Solar System Bombardment III*, Abstract #3009.

SSERVI-2015-030***
R. W. K. Potter** and D. A. Kring (2015) Testing the collisional erosion hypothesis for the Hadean Earth. *Workshop on Early Solar System Bombardment III*, Abstract #3010.

SSERVI-2015-031***
W. F. Bottke, D. Vokrouhlicky, S. Marchi, A. Jackson, H. Levison and T. Swindle (2015) The Earliest lunar bombardment produced by Moon-forming impact ejecta. *Workshop on Early Solar System Bombardment III*, Abstract #3012.

SSERVI-2015-032
M. D. Norman (2015) The nature of the 4.2 Ga impact episode on the Moon: Evidence from North Ray Crater breccias, Apollo 16. *Workshop on Early Solar System Bombardment III*, Abstract #3014.

SSERVI-2015-033
R. J. Walker, O. B. James, D. A. Kring, J. Liu, M. G. Sharp, and I. S. Puchtel (2015) Highly siderophile element characteristics of lunar impact melt breccias: A picture begins to emerge. *Workshop on Early Solar System Bombardment III*, Abstract #3016.

SSERVI-2015-034
K. Righter and M. Cosca (2015) 40Ar/39Ar age of hornblende-bearing R chondrite LAP 04840. *Workshop on Early Solar System Bombardment III*, Abstract #3022.

SSERVI-2015-035
K. Righter (2015) Re-evaluation of HSE data in light of high P-T partitioning data: Late chondritic addition to inner Solar System bodies not always required for HSE. *Workshop on Early Solar System Bombardment III*, Abstract #3023.

SSERVI-2015-036
P. J. McGovern, R. W. K. Potter**, G. S. Collins, D. A. Kring, M. L. Grange, and A. A. Nemchin (2015) Pulses of magma movement triggered by the South Pole-Aitken basin Impact. *Workshop on Early Solar System Bombardment III*, Abstract #3027.

SSERVI-2015-037
T. D. Swindle and D. A. Kring (2015) Was there concentration of lunar and asteroidal impacts at ~4000 Ma? *Workshop on Early Solar System Bombardment III*, Abstract #3030.

SSERVI-2015-038
D. Hurwitz** and D. A. Kring (2015) Potential sample sites for South Pole-Aitken basin impact melt within the Schrödinger basin. *Workshop on Early Solar System Bombardment III*, Abstract #3035.

SSERVI-2015-039
D. Hurwitz** and D. A. Kring (2015) Identifying the geologic context of Apollo 17 aphanitic and poikilitic impact melt breccias. *Workshop on Early Solar System Bombardment III*, Abstract #3037.

SSERVI-2015-040
M. T. Touboul, I. S. Puchtel, and R. J. Walker (2015) The tungsten isotope composition of the Moon: New constraints on the giant impact. *Workshop on Early Solar System Bombardment III*, Abstract #3040.

6. **List of undergraduate students, graduate students, and postdocs**

Postdoctoral Researchers
Dr. Katherine Bermingham *(University of Maryland)*
Dr. Patrick Donohue *(University of Notre Dame)*
Dr. Amy L. Fagan (*USRA-LPI*) – now at the University of Western Carolina
Dr. Debra Hurwitz *(USRA-LPI)*
Dr. Jin Liu (*University of Maryland*) – now at the University of Alberta
Dr. Ross Potter *(USRA-LPI)* – now at Brown University
Dr. Joshua Snape *(Swedish Museum of Natural History)*
Dr. Yann Sonzogni *(USRA-LPI)*

Field Training and Research Program at Meteor Crater
2014 Student Participants
Corwin Atwood-Stone (*University of Arizona*)
Aaron Boyd (*Arizona State University*)
Jessie Brown (*University of New Brunswick*)
Laura Corley (*University of Hawaii at Manoa*)
Natalie Curran (*University of Manchester*)
Connor Davis (*Western University*)
Katrina Korman (*Temple University*)
Aviva Maine (*Northern Arizona University*)
Francesca McDonald (*University of Manchester*)
Stephanie Montalvo Delgado (*University of Puerto Rico at Mayaguez*)
Raquel Nuno (*Arizona State University*)
Seda Oezdemir (*University of Vienna*)
Kathryn Rathbun (*University of Iowa*)
Nisa Rhodes (*University of Texas at El Paso*)
Hannah Susorney (*Johns Hopkins University*)
David Weiss (*Brown University*)

Student Researchers working with Our Partners
Jessica Barnes *(Open University)*
Sky Beard *(University of Arizona)*
David Blair (*Purdue University)*
Natalie Curran (*The University of Manchester*)
Jasmeet Dhaliwal (*University of California, San Diego*)
Amber Gullikson (*Northern Arizona University*)
Mark Leader (*University of Texas, Austin*)
Myriam Lemelin (*Université de Sherbrooke & University of Hawaii)*
Patrick Lowe *(University of Notre Dame)*
Daniela Nowka (*Freie Universität Berlin)*
Nicola Potts (*The Open University*)
Rushal Rege (*Columbia University*)
Carolyn Roberts (*SUNY at Buffalo)*
Katherine Robinson *(University of Hawaii)*
Kirby Runyon *(Temple University)*
Fiona Thiessen *(Swedish Museum of Natural History)*

Postdoc and Student Publication Contributions

- Peer-Reviewed Publications
  - 3 peer-reviewed publications led by postdoctoral researchers (postdocs)
  - 4 peer-reviewed publications led by students
- Extended Abstracts
  - 6 postdoc-led oral presentations, 1 postdoc-led poster
  - 2 student-led oral presentations, 8 student-led posters
- Conference Abstracts
  - 1 postdoc-led oral presentations, 2 postdoc-led posters
  - 5 student-led oral presentations, 1 student led poster

Overall Postdoc and Student Contribution Statistics	
Type of Publication:	*With Contributions From:*
9 peer-reviewed publications	5 postdocs
	16 students
26 extended abstracts	
13 oral presentations	4 postdocs
	4 students
13 poster presentations	2 postdocs
	10 students
11 conference abstracts	
8 oral presentations	2 postdocs
	14 students
3 poster presentations	2 postdocs
	1 student

MIHALY HORANYI

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

University of Colorado, Boulder, CO

February 13, 2015

NASA SSERVI
Institute for Modeling Plasmas, Atmospheres, and Cosmic Dust (IMPACT)

Year 1 Report

Period of Performance: 04/01/2014 - 03/31/2015

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1. Summary

IMPACT remains dedicated to studying the effects of hypervelocity dust impacts into refractory, icy, and gaseous targets; to building new laboratory experiments to address the effects of UV radiation and plasma exposure of the surfaces of airless planetary objects; to developing new instrumentation for future missions to make in situ dust and dusty plasma measurements in space; and to 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.

2. Project Reports

Accelerator Projects

Significant continuing effort has been put into maintaining and improving the performance and reliability of the IMPACT dust accelerator. Numerous incremental improvements have been made to the vacuum systems, electronics hardware, and software control systems, and the accelerator performance is now highly reliable with very few "down" days. As an example of the improved performance, we recently recorded a new particle speed record of 107.6 km/s, and we regularly record particles in excess of 70 km/s (all of which break our previous speed records from even a year ago).

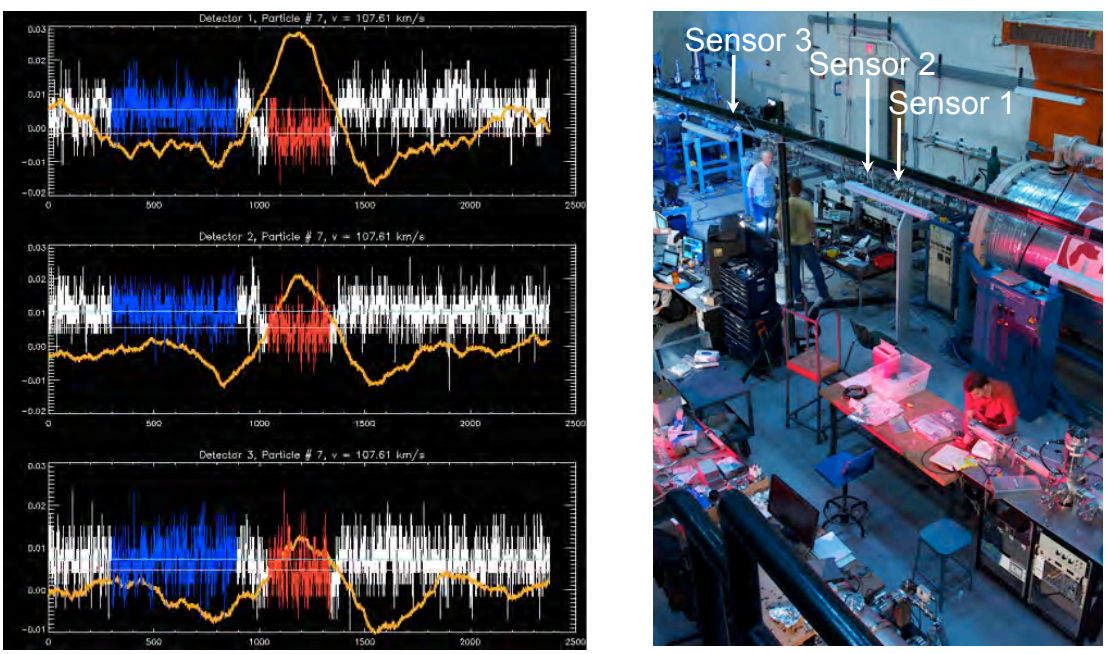


Figure 1. The SSERVI IMPACT team has set a new speed record in their micrometeoroid (dust) accelerator. The raw (white) and filtered (orange) lines show signals from three beamline particle detectors for a dust grain accelerated to 107.6 km/s. (The red and blue overplots are the regions used for determining the raw signal height and baseline, respectively). The FPGA-based particle selection unit uses real-time signal filtering to detect and trigger on particles with raw signal-to-noise ratios well below 1. The record-setting particle was a spherical iron grain with diameter 27 nm, charged to 0.21 fC for acceleration.

In addition to the general performance improvements, the IMPACT dust accelerator is presently implementing two major target upgrades: a cryogenic ice target for impact studies into icy surfaces, and a high-pressure gas target for micrometeoroid ablation studies. We briefly describe the physics basis and the current status of each.

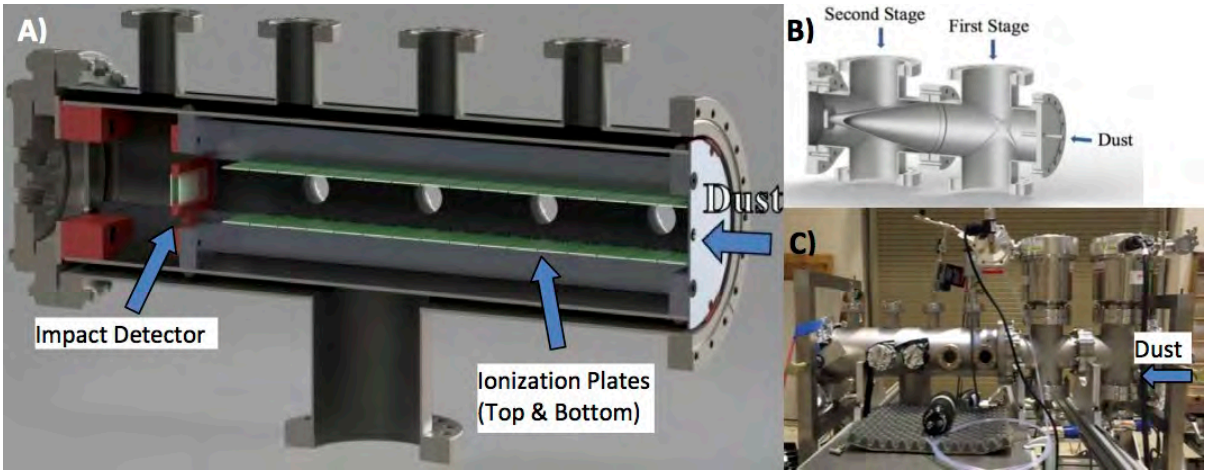


Figure 2. *A)* Cutaway CAD drawing of the ablation chamber. *B)* Cutaway CAD drawing of the differential pumping system. *C)* Photo of the fully operational ablation system containing the differential pumping and the ablation chamber. This system connects to the end of the dust beamline.

The gas ablation target consists of a differentially pumped chamber, Fig. 2, 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 spatially-resolved measurements of charge production during ablation, and localized light-collection optics enable an assessment of the light production (luminous efficiency). Such studies are critical to the understanding of past and future ground-based measurements of meteor ablation in Earth's atmosphere, which in turn can potentially provide the best estimates of the interplanetary dust particle flux.

We have performed a set of preliminary experiments, which have already yielded fruitful results. The ionization setup was used across a wide velocity and pressure range, demonstrating that the experimental setup is operational and robust, providing spatially and temporally resolved ionization measurements. In this first run, we determined the ionization efficiency (β) for iron grains impacting N_2 gas in a previously unexplored velocity regime. Fig. 3 shows the number of equivalent electrons that were collected on each channel for one particular ablation event in the dataset, and the measured β values from this run, plotted with the only other $Fe+N_2$ laboratory measurement of β (Friichtenicht et al., 1967), as well as the Jones (1997) theory of ionization coefficient at lower velocities, which is used by leading ablation simulation codes. The newly measured β extends down to 10 km/s, which has never been performed before in the laboratory.

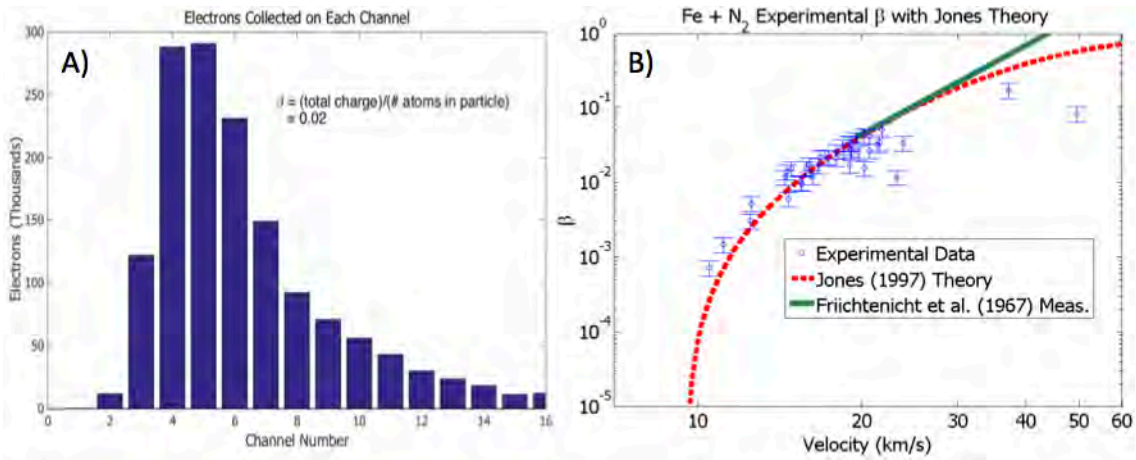


Figure 3. *A)* Total collected charge for a single ablation event. *B)* First experimental results measuring β for Fe+N_2. The dataset extends to lower velocities that have never been measured before in a lab.

The ice target consists of a LN_2 cryogenic system connected to both a water-ice deposition system as well as a movable freezer/holder for a pre-mixed liquid cartridge. Planned experiments include the bombardment of a variety of frozen targets and simulated ice/regolith mixtures, and the assessment of all impact products (solid ejecta, gas, plasma) as well as spectroscopy of both the impact-produced light flashes and the reflected spectra (UV, visible, IR). Such measurements are highly relevant to both physical and chemical surface modification of airless bodies due to micrometeoroid impacts.

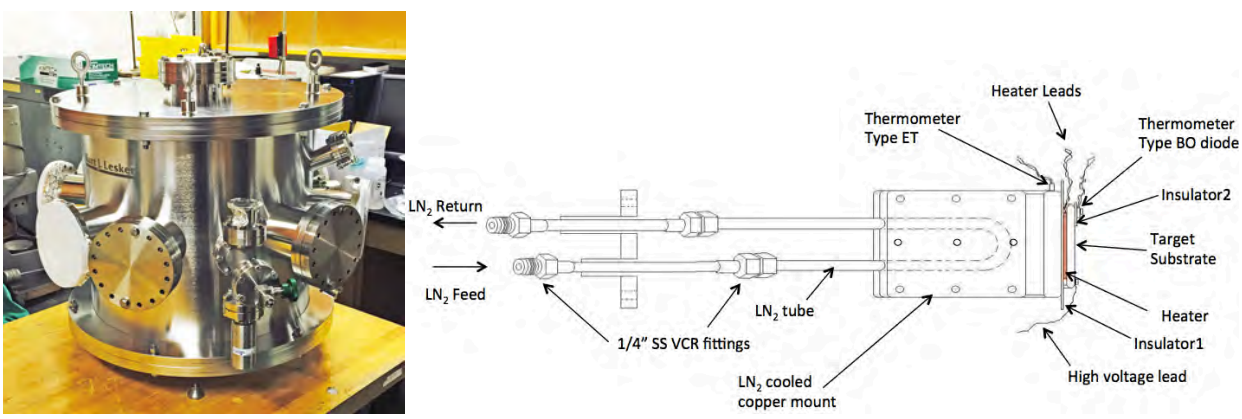


Figure 4. *A)* Ice-target vacuum chamber, with ports for mass spectrometer, laser ice-thickness measurements, vapor input, vacuum pumping, and cryogenic systems. *B)* Schematic drawing of cryogenic target head.

While the ice target is at an earlier development stage compared to the gas ablation target, we have reached several technical design milestones. Firstly, we have designed and fabricated the target chamber, which is designed for UHV operation and includes ports for cryogenic and vacuum systems, as well as diagnostic access for a time-of-flight mass-spectrometer, laser-interferometer for ice growth thickness, and multiple views for IR/Visible spectroscopy (Fig. 4a). We have also designed and fabricated the cryogenic target itself (Fig. 4b), which incorporates thermostat-controlled heaters for surface temperature control.

Integration of the ice-growth system, ice-target chamber, and IMPACT accelerator are underway now.

Small-scale Laboratory Experiments

Several tabletop laboratory experiments were successfully completed to investigate spacecraft charging effects (Xu et al., 2014a and 2014b) and the interaction of magnetic anomalies with flowing plasmas (Howes et al., 2015). We have updated our experimental setups to address charging, mobilization, and transport of dust on exposed surfaces (Fig. 5.)

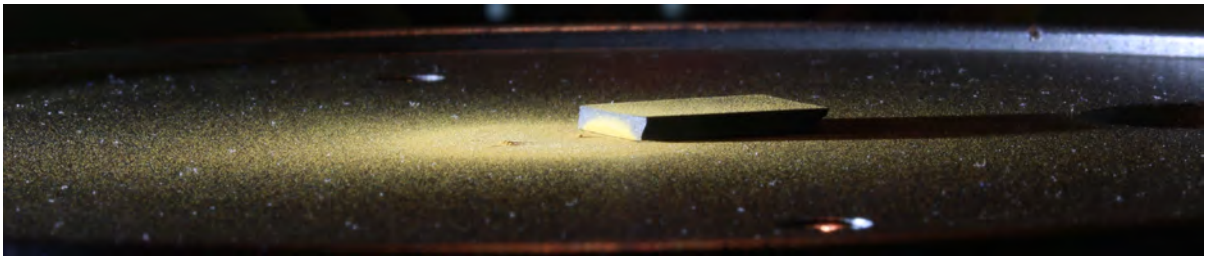


Figure 5. JSC-Mars-1 (< 50 µm diameter particles) dust pile (3 mm in diameter, 1 mm high) rests on a graphite surface (22 cm in diameter, electrically floated). An insulating block (2 mm high) is placed 3 mm away from the dust pile. Energetic electrons (130 eV beam) come from the top to the dust surface and also create a dense plasma ($n > 10^9$ cm^{-3}). The picture is taken after running for 5 minutes. Dust particles landed on the higher block and spread out on almost the entire graphite surface.

Other experiments addressed the use of Langmuir probes on spacecraft for characterizing the ambient plasma parameters in space (Xu et al., 2015). When their boom is short compared to the plasma Debye length, which is typically the case for engineering reasons, the probes remain immersed in the spacecraft sheath. This effect causes the current-voltage (I-V) characteristics to deviate from that of a probe far away from the spacecraft. We developed a new method to identify when a Langmuir probe is in the sheath, based on the secondary electrons emission from the probe itself. These results are applicable to the case of electron emission due to different mechanisms, for example photo or thermionic emissions, as well.

Theory Support

We studied the general mechanisms of the solar wind interaction with lunar crustal magnetic anomalies (LMAs) using three-dimensional fully-kinetic and electromagnetic simulations (Deca et al., 2014, 2015). We confirmed that LMAs may indeed be strong enough to stand off the solar wind from directly impacting the lunar surface forming a so-called 'mini-magnetosphere', as suggested by spacecraft observations and theory. We followed the evolution of the field structure and particle dynamics, and showed that the LMA configuration is driven by electron motion because its scale size is small with respect to the gyro-radius of the solar wind ions. We identified a population of back-streaming ions, the deflection of magnetized electrons via the E×B drift motion, and the subsequent formation of a halo region of elevated density around the dipole source (Fig. 6). The presence and efficiency of these mechanisms are heavily impacted by the upstream plasma conditions. Understanding the detailed physics of the solar wind interaction with LMAs, including magnetic shielding, particle dynamics and surface charging is vital to evaluate its implications for lunar exploration, and also likely to hold the key to understand the formation of lunar swirls. These

codes are now also implemented to guide the design and help in the analysis and interpretation of our laboratory experiments.

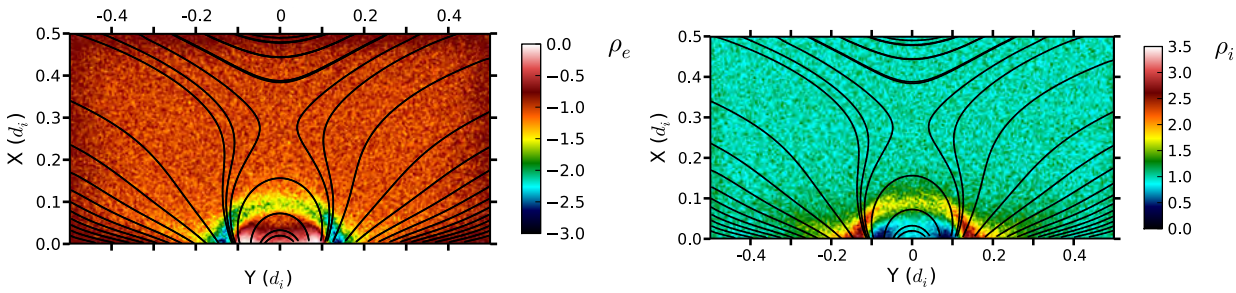


Figure 6. 2-D electron (left) and ion (right) charge density profiles, scaled to the initial density, n_{SW}, and along the dipole axis (Y direction) at z = 0 after the simulation has reached quasi-steady state. The solar wind is flowing perpendicular (in the -X direction) to the lunar surface at x = 0. Superimposed in black are magnetic field lines.

3. 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.

SEEED and IMPACT

SEEED co-investigator Prof. I. Garrick-Bethell (UC Santa Cruz) visited IMPACT to give a LASP seminar and to discuss laboratory experiments, computer simulations, as well as space experiments to investigate lunar swirls.

CLASS and IMPACT

CLASS PI, Prof. D. Britt (U. Central Florida) visited IMPACT in the summer of 2014, and in February 2015 for a LASP seminar, and to discuss and plan micrometeoroid bombardment experiments which address the physical properties of icy-regolith surfaces.

International Partners

We continued our close collaborations with our international partners at the University of Stuttgart (a member of the German Network for Lunar Science and Exploration) and the University of Leuven, Belgium.

Aerospace Engineering Masters students Jonas Simolka (1/2014 - 11/2014) and Georg Mayer (5/2014 - 2/2015) from Germany completed their dissertations in our laboratory. Jonas worked on the development of our gas target and ablation experiments. Georg designed and completed experiments addressing the signals generated on electric antennas by dust impacts. Jan Deca completed his Ph.D. in Leuven and joined IMPACT as a postdoc.

M. Horanyi participated in a week-long visit to Korea, together with other SSERVI scientists (C. M. Pieters, B. Weiss, J. Halekas, Ian Garrick-Bethel). The visit included a Lunar Science Workshop organized by the School of Space Research at Kyung Hee University, and discussions at the Korean Aerospace Research Institute (KARI) and the Astronomy and Space Science Institute (KASI).

4. EPO Highlights

Junior Aerospace Engineering Project

Tom Mason and Erin Wood in delivered a two-week "Rockets for Junior Astronauts" program for 14 underserved students at the Casa de la Esperanza housing community in Longmont, CO (Fig. 7). As they progressed from very simple paper designs through more advanced foam, plastic, and water bottle rockets, students were introduced to the history of rocket development, future NASA exploration plans, different types of rocket propulsion, basic engineering design concepts, and Newton's laws of motion. The beginning rocket component is the first in a five-year program, which will direct students through a series of more complex science and engineering content via an advanced rocket camp in year three, and conclude with a lunar-themed robotics project in year five. The program received attention from our local news media:

1) http://www.thedenverchannel.com/news/local-news/nasa-funded-summer-camp-designed-to-get-colorado-children-interested-in-math-science08082014
2) http://www.timescall.com/News/ci_26295256/Longmont-students-learn-about-science-engineering-at-rocket-camp

Figure 7. *Kenya Falcon (right) and Alexis Mosqueda put the finishing touches on their two-liter water bottle rocket. Their bottle won the competition for the highest altitude, reaching an estimated 90 feet when launched. (Credit: Matthew Jonas/Longmont Times-Call)*

International Observe the Moon Night (IOMN)

IMPACT has been and will remain a supporter and participant in International Observe the Moon Night (InOMN). InOMN is an annual event aimed at increasing the general public's knowledge and awareness of lunar science. Every year since 2010 IMPACT/CCLDAS has participated by providing knowledgeable staff and two reflecting telescopes (with 15" and 17" primary mirrors) placed on Boulder's busy Pearl Street Mall, after obtaining all the appropriate permits from the city. Typically there are a few hundred people that attend and take a chance to look at our moon, maybe for the first time, through a telescope and learn something they didn't know from IMPACT staff.

5. Publications

(******** joint NLSI Team Publication; student author)

Published Refereed Publications

SSERVI-2014-056 A. Collette, Z. Sternovsky, and M. Horanyi, Production of Neutral Gas by Micrometeoroid Impacts, *Icarus, 227*, 89-93, 2014

SSERVI-2014-057 X. Wang, D. Malaspina, E. Ergun, M. Horanyi, Photoelectron-mediated spacecraft potential fluctuations, *J. Geophys. Res., 119*, 1024 - 1101, 2014a

SSERVI-2014-058 X. Wang, D. M. Malaspina, H.-W. Hsu, R. E. Ergun, and M. Horanyi, Effect of magnetic field on photoelectron-mediated spacecraft potential fluctuations, *J. Geophys. Res. 119*, 7319-7326, 2014b

SSERVI-2014-059 A. Zakharov, M. Horanyi, P. Lee, O. Witasee, F. Cipriani, Dust at the Martian moons, *Planetary Space Sci., 102*, 171-175, 2014

SSERVI-2014-092 J. Deca, A. Divin, G. Lapenta, B. Lembège, S. Markidis, and M. Horányi, Electromagnetic Particle-in-Cell Simulations of the Solar Wind Interaction with Lunar Magnetic Anomalies, *Phys. Rev. Lett., 112*, 141102, 2014

SSERVI-2014-179 A. Collette, E. Grun, D. Malaspina, Z. Sternovsky, Micrometeoroid Impact-Charge Yield for Common Spacecraft Materials, *J. Geophys. Res., 119*, 6019-6026 , 2014

SSERVI-2014-181 D.A. Mendis and M. Horanyi, The Global Morphology of the Solar Wind Interaction with Comet Churyumov-Gerasimenko, *Astrophys. J., 794,* 14 - 21, 2014

SSERVI-2014-292 M. Horanyi, Z. Sternovsky, M. Lankton, C. Dumont, S. Gagnard, D. Gathright, E. Grun, D. Hansen, D. James, S. Kempf, B. Lamprecht, R. Srama, J. R. Szalay, G. Wright, The Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) Mission*, Space. Sci. Rev., 185*, 93 -113, 2014

Refereed Publications in Press

SSERVI-2015-294 X. Wang, H. -W. Hsu and M. Horanyi, Identification of Langmuir probe in the sheath of spacecraft: The effect of secondary electron emission from the probe, *J. Geophys. Res.*, in press, 2015

SSERVI-2015-293 S. Kempf, A. Cruz, M. Horanyi, R. Srama, On the response of PVDF dust detectors to oblique impacts, *Panetary Space Sci.*, in press, 2015

Refereed Publications in Review

SSERVI-2014-238 C. T. Howes, X. Wang, and M. Horányi, Laboratory investigation of lunar surface electric potentials in magnetic anomaly regions, *GRL*, submitted, 2015

SSERVI-2015-047 M. Horanyi, J. Szalay, S. Kempf, J. Schmidt, E. Grun, R. Srama, Z. Sternovsky, Detecting a permanent dust cloud engulfing the Moon, Nature, submitted, 2015

SSERVI-2015-046 Jan Deca, Andrey Divin, Bertrand Lembege, Mihaly Horanyi, Stefano Markidis and Giovanni Lapenta, General Mechanism and Dynamics of the Solar Wind Interaction with Lunar Magnetic Anomalies from 3-D PIC Simulations, *JGR - Space*, submitted, 2015

6. Conference papers, extended abstracts, posters and presentations

Total number of conference papers, extended abstracts, poster and oral presentations: 34. (http://impact.colorado.edu/publications.html)

Published Conference Proceedings and Abstracts

Z. Sternovsky, S. Gagnard, D. Gathright, E. Gruen, D. James, S. Kempf, M. Lankton, M. Horanyi, R. Srama, J. Szalay, Modeling the UV Signal Scattered into the Lunar Dust EXperiment (LDEX) from the Surface, 45th Lunar and Planetary Science Conference (2014), Abstract #2740

R. C. Elphic, B. Hine, G. T. Delory, J. S. Salute, S. Noble, A. Colaprete, M. Horanyi, P. Mahaffy, LADEE Science Team, The Lunar Atmosphere and Dust Environment Explorer (LADEE): Initial Science Results, 45th Lunar and Planetary Science Conference (2014), Abstract #2677

P. Lee, M. Bicay, A. Colaprete, R. Elphic, A. Genova, B. Hine, M. Horanyi, B. Jaroux, D. Korsmeyer, B. S. Lewis, S. P. Worden, Phobos and Deimos and Mars Environment (PADME): A LADEE-Derived Mission to Explore Mars's Moons and the Martian Orbital Environment, 45th Lunar and Planetary Science Conference (2014), Abstract #2288

J. S. Halekas, A. R. Poppe, G. T. Delory, R. C. Elphic, V. Angelopoulos, M. Horanyi, J. Szalay, ARTEMIS Observations and Data-Based Modeling in Support of LADEE, 45th Lunar and Planetary Science Conference (2014), Abstract #1548

J. R. Szalay, M. Horanyi, A. R. Poppe, J. S. Halekas, LDEX Observations and Correlations with ARTEMIS Measurements, 45th Lunar and Planetary Science Conference (2014), Abstract #1500

A. R. Poppe, J. S. Halekas, J. R. Szalay, M. Horanyi, G. T. Delory, Model-Data Comparisons of LADEE/LDEX Observations of Low-Energy Lunar Dayside Ions, 45th Lunar and Planetary Science Conference (2014), Abstract #1393

S. Kempf, E. Grun, M. Horanyi, D. James, M. Lankton, R. Srama, J. Szalay, Z. Sternovsky, Observations of the Lunar Dust Exosphere with LDEX, 45th Lunar and Planetary Science Conference (2014), Abstract #1389

M. Horanyi, S. Gagnard, D. Gathright, E. Gruen, D. James, S. Kempf, M. Lankton, R. Srama, Z. Sternovsky, J. Szalay, The Dust Environment of the Moon as Seen by the Lunar Dust Experiment (LDEX), 45th Lunar and Planetary Science Conference (2014), Abstract #1303

Scott L. Murchie, Nancy L. Chabot, Julie C. Castillo Rogez, Raymond E. Arvidson, Debra L. Buczkowski, Douglas A. Eng, Artur B. Chmielewski, Justin N. Maki, Ashitey Trebi Ollenu, Bethany L. Ehlmann, Patrick N. Peplowski, Harlan E. Spence, Mihaly Horanyi, Goestar Klingelhoefer, John A. Christian. Carolyn M. Ernst, The Mars Moons Exploration, Reconnaissance and Landed Investigation, , 46th Lunar and Planetary Science Conference (2015), Abstract #2047

Pascal Lee, Mehdi Benna, Daniel Britt, Anthony Colaprete, Warren Davis, Greg Delory, Richard Elphic, Ejner Fulsan, Anthony Genova, Daniel Glavin, William Grundy, William Harris, Brendan

Hermalyn, Butler Hine, Mihaly Horanyi, Douglas Hamilton, Robert Johnson, Thomas Jones, Sasha Kempf, Brian Lewis, Lucy Lim, Paul Mahaffy, John Marshall, Patrick Michel, David Mittlefehldt , Sam Montez, Yung Nguyen, Brandon Owens, Maurizio Pajola, Ryan Park, Cynthia Phillips, Laura Plice, Andrew Poppe, Joseph Ed Riedel, Attilo Rivoldini, Pascal Rosenblatt, Micah Schaible, Mark Showalter, Heather Smith, Zoltan Sternovsk, Peter Thomas, Hajime Yano, and Michael Zolensky, PADME (Phobos And Deimos & Mars Environment): A Proposed NASA Discovery Mission to Investigate the Two Moons of Mars, 46th Lunar and Planetary Science Conference (2015), Abstract #2856

M. Horanyi, J. Szalay, S. Kempf, J. Schmidt, E. Gruen, R. Srama, Z. Sternovsky, LDEX Observations of the Dust Environment of the Moon, 46th Lunar and Planetary Science Conference (2015), Abstract #1684

7. List of undergrad students, grad students, postdocs, and new faculty

Graduate Students	**Project**
Anthony Shu	Impact phenomena
Jamey Szalay	LDEX Theory support
Leela O'Brien	Detector design and fabrication
Evan Thomas	Ablation phenomena
Rudy Namikis	Dust instrument data analysis
Marcus Piquette	Surface/plasma interaction modeling
JR Rocha	Instrument development
Ben Southwood	Dust dynamics modeling
Summer Graduate Interns	
Connor Flexman (Brown U, RI)	Small accelerator (20 kV) impact charge experiments
Undergraduate Students	
Forrest Barnes	Control software development
John Fontanese	Small accelerator experiments
William Goode	Mechanical design
Andrew (Oak) Nelson	Ice target development
Andrew Seracuse	Beam detector development
Joseph Schwan	Dust dynamics in plasma
Robert Beadles	Langmuir probes in sheath
Juliet Pilewskie	Dust dynamics modeling
Tanya Shultz	Lunar swirls modeling
Alexandra Okeson	Dust instrument software development
Jared Stanley	LDEX modeling support
High School Students	
Dolfin Olsen	mechanical design of motorized translation table
Postdocs	
Jan Deca	Computer simulations of plasma - surface interactions
Retired Volunteer Scientist	
Dr. Richard Dee	Cryogenic target development

JENNIFER L. HELDMANN

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

NASA Ames Research Center, Moffett Field, CA

Annual Report Format for SSERVI Teams (Year 1, 2014-2015)
FINESSE: Field Investigations to Enable Solar System Science and Exploration

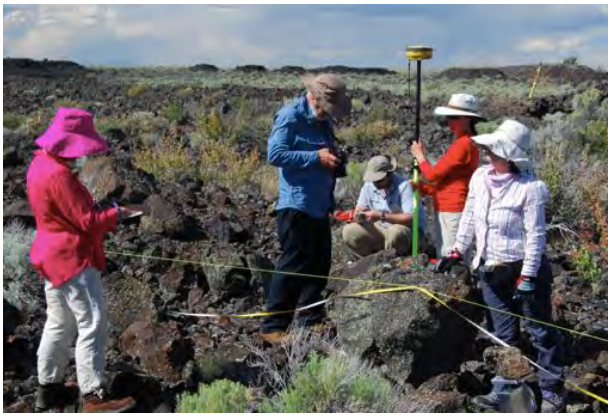
1. Team Project reports

FINESSE has completed an ambitious first year as a SSERVI team, complete with two substantial field deployments to study impact cratering and volcanics at Craters of the Moon (COTM) National Monument and Preserve in Idaho and at the West Clearwater Impact Structure (WCIS) in northern Canada, respectively. Significant pre-planning was required for each field deployment to ensure a safe and productive field campaign. The FINESSE team spent substantial time to conduct a science traceability matrix where the team outlined science objectives, determined required measurements to achieve these objectives, and traced the measurement needs to sample and instrument requirements. Using this information, required field and laboratory instrumentation and equipment was identified and sourced. Detailed field plans were generated and included complex logistics planning (e.g., team scheduling, flight plans, accommodations, obtaining required research permits, daily science activities and field sites, coordinating visitors and media events, etc). All deployments were approved through the NASA Ames Extreme Environments Research Review Board (EERRB).

Below we summarize examples of the science and exploration activities conducted at both field locations.

Craters of the Moon National Monument and Preserve.

Field deployments aimed at reconnaissance geology and data acquisition were conducted during Year 1 of FINESSE at Craters of the Moon National Monument and Preserve. Targets for data acquisition included selected sites at Kings Bowl eruptive fissure, lava field and blowout crater, Inferno Chasm vent and outflow channel, North Crater lava flow and Highway lava flow. Field investigation included (1) differential GPS (dGPS) measurements of lava flows, channels (and ejecta block at Kings Bowl); (2) LiDAR imaging of lava flow margins, surfaces and other selected features; (3) digital photographic documentation; (4) sampling for geochemical and petrographic analysis; (5) UAV aerial imagery of Kings Bowl and Inferno Chasm features; and (6) geologic assessment of targets and potential new targets.



FINESSE team conducting fieldwork at Craters of the Moon National Monument and Preserve, Idaho.

Multiple scientific investigations are being conducted in association with the Craters of the Moon field site. Representative examples are described below.

King's Bowl. King's Bowl (KB) eruptive fissure and lava field on the eastern Snake River Plain (ESRP) is recognized as a terrestrial analog for pit-crater collapse and eruptive fissures on the Moon. King's Bowl is an "aborted" eruption of no more than ~0.02 km3 of lava (~3 km^2 area) dated at 2,220 ± 100 B.P that was cut short in early stages of shield growth. Ongoing FINESSE fieldwork at KB includes differential GPS surveys (pit craters, lava lake, and pyroclastic ejecta), sample collection, documentation of size, density, and location of blocks ejected from the central pit, and investigation of outcrops to assess details of the geologic history. Our quantitative analysis of KB pit ejecta indicates that the largest phreatic explosion released 6.8×10^{10} to 3.0×10^{11} J equivalent to vaporizing 30-130k liters of water and expelled ~6.1×10^{7} kg rock mass. This study suggests similarities to impact crater ejecta on Earth and other planetary bodies and a similarity of pit formation whether derived by impact or phreatic explosion processes.

Inferno Chasm. Terrestrial volcanic features with similar morphologies to lunar rilles can provide insight into their formation on the Moon. Inferno Chasm in Idaho is a basaltic low-shield with a vent and sinuous channel. We documented the geology and morphology of Inferno Chasm using LiDAR, a dGPS, Unmanned Aerial Vehicles (UAVs), and sampling. Outcrops of the vent walls expose massive layers 2-3 m thick with textures that suggest highly welded spatter overlain by a 1-2 m thick sequence of thinner layers (overspills, shelley, gaseous blisters) each 10s of cm thick. Field observations of the wall material at Inferno Chasm suggest the feature was constructed through a combination of thin lava overflow, rheomorphic flow of congealed spatter, and intense welding of deeper parts, with or without additional lava injection, to form the thick, massive layers. Isis, a rille in Serenitatis Basin on the Moon, has several similarities in both morphology and scale to Inferno Chasm. Both are topographic highs with a central channel ~2-3 km long. No distal deposits are identified beyond each channel. We suggest Isis was formed by construction, from a highly gaseous, fire fountain eruption that created spatter that collected to form the cone and spatter-fed flows rather than by thermal erosion. Our work in Idaho is thus helping to inform our understanding of volcanic processes on the Moon.

Exploration Research. Exploration research focused at COTM was in support of the scientific investigations. The MIT (Massachusetts Institute of Technology) and NASA Kennedy teams conducted UAV flights to benefit science (data collection over terrains inaccessible from the ground but of high science value), and exploration (analog to non-contact data acquisition at planetary targets). We are also systematically studying the design, development, evaluation, and analysis of the communications and knowledge sharing processes for the science and engineering teams conducting planetary science analog field research. One critical aspect of the FINESSE project is the development of effective communication and information sharing between scientists and engineers, and between humans and robotic assistants, in support of complex field exploration.

West Clearwater Impact Structure.

The West and East Clearwater Lake impact structures are two of the most distinctive and recognizable impact structures on Earth. These structures are located in northern Quebec, Canada ~125 km east of Hudson Bay. The Clearwater Lake structures formed in the Precambrian Canadian Shield. Target lithologies comprise predominantly granitic gneiss, granodiorite, and quartz monzodiorite with cross cutting diabase dykes. The currently accepted diameters are 36 km and 26 km for the West and East structures, respectively. Long thought to represent a rare example of a double impact, recent age dating has called this into question with ages of ~286 Ma and ~460–470 Ma being proposed for the West and East structures, respectively.

FINESSE team at West Clearwater Impact Structure, Canada.

Over the course of the 5-week field FINESSE campaign, the team focused on several WCIS research topics, including impactites, central uplift formation, the impact-generated hydrothermal system, multichronometer dating of impact products, and using WCIS as an analog test site for crew studies of sampling protocols.

The FINESSE team was able to visit and map all of the major islands within West Clearwater Lake. Excellent cliff exposures around the coasts of many of the islands allowed a general stratigraphy of impactites to be defined. Notable differences to previous work includes the discovery of a monomict lithic breccia and a medium to coarse grained impact melt rock. Below we describe the various impact-relevant lithologies studied and identified during the FINESSE campaign.

Fractured basement. The uplifted target rocks range from intact to highly brecciated. Shatter cones are common but poorly developed on the central islands. Veins of impact melt rock are common. It is not clear if these represent in situ pseudotachylite or injected shock melt.

Monomict lithic breccia. This impactite has been documented on several islands. It is melt-free and is largely monomict.

Impact melt-bearing lithic breccia. One of the most distinctive impactites at West Clearwater is a breccia containing variable proportions of red, oxidized impact melt particles set in a clastic matrix. This impactite can form cliffs >40 m high in places and is missing in others so that clast-rich impact melt rocks immediately overly fractured basement. In several locations, melt particles were observed aligned parallel with the upper melt rock contact. Lithic clasts are frequently rimmed in melt.

Clast-rich fine-grained impact melt rock. The base of impact melt rock sequence is clast-rich. This unit forms cliffs up to 35 m thick in places.

Clast-poor fine-grained impact melt rock. Upwards from the clast-rich impact melt rock is a clast-poor variety. The contact between the two ranges from gradual to abruptly gradational.

Clast-poor medium-grained impact melt rock. The uppermost impactite unit is a medium- to coarse-grained impact melt rock. It was found on the highest points of the majority of the ring islands.

In addition, ample rock samples were returned from West Clearwater for geochronology study. Geochronology work will center around laboratory analyses of these samples (and samples collected in the future or obtained from archives housed at the Canadian Geological Survey). Samples returned from the FINESSE field season have been evaluated for suitability for geochronologic analysis, and selected samples have been crushed for mineral separation and/or sawed for the preparation of polished petrologic thin sections. Heavy minerals (e.g., zircon, titanite, and apatite) will be separated from the crushed material for (U-Th)/He geochronology in the coming months. The sections will be used for laser ablation $^{40}Ar/^{39}Ar$ research after neutron irradiation.

Exploration work at Clearwater focused on an opportunistic experiment to test factors that contribute to the decisions a remote field team (for example, astronauts conducting extravehicular activities (EVA) on planetary surfaces) makes while collecting samples for return to Earth. We found that detailed background on the analytical purpose of the samples, provided to the field team, enables them to identify and collect samples that meet specific analytical objectives. However, such samples are not always identifiable during field reconnaissance activities, and may only be recognized after outcrop characterization and interpretation by crew and/or science team members. Recommendations have been identified such as allocating specific time in astronaut timeline planning to collect specialized samples, that this time follow human or robotic reconnaissance of the geologic setting, and that crewmember training should include exposure to the laboratory techniques and analyses that will be used on the samples upon their return to terrestrial laboratories.

Resource Prospector (RP) and Mojave Volatiles Prospector (MVP)

In addition to the fieldwork at COTM and West Clearwater, FINESSE team members have been able to leverage our SSERVI / FINESSE knowledge base to contribute to the Resource Prospector (HEOMD) and Mojave Volatiles Prospector (SMD) projects. RP is an HEOMD Phase A mission concept to conduct a lunar polar rover mission to characterize the distribution of water and other volatiles at the surface and near subsurface of the Moon, plus demonstrate ISRU (in situ resource utilization). FINESSE Deputy PI Colaprete is the PI for RP. RP work this year has involved science requirements definition, refinement of concepts of operations, landing site selection studies, traverse planning exercises to demonstrate mission feasibility, and payload element development and testing (near-infrared and neutron spectrometers). To support this work, FINESSE members have leveraged additional SMD funds (Moon Mars Analog Mission Activities grant to PI Heldmann) to conduct an analog field campaign to test

NASA Ames K-Rex rover used for MVP.

both concepts of operations and integrated RP instruments on a rover platform within the field environment. This field campaign was dubbed MVP (Mojave Volatiles Prospector). The rover was remotely operated in the Mojave Desert from a Science Operations Center based at NASA Ames Research Center. MVP focused on both hardware and operations testing while conducting a bona fide scientific investigation regarding Mojave desert science. FINESSE, RP, and MVP have all mutually benefited from the expertise of these teams to increase the robustness of each activity.

2. Inter-team Collaborations

FINESSE capitalizes on multiple inter-team collaborations as described below.

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 impactites 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). Given the logistical challenges of accessing the site, our collaboration with UWO has helped the FINESSE team to embark on these unprecedented studies of a superb impact analog site.

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 deployed to Craters of the Moon with FINESSE this year and continues to analyze both satellite and ground truth data. Her FINESSE work will continue as an international SSERVI collaborator.

Laval University, Canada.

In addition to our collaborations with the UWO, we have also developed a collaboration with Laval University outside of the SSERVI framework. We are working with Dermot Antoniades who is a professor at Laval University, which is also host to the Centre des etude Nordiques (Center for Northern Studies) or CEN. Antoniades has submitted proposals to conduct limnological studies of the Clearwater Lakes and will conduct bathymetric echo sounding (to map the lake bathymetry) and sub-bottom profiling (to characterize what lies beneath the sediment-water interface). Dermot will be

conducting this mapping and profiling in order to select a region for sediment coring in the Spring of 2016. The proposed characterization of the submerged portions of the West Clearwater Impact Structure is also useful to the FINESSE team for understanding the WCIS impact and subsequent geologic modification, and thus we are collaborating with the Laval team to share expertise regarding science and data collection methodologies and logistics regarding this field site.

RIS4E.

The SSERVI FINESSE and RIS4E teams share a close collaboration particularly in terms of using terrestrial field analogs to further understand planetary processes such as impacts and volcanism. Given the complimentary nature of the FINESSE and RIS4E research objectives, we share Co-Is (e.g., Brent Garry, Noah Petro, Andrea Jones of NASA Goddard) on both teams who help to cross-pollinate our efforts and share joint research interests. Both RIS4E and FINESSE have also hosted Co-Is from each other's teams on field deployments. For example, FINESSE Co-I Scott Hughes participated in the RIS4E Hawaii field campaign to study volcanic lavas, while RIS4E Co-I and post-doc Kelsey Young participated in the FINESSE-led deployment to the West Clearwater Impact Structure. Plans for future field deployments by both teams will continue to incorporate Co-Is and Collaborators from both RIS4E and FINESSE.

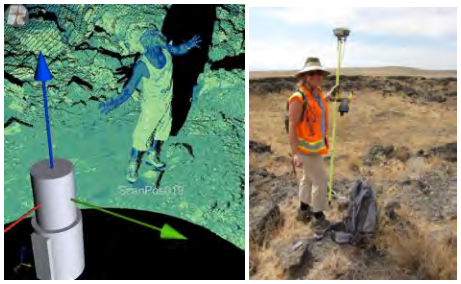
KIGAM (Korea Institute of Geoscience and Mineral Resources).

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 conduct research and field test her newly developed XRF instrument while simultaneously conducted 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.

3. EPO Report

The FINESSE team organized and supported multiple EPO activities this year.

Spaceward Bound: Immersive Field Experiences for Teachers. Two Idaho teachers joined the FINESSE team to participate in fieldwork at Craters of the Moon National Monument and Preserve in August 2014. The teachers hiked through the lava flows, helped operate field instruments, and collected dGPS and LiDAR data. FINESSE researchers reported that Heather Guy, an elementary school teacher, "asked a lot of questions" and "was very curious about the process of how scientists actually work." Jeff



Teachers supporting FINESSE fieldwork at Craters of the Moon National Monument and Preserve. Left: A LiDAR scan of Jeff Karlin inside a lava tube. Right: Heather Guy collects dGPS data.

Karlin, a high school teacher "was a joy to work with," with "boundless enthusiasm," and "more graceful than a gazelle carrying the instruments over lava flows." Both teachers were active participants in the fieldwork and associated science discussions, even leading insightful science conversations. The teachers had glowing reports of their field experience, calling it "eye-opening" and "incredible." FINESSE scientists have kept in touch with both teachers since the summer, with additional planned connections and coauthorship on an AGU publication. This program was supported through a partnership with the Idaho State Space Grant.

Haven House Family Shelter NASA Ames Tour. The FINESSE team partnered with the Haven House Family Shelter to bring 65 children and 16 adults to the NASA's Ames Research Center in July 2014. The children and their families were part of the "Beyond the Bed" program at the Haven House Family Shelter, which combines shelter/housing with comprehensive services that enable homeless families and individuals to rapidly return to permanent housing and self-sufficiency. The Haven House-Ames partnership was established by FINESSE Deputy-PI, Darlene Lim, who has been running a STEM speakers' series at the shelter since 2013. Twelve volunteers from Ames led tours at each facility, with substantial support from SSERVI Central.

International Observe the Moon Night (InOMN). The FINESSE team supported InOMN events at team member institutions. Andrea Jones organized and facilitated the InOMN event at NASA's Goddard Space Flight Center, which Brent Garry supported. Jennifer Heldmann organized and presented in a virtual InOMN event from NASA Ames.

Public Engagement Potpourri. @FINESSE_NASA shared photos and updates with 100,000s of people from the West Clearwater Lake Impact Structure during a field campaign in August 2014. The FINESSE team hosted a media day at Craters of the Moon and gave public talks at the Visitor Center during the summer 2014 field excursion. Several NASA Ames press releases have resulted from FINESSE work, and FINESSE research has been featured on The Discovery Channel and The Science Channel. EPO and project activities are regularly updated on the NASA FINESSE website.

A photo Tweeted by FINESSE Collaborator and Canadian Astronaut David Saint-Jacques (@Astro_DavidS) from the West Clearwater Impact Structure. The team tagged their posts from this field campaign with #WCIS14.

4. Publications – Year 1 of this project has resulted in 65 referenced works. Journal articles are listed here:

Sears, D.W.G., The Known Asteroids: A Review, Space Sci Reviews (in review), 2015.

Kim, K., Lee, J., Seo, H., Ju, G., Le, S., Choi, G., Sim, E., and T. Lee. An introduction to the lunar and planetary science activities in Korea, Advances in Space Res., Volume 54, Issue 10, 2014.

Heldmann, J.L., Colaprete, A., Elphic, R., Mattes, G., Ennico, K., Fritzler, E., Marinova, M., McMurray, R., Morse, S., Roush, T., and C. Stoker. Real-time science operations to support a lunar polar volatiles rover mission. Advances in Space Res., doi:/10.1016/j.asr.2014.07.037, 2014.

Cohen, B.A., Lim, D., Young, K., Squyres, S., Elphic, R., and G. Osinski. Pre-mission requirements to enable successful sample collection by a remote field / EVA team. In prep, 2015.

Sears, D.W.G., Hughes, S.S., Kobs-Nawotniak, S., Borg, C., Kim, K.J., Sears, H., Skok, J.R., Lim, D., Heldmann, J.L., Haberle, C., Downs, M., Tornabene, L., and G.R. Osinski. A Study of the Kings Bowl Phreatic Explosion Crater as an Analog to Pits on Solar System Exploration Target Bodies, Earth Planet. Sci. Letters, submitted 2015.

Sears, D.W.G., Sears, H., and M. Carter. Thermal and Radiation History of Recently Recovered Antarctic CO chondrites and Notes on the Determination of Petrographic Types of CO Chondrites, Geochem. Cosmochem. Acta, submitted 2015.

Sears, D.W.G., Tornabene, L., Osinski, G.R., Hughes, S.S., and J.L. Heldmann. The "ponds" on asteroid (433) Eros: Possible new insights from experiment, Vesta, Mars, and terrestrial analogs. Planet and Space Sci., in revision, 2015.

5. Conference papers, extended abstracts, posters and presentations.

Total number of Conference Papers, extended abstracts, poster presentations and oral presentations: 58. Here we list extended abstracts (e.g., mini-publications). These include publications from LPSC, IAC, LEAG, and IEEE. Student authors are <u>underlined</u> and are included in 12 references below. An asterisk denotes cross-team publications. A full list of publications can be found on the FINESSE website at http://spacescience.arc.nasa.gov/finesse/publications/.

Sears, D.W.G., Tornabene, L.L., Osinski, G.R., and J.L. Heldmann. The ponds on Eros: Possible new insights from Vesta, Mars, and terrestrial analogs. Lunar and Planetary Science Conference, Houston, TX, 2014.

Osinksi, G.R., Tornabene, L.L., Sears, D.W.G., Hughes, S.S., and J.L. Heldmann. Impact craters as probes of fluids on differentiated bodies. Lunar and Planetary Science Conference, abstract #2439, Houston, TX, 2014.

Garry, W.B. The Mare Imbrium flow field: Regional geologic context of the Chang'e 3 landing site. Lunar and Planetary Science Conference, Abstract #2169, Houston, TX, 2014.

<u>Mercer, C.M</u>., Young, K.E., Weirich, J.R., Hodges, K.V., Jolliff, B.L., Wartho, J.A., and M. van Soest. Diverse impact histories of Apollo 17 melt breccias revealed by in situ 40Ar/39Ar geochronology. Lunar and Planetary Science Conference, Abstract #2669, Houston, TX, 2014.*

Young, K.E., <u>Mercer, C.M</u>., van Soest, M.C., Hodges, K.V., Wartho, J.-A., and M.B. Biren. An examination of noble gas geochronology and thermochronology in the context of dating impact events. Lunar and Planetary Science Conference, Abstract #2670, Houston, TX, 2014.*

Neish, C.D., Madden, J., Carter, L.M., Hawke, B.R., Giguere, T., Bray, V.J., Osinski, G.R., Cahill, J.T.S. Global distribution of lunar impact melt flows. LPSC 45, oral presentation. Houston, TX, 2014

Diaz, A., and D. Newman. Musculoskeletal human-spacesuit interaction model. IEEE Aerospace Conference, Big Sky, MT, 2014.

Vasquez, R.A., Middleton, A.J., Duda, K.R., and D. Newman. The V2Suit "Down" tracking algorithm. IEEE Aerospace Conference, Big Sky, MT 2014.

Kim, K.J., Elphic, R.C., Stoker, C.R., Heldmann, J.L., Choi, I., and H. Kusano. Preliminary results of an elemental analysis using a portable x-ray spectrometer for lunar surface exploration applications. COSPAR, Moscow, Russia, 2014.

Caldwell, B. Development of a Spaceflight Common Operating Picture for Exploration Design in the SSERVI FINESSE Team. Internat. Astronaut. Congress, Toronto, Canada, 2014.

Lim, D., Heldmann, J.L., Colaprete, A.C., Cohen, B., Elphic, R., Garry, B., Hodges, K., Abercromby, A., Gernhardt, M, Squyres, S., Fong, T, Deans, M., Osinski, G., McKay, C., Garry, W., Hughes, S., Petro, N., Sears, D. Terrestrial analog field investigations to enable science and exploration studies of impacts and volcanism on the Moon, NEAs, and moons of Mars. Internat. Astronaut. Congress, Toronto, Canada, 2014.

Garry, W.B., Hughes, S.S., Kobs, S.E., Neish, C.D., Haberle, C.W., Heldmann, J.L., and D. Lim. The Geology of Inferno Chasm, Idaho: A Terrestrial Analog for Lunar Rilles? Annual Meeting of the Lunar Exploration Analysis Group. October 2014.

Kerrigan, M. and G. Osinski. Overview of impact-generated hydrothermal activity at the West Clearwater Lake Impact Structure. Lunar and Planetary Science Conference, Houston, TX, 2015.

Wilks, R., and G.R. Osinski. Impact melt veins in the central uplift of the West Clearwater Lake Impact Structure, Northern Quebec, Canada. Lunar and Planetary Science Conference, Houston, TX, 2015.

Kerrigan, M., Osinski, G.R., and R.A.F. Grieve. Hydrothermal mineralization within the impact melt sheet of the East Clearwater Lake Impact Structure, Canada. Lunar and Planetary Science Conference, Houston, TX, 2015.

Rae, A.S.P., Morgan, J.V., Collins, G.S., Osinski, G.R., and R.A.F. Grieve. Observational constraints on central uplift formation: The West Clearwater Lake Impact Structure, Canada. Lunar and Planetary Science Conference, Houston, TX, 2015.

Osinski, G.R., Brunner, A., Collins, G.S., Cohen, B.A., Coulter, A., Elphic, R., Grieve, R., Heldmann, J.L., Hodges, K., Horne, A., Kerrigan, M., Lim, D., Misener, R., Morgan, J., Rae, A.S.P., Saint-Jacques, D., Skok, J.R., Squyres, S., Tornabene, L., Wilks, R., and K. Young. Revisiting the West Clearwater Lake Impact Structure, Canada. Lunar and Planetary Science Conference, Houston, TX, 2015.*

Heldmann, J.L., Colaprete, A., Cook, A., Roush, T., Deans, M., Elphic, R., Lim, D., Skok, J.R., Button, N.E., Karunatillake, S., and G. Garcia. Mojave Volatiles Prospector (MVP): Science and operations results from a lunar polar rover analog field campaign. Lunar and Planetary Science Conference, Houston, TX, 2015.

Roush, T.L., Colaprete, A.C., Heldmann, J.L., Lim, D., Cook, A., Elphic, R., Deans, M., Fluckiger, L., Fritzler, E., and D. Hunt. Attempt of serendipitous science during the Mojave Volatile Prospector field expedition. Lunar and Planetary Science Conference, Houston, TX, 2015.

Deans, M., Lees, D.S., Cohen, T., Lee, Y., Smith, T., Wolfe, S.R., Heldmann, J., Colaprete, A., Elphic, R., and D. Lim. Tools for enabling real time volatile prospecting with surface rovers. Lunar and Planetary Science Conference, Houston, TX, 2015.

Button, N.E., Skok, J.R., Heldmann, J.L., Thompson, D., Ortega, K., Francis, R., Deans, M., Lees, D., Garcia, G., and S. Karunatillake. Classifying planetary surfaces with

results from the TextureCam processing with the Mojave Volatiles Prospector (MVP) rover mission. Lunar and Planetary Science Conference, Houston, TX, 2015.

Elphic, R.C., Heldmann, J.L., Colaprete, A., Hunt, D.R., Deans, M.C., Lim, D.S., Foil, G., and T. Fong. Neutron spectrometer prospecting during the Mojave Volatiles Project analog field test. Lunar and Planetary Science Conference, Houston, TX, 2015.

Garry, W.B., Hughes, S.S., Kobs, S., Neish, C., Haberle, C.W., Heldmann, J.L., Lim, D., and the FINESSE Team. The geology of Inferno Chasm, Idaho: A terrestrial analog for lunar rilles. Lunar and Planetary Science Conference, Houston, TX, 2015.

Hughes, S.S., Kobs Nawotniak, S., Sears, D.W.G., Garry, W.B., Haberle, C.W., Bleacher, J.E. Lim, D., Heldmann, J.L., and the FINESSE Team. King's Bowl, Idaho - A volcanic analog for fissure eruptions, pit craters and dike injection along Rima Hyginus, Moon, and Cyane Fossae, Mars. Lunar and Planetary Science Conference, Houston, TX, 2015.*

Sears, D.W.G., Hughes, S.S., Kobs, S., Borg, C., Kim, K., Sears, H., Skok, J.R., Lim, D., Heldmann, J.L., Haberle, C., Downs, M., Tornabene, L., and G.R. Osinski. A study of King's Bowl phreatic explosion crater as a planetary analog. Lunar and Planetary Science Conference, Houston, TX, 2015.

6. List of undergrad students, grad students, postdocs, and new faculty.

Several undergraduate students, graduate students, post-doctoral researchers, and new faculty have benefitted from collaboration with the FINESSE team to conduct science and exploration research while simultaneously training the next generation of researchers. Specific examples are cited below.

• **Undergraduate Students**:

- Taylor Judice and David Susko (Louisiana State University). Judice and Susko are both are senior undergraduates in Geology and Geophysics at LSU, working with FINESSE Co-I J.R. Skok and Collaborator Suniti Karunatillake. Judice and Susko have benefitted from networking within the FINESSE team, being exposed to exciting planetary science research, and being presented with graduate school opportunities upon completion of their undergrad senior research theses this year.

- Chris Borg is an undergraduate student at the University of Idaho. Borg is conducting his undergraduate thesis with advisors and FINESSE Co-Is Scott Hughes and Shannon Kobs-Nawotniak. Borg conducted fieldwork at Craters of the Moon with the FINESSE team this year and is now analyzing basaltic samples in the laboratory.

• **Graduate Students**:

- Chris Haberle is a graduate student at Arizona State University working under advisor Phil Christensen. Haberle's PhD dissertation is focusing on terrestrial remote sensing with planetary applications. His research is focused on the FINESSE field sites at Craters of the Moon in Idaho, conducting remote reconnaissance supported by field work ground-truthing. Haberle routinely deploys to COTM with the FINESSE team and has proved instrumental in field site selection, field work itself, and follow-up scientific interpretation and analysis.

- Anna Brunner and Audrey Horne are graduate students at Arizona State University working under advisor Kip Hodges (FINESSE Co-I). Brunner and Horne's PhD theses focus on geochronology of impact structures. Their doctoral research is focused on the FINESSE field sites at West Clearwater Impact Structure. Work this year

focused on sample collection during the WCIS field campaign, and now these students area focused on sample analysis.

- Adam Coulter, Rebecca Wilks, and Mary Kerrigan are graduate students at the University of Western Ontario working under advisor Gordon Osinski (FINESSE Collaborator). This research is focused on the mechanics of impact cratering including impact rock modification (e.g., melt rock and breccia emplacement, target rock properties, geomorphology, etc). Their PhD research is focused at the FINESSE field sites at West Clearwater Impact Structure.

- Auriol Ray is a graduate student at Imperial College London. His PhD research focuses on impact cratering, specifically rock mechanics, shock attenuation, and structural formation. Ray's research is heavily based on the fieldwork conducted at WCIS through FINESSE this year.

-Nikhil Vadhavkar and Forrest Meyen are graduate students at the Massachusetts Institute of Technology (MIT) working with advisors and FINESSE Co-Is Dava Newman and Nicholas Roy. Nikhil and Forrest are focused on exploration research including traverse path planning, tools and capabilities for science-based EVA (extra-vehicular activity) on planetary surfaces, and UAV-based data acquisition. The MIT team deployed to Craters of the Moon with FINESSE to conduct fieldwork this year.

• **Post-doctoral Researchers:**

- J.R. Skok is a post-doctoral researcher affiliated with Louisiana State University and NASA Ames. Skok's research focuses on volcanic processes, impact cratering, and resultant landforms as well as planetary mission concepts and operations. Through FINESSE, Skok deployed to both Craters of the Moon in Idaho and West Clearwater Impact Structure in Canada this year. Skok also participated in the MVP (Mojave Volatiles Prospector) lunar rover field campaign through his collaborations with FINESSE personnel.

- Kelsey Young is a post-doctoral researcher based at NASA's Goddard Spaceflight Center. Young is a Co-I on the SSERVI RIS4E team and a Collaborator with FINESSE. Her work focuses on planetary impacts, volcanism, and exploration topics, and thus Young deployed to the West Clearwater Impact Structure with the FINESSE team this year.

- Deepak Dhingra is currently a post-doctoral researcher in the Department of Physics at the University of Idaho. Dhingra recently received his PhD from Brown University where he worked under advisor Carle Pieters (SSERVI PI). Dhingra is now joining the FINESSE team to conduct fieldwork at Craters of the Moon and conduct ground truth studies to assess volcanic mineralogy and petrology in association with various landforms.

• **New Faculty:** Dr. Shannon Kobs-Nawotniak is an Assistant Professor in the Department of Geosciences at Idaho State University. Kobs-Nawotniak focuses on physical volcanology, computational fluid dynamics, and high performance computing. She investigates the dynamics of explosive volcanic eruptions, ranging in scale from the origins and underpinnings of monogenetic volcanic fields through eddy-scale mixing in eruption columns through field work, experimental analog models, and computational analyses to evaluate volcanic eruptions and their potential hazards. She has benefited from her collaboration with the NASA FINESSE team in developing and leading the quantitative research component to numerically model COTM eruptions and place

constraints on volatile contents of the COTM lavas, leading fieldwork activities at COTM, and advising student research projects based on the FINESSE COTM field campaigns. She also recently acquired a new field FTIR spectrometer which is being tested and used for scientific research during the FINESSE COTM deployments.

TIMOTHY GLOTCH

Remote, In Situ and Synchrotron Studies for Science and Exploration (RIS^{4}E)

Stony Brook University, Stony Brook, NY

Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS^{4}E)—2014-2015 Annual Report

1. Team Project Reports

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 first 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 synthesis and characterization of new mineral standards, acquisition of mid-IR (MIR) emissivity and temperature-dependent visible/near infrared (VNIR) reflectance spectra in simulated lunar/asteroid environments, and testing and validation of advanced light scattering and radiative transfer models for quantitative interpretation of remote spectral data. Mineral synthesis efforts have focused on two phases of high importance for lunar spectroscopic studies—pure An98 plagioclase feldspar, and 4 different compositions of pigeonite, a low calcium clinopyroxene. Pigeonite synthesis was especially challenging, as its stability field is extremely narrow, and the mineral tends to exsolve into separate Ca-poor and Ca-rich phases. We have successfully synthesized both plagioclase and pigeonite (Figure 1) and have moved into production mode, making additional aliquots of the sample for spectral characterization and space weathering (Theme 1) and toxicity (Theme 3) experiments. A major accomplishment of this synthesis work is the generation of large (>100 μm) crystals, enabling high quality MIR emissivity and VNIR reflectance measurements. Descriptions and results of the synthesis experiments can be found in DiFrancesco et al. (2015) and Sinclair et al. (2015).

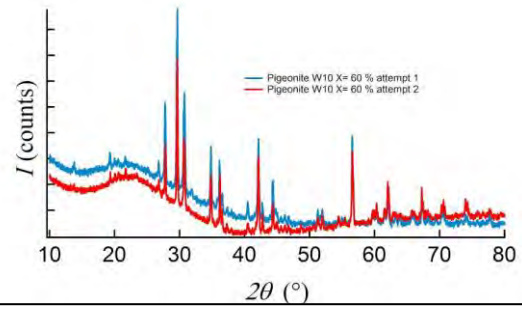


Figure 1. X-ray diffraction patterns of synthetic pigeonite. Peak positions and shapes indicate that there is little to no zoning in Fe/(Fe+Mg) or Ca. Minor (<5%) augite is likely present in the sample.

We have also begun acquiring spectra of mineral standards and mineral mixtures in a simulated lunar environment. In October, the Planetary and Asteroid Spectroscopy Environmental Chamber (PARSEC) was commissioned and tested in the Vibrational Spectroscopy Laboratory at Stony Brook. This chamber allows us to acquire MIR emissivity and VNIR reflectance spectra under simulated lunar or asteroid conditions. The initial work performed with PARSEC is reported in Shirley et al. (2015). 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 and to generate optical constants for use in those models (Arnold et al., 2015; Ito et al., 2015; Legett et al., 2015; Rucks et al., 2015). Graduate student Melinda Rucks (Stony Brook Geosciences) won a NESF graduate student poster award for her work on this subject. Finally, we have utilized existing remote sensing data sets to provide new insights into the geology of the Moon (Glotch et al., 2015a) and Phobos (Glotch et al., 2015b).

Theme 2: Maximizing Exploration Opportunities: Development of Field Methods for Human Exploration. The major activities in this theme involved a 2-week long field excursion to the 1974 lava flow on the flanks of the Kilauea volcano on the Big Island of Hawaii. This and future

field excursions have two main science and exploration goals: (1) to test the use of handheld scientific instruments for sample selection and high grading (Young et al., 2015; Ito et al., 2015), and (2) to characterize the topography of lava flows and pits to determine if there is a relationship between flow topography and pit provenance (i.e. lava tube or collapse; Whelley et al., 2015). The field campaign was conducted by 11 researchers, including 1 postdoctoral researcher, 2 graduate students, and a collaborator from the FINESSE team. The trip resulted in detailed topographic characterization of 2 collapse pits and several portions of the 1974 flow using LiDAR (see https://www.youtube.com/watch?v=kASkg7ili-M&feature=youtu.be for a visualization of this data). A major effort during the field campaign involved testing and calibration of a multispectral MIR camera (Figure 2). This work showed that multispectral IR imagery can be used to guide sample selection in the field. Work is currently being done in the lab to streamline data calibration and processing, enabling more efficient data collection in future field excursions.

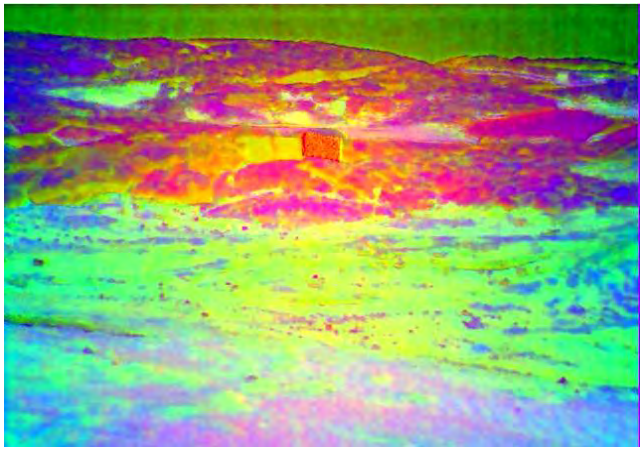


Figure 2. False-color infrared image shows compositional differences between pahoehoe laval (purple/red) and basaltic ash (green/blue). Differences within the ash unit are clearly visible, and led to specific sample selections in the field.

Subsequent to the field campaign, GSFC postdoctoral researcher Kelsey Young traveled to JSC to conduct handheld XRF analyses on the team's 2014 field samples. Young used the same model that was used during the 2010 and 2011 Desert RATS field campaigns, which will help enable comparisons between the RIS^{4}E data and prior analog field tests in volcanic fields. This handheld XRF will also be used in the 2015 Hawaii field campaign.

Theme 3: Protecting our Explorers: Understanding How Planetary Surface Environments Impact Human Health. Future explorers will be exposed to inhalable dust native to planetary surfaces. Regolith on airless bodies is expected to be highly reactive and potentially toxic. In the first year of work, the RIS^{4}E team tested the toxicity of several lunar simulants. We also tested the reactivity, as measured by the production of H_2O_2 and $OH^{\cdot}$ from lunar simulants and mineral separates in distilled water and simulated lung fluid. We tested a range of lunar simulants for both their cytotoxicity (cell damage) using mouse lung cell cultures and genotoxicity (mitochondrial and nuclear DNA damage) using mouse brain cell cultures.

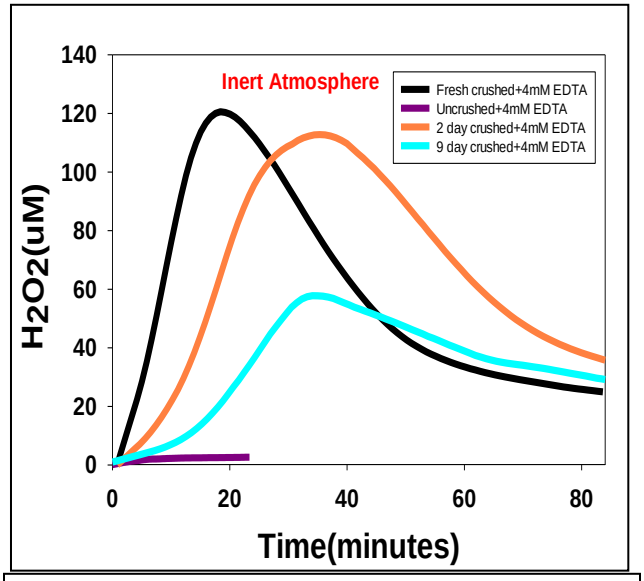


Figure 3. H_2O_2 production for OB-1 lunar simulant crushed and left out for various lengths of time. Freshly crushed simulant produces most H_2O_2.

Stony Brook undergraduate and summer intern Sara Port, working with Co-I Hurowitz,

used electron paramagnetic resonance (EPR) spectroscopcy to test hydroxyl radical production for pulverized minerals. They found that just the act of grinding a mineral (an analog for micrometeorid bombardment that occurs continuously on airless bodies) substantially increases the production of $OH^{\cdot}$ when that mineral comes into contact with a fluid. These results are nearly ready to be submitted to JGR Planets, with Port as the first author.

Stony Brook graduate student Jasmeet Kaur, working with Co-I Schoonen, tested the generation of H_2O_2 by several pulverized lunar simulants. There are two major results for this work: (1) the simulants with the highest proportions of glass were the most reactive (as measured by H_2O_2 production), and (2) the reactivity of the simulants decreased with time after being pulverized (Kaur et al., 2015).

We also tested the effects of lunar simulants directly on cells. Stony Brook postdoc Jill Nissen (Pharmacology), working with Co-I Tsirka, exposed mouse lung cell cultures to a variety of lunar simulants and found an increased level of Caspase-3 (a marker of cell death) expression for agglutinated lunar simulants. Stony Brook graduate student Rachel Caston (Pharmacology), working with Co-I Demple found that a glass-rich lunar simulant (CMSCLS) caused considerably more DNA damage than other simulants. Additionally, the fine component of JSC-1A caused substantially more cell death than the bulk simulant. Rachel won a NESF graduate student poster award for her work on this subject.

Theme 4: Maximizing Science from Returned Samples. Early work in Theme 4 has focused on X-ray absorption spectroscopy (XAS) and transmission electron microscope (TEM) electron energy loss spectroscopy (EELS) for a suite of synthetic glasses synthesized by Collaborator McCanta. XAS work on the glasses, performed by Co-I's Dyar, Sutton, and Lanzirotti, has resulted in a preliminary multivariate model for predicting %Fe in silicate glasses (Figure 4). The %Fe error bar generated by this model is now equivalent to that of the Mössbauer data used to validate it. We have hired a python programmer who is generating the final code to calculate %Fe in silicate glasses using synchrotron XAS methods. By the end of 2015, this code will be publicly distributed and used at synchrotron beamlines around the world.

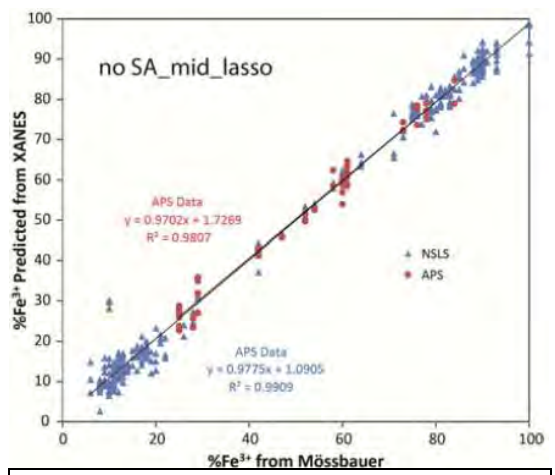


Figure 4. Comparison of $\%Fe^{3+}$ values calculated from XAS data with those from Mössbauer data. Red points are from APS and blue are from NSLS. There is no significant difference between the data measured at each synchrotron. R^2=0.992. From McCanta et al. (2015).

Postdoc Burgess (Naval Research Laboratory), working with Co-I's Stroud and De Gregorio, has been using the same glasses and developing the techniques required to calculate Fe^{2+}/Fe^{3+} ratios using TEM EELS techniques. This work will result in a suite of standard spectra that can be used by researchers around the world to determine the Fe oxidation state of small, precious samples using EELS. This work is reported Burgess et al. (2015).

Additional work on the general applicability of multivariate models to spectral unmixing is being conducted by graduate student C. J. Carey (UMass) and Postdoc Elizabeth Sklute (Mt. Holyoke) with Co-I's Mahadevan and Dyar. A paper describing a multivariate model for use with Raman spectra is currently in review at *Journal of Raman Spectroscopy* (Carey et al., 2015).

2. Inter-team Collaborations

The RIS^{4}E team is dedicated to the concept of inter-team collaboration within the overall structure of SSERVI. Our experiences in Year 1 have provided evidence that the whole of SSERVI is greater than the sum of its parts.

Collaboration with the FINESSE Team.

Our major inter-team collaboration in Year 1 has been with the FINESSE team. Early in Year 1, two FINESSE team members, Scott Hughes and Derek Sears, were added as official RIS^{4}E Collaborators. Hughes is an expert volcanologist, whose interest in mafic geochemistry is a strong complement to the physical volcanology expertise of our Theme 2 field leads Jacob Bleacher and Brent Garry. Sears is a meteoriticist, but also has strong interests in thermochronology. We have tentative plans to include Sears in a future RIS^{4}E field season.

Hughes accompanied the RIS^{4}E field team to Hawaii in Sept. 2014, and provided valuable insight into the petrogenesis and evolution of Hawaiian volcanism. Hughes' inclusion in RIS^{4}E field activities is a prime example of an opportunity that was clearly enabled by the virtual institute concept. Bleacher, Garry, and Hughes were already collaborators, but previous to the first RIS^{4}E field season, they had no plans or opportunity for joint field work in Hawaii. Garry is also a FINESSE Co-I and is working closely with Hughes and other members of the FINESSE field team at Craters of the Moon. It is likely that one or more papers with both RIS^{4}E and FINESSE authors comparing and contrasting science and operations at these sites will be submitted in the future.

In addition to Hughes' involvement in RIS^{4}E field work, Kelsey Young, a RIS^{4}E postdoc at GSFC, participated in the FINESSE field campaign to the West Clearwater Impact Structure. This trip provided Young with the opportunity to expand upon her Ph.D. work on terrestrial impact structures, and provided the RIS^{4}E team with the opportunity to engage in impact crater studies, which is not a major focus of our team.

Collaboration with the DREAM2 Team

A substantial portion of the RIS^{4}E field investigation was devoted to characterizing the topography of two collapse pits on the Kilauea volcano in Hawaii. These pits are interesting from an exploration perspective because if they extend below the subsurface, they could provide refuge for explorers during solar radiation events. Separately from our field work, DREAM2 Co-I Mike Zimmerman has been modeling the radiation environment and volatile retention capability of lunar pits. RIS4E Co-I's Bleacher and Garry are collaborating with Zimmerman to provide field LiDAR data for pit crater dimensions and to provide geologically realistic constraints on models of volatile retention in the subsurface of airless bodies.

Collaboration with Korean SSERVI Team

PI Glotch has been in discussions with Dr. Moonkyung Chung of the Korea Institute of Civil Engineering and Building Technology (KICT) regarding synthesis of lunar simulants. KICT has plans to synthesize massive quantities of lunar simulants, focusing on mimicking the physical properties of lunar regolith. PI Glotch as agreed to act as a peer reviewer and advisor on lunar simulant synthesis for the KICT team.

Other International Collaborations

Dr. Ed Cloutis (University of Winnipeg) is a RIS^{4}E collaborator and a Canadian Lunar Research Network (CLRN) team member, providing a link between the two teams. Dr. Neil Bowles (University of Oxford) is a RIS^{4}E collaborator, providing a link to the UK and broader European Solar System science and exploration communities.

3. RIS^{4}E Education and Public Outreach

Figure 5. The RIS^{4}E field team at work in the Kilauea SW Rift Zone in 2014, in a picture shared through RIS^{4}E social media.

RIS^{4}E Journalists

The RIS^{4}E Education and Public Outreach (E/PO) team has supported RIS^{4}E E/PO Collaborator Barbara Selvin in organizing a Special Topics Course for undergraduate journalism students at Stony Brook University that uses RIS^{4}E science as a lens for teaching the students about science and science journalism, and gives them practical experience reporting on scientific research. In Year 1 we laid the groundwork for this course, currently underway in the 2015 spring semester. Students will visit a number of RIS^{4}E facilities where they will learn about scientific tools, watch scientific research in action, and have conversations with RIS^{4}E scientists to better understand the scientific process, so that they will be better prepared to report on scientific content. The RIS^{4}E journalism students will also join, and report on, the RIS^{4}E field excursion to Hawaii Volcanoes National Park in the spring of 2015.

Science Communication Workshop

The RIS^{4}E E/PO team began preparations for a Science Communications Workshop for leading, and rising, SSERVI scientists that will be offered in association with the 2015 SSERVI Exploration Science Forum at NASA Ames Research Center in July. This workshop will be led by RIS^{4}E E/PO team member Liz Bass, the Director of the Alan Alda Center for Communicating Science at Stony Brook.

RIS^{4}E Resource Documents

We are finalizing a set of educational materials that highlight the four themes of RIS^{4}E science (Preparation for Exploration, Maximizing Exploration Opportunities, Protecting our Explorers, Maximizing Science from Returned Samples), as well as a document that compares the Moon to other airless bodies in the Solar System. Once completed, these five resource documents will be made available to the public through the RIS^{4}E website, RIS^{4}E journalism students, International Observe the Moon Night hosts, and to all SSERVI teams.

Figure 6. RIS^{4}E team members share and describe their research in blog posts. This image of PRISM, a microscope that will support RIS^{4}E research, was shared in a post by co-I Rhonda Stroud.

Team Outreach

The RIS^{4}E team is committed to sharing its science and discoveries with the public. The team regularly posts blog entries on the RIS^{4}E website describing research plans and activities. The team also shares updates through social media (Twitter: @RIS4E_SSERVI; Facebook: RIS4E Science and Exploration), through public presentations, and through short-term student engagement activities such as virtual interviews with middle school students at the Christa McAuliffe Charter School and a Planetary Science Student-Scientist Mixer at the 2014 American Geophysical Union Fall Meeting in San Francisco.

4. Year 1 Publications (including those with imminent submission dates):

[9] Port, S. T., J. A. Hurowitz, and M. A. A. Schoonen (2014), Measurement of hydroxyl radical production by pulverized minerals using electron spin resonance spectroscopy: implications for the reactivity of planetary regolith, *J. Geophys. Res.*, manuscript in preparation, SSERVI Publication # SSERVI-2014-240.

[8] Burbine T. H., Binzel R. P. and Burt B. J. (2015) Percentages of Ordinary Chondrite Mineralogies among S-complex and Q-type Near-Earth Asteroids. *Meteoritics & Planetary Science*, in preparation. (no SSERVI number yet)

[7] Arnold, J. A., T. D. Glotch, P. G. Lucey, E. Song, I. R. Thomas, and N. E. Bowles (2015), Lunar olivine as seen by Diviner and M^3: A comparison of MIR and VNIR spectral data, J. Geophys. Res., manuscript in preparation. (no SSERVI number yet)

[6] Burbine, T. H. (2015), Advances in determining asteroid mineralogies, *Chemie der Erde-Geochem*., in review, SSERVI Publication # SSERVI-2014-272.

[5] Carey, C. J., M. D. Dyar, T. Boucher, S. Mahadevan, and P. Bartholomew (2015), Machine learning tools for mineral recognition and classification from Raman spectroscopy, *J. Raman Spectroscopy*, in review, SSERVI Publication # SSERVI-2014-234.

[4] Jaret, S. J., W. R. Woerner, B. L. Phillips, L. Ehm, H. Nekvasil, S. P. Wright, and T. D. Glotch (2015), Maskelynite formation via solid-state transformation: Evidence of infrared and X-ray anisotropy, *J. Geophys. Res*., in press, SSERVI Publication # SSERVI-2014-245.

[3] Cloutis, E. A., J. A. Sanchez, V. Reddy, M. J. Gaffey, R. P. Binzel, T. H. Burbine, P. S. Hardersen, T. Hiroi, P. G. Lucey, J. M. Sunshine, and K. T. Tait (2015), *Icarus*, in press. (no SSERVI number yet).

[2] Glotch, T. D., J. L. Bandfield, P. G. Lucey, P. O. Hayne, B. T. Greenhagen, R. R. Ghent, J. A. Arnold, and D. A. Paige (2015a), Formation of lunar swirls by magnetic field standoff of the solar wind, *Nature Communications*, 6, 6189, doi:10.1038/ncomms7189, SSERVI Publication # SSERVI-2014-158.

[1] Izawa, M. R. M., D. M. Applin, L. Norman, and E. A. Cloutis (2014), Reflectance spectroscopy (350-2500 nm) of solid state polycyclic aromatic hydrocarbons, *Icarus*, 237, 159-181, SSERVI Publication # SSERVI-2014-244.

5. Total number of Conference Papers, extended abstracts, poster presentations and oral presentations: 66

Full list of abstracts can be found at https://ris4e.labs.stonybrook.edu/publications/

2015 LPSC Abstracts:

Arnold, J. A., M. J. Rucks, and T. D. Glotch (2015), Mid-IR optical constants of triclinic minerals, *Lunar Planet. Sci. XLVI*, abstract 2707.

Bleacher, J. E., C. W. Hamilton, S. Scheidt, W. B. Garry, A. deWet, P. Whelley, and D. A. Williams (2015), No erosion needed: Development of streamlined islands during lava channel construction, *Lunar Planet. Sci. XLVI*, abstract 2182.***

Burbine, T. H., R. P. Binzel, and B. J. Burt (2015), Percentage of ordinary chondrite mineralogies among S-complex and Q-type near-Earth asteroids, *Lunar Planet. Sci. XLVI*, abstract 2700.

Burgess, K. D., R. M. Stroud, B. T. De Gregorio, M. D. Dyar, and M. C. McCanta (2015), Measurement of Fe oxidation state using aberration-corrected scanning transmission electron microscopy, *Lunar Planet. Sci. XLVI*, abstract 1965.

Carey, C., M. D. Dyar, T. F. Boucher, S. Giguere, C. M. Hoff, L. B. Breitenfeld, M. Parente, T. J. Tague, Jr., P. Wang, and S. Mahadevan (2015), Baseline removal in Raman spectroscopy: Optimization techniques, *Lunar Planet. Sci. XLVI*, abstract 2464.

Cloutis, E. A. (2015), Fe-bearing glassy materials: Spectral reflectance properties, *Lunar Planet. Sci. XLVI*, abstract 1234.

De Gregorio, B. T., R. M. Stroud, J. Davidson, L. R. Nittler, C. M. O'D. Alexander, K. Burgess, and A. L. D. Kilcoyne (2015), Chemical heterogeneity of organic matter in minimally-heated chondrites, *Lunar Planet. Sci. XLVI*, abstract 2951.

DiFrancesco, N. J., A. E. Coraor, H. Nekvasil, D. H. Lindsley, A. Sinclair, S. J. Jaret, and T. D. Glotch (2015), Synthesis of "large" iron-bearing anorthitic plagioclase crystals for lunar spectroscopic and space weathering studies, *Lunar Planet. Sci. XLVI*, abstract 1804.

Giguere, S., C. Carey, M. D. Dyar, T. F. Boucher, M. Parente, T. J. Tague, Jr., and S. Mahadevan (2015), Baseline removal in LIBS and FTIR spectroscopy: Optimization techniques, *Lunar Planet. Sci. XLVI*, abstract 2775.

Glotch, T. D., M. D. Dyar, J. E. Bleacher, M. A. A. Schoonen, N. E. Petro, A. J. P. Jones, and the RIS^{4}E Team (2015), Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS^{4}E): First year of science and exploration, *Lunar Planet. Sci. XLVI*, abstract 2178.

Glotch, T. D., C. S. Edwards, and D. S. Ebel (2015), Spectral properties of Phobos from the Mars Global Surveyor Thermal Emission Spectrometer: Evidence for water and carbonate, *Lunar Planet. Sci. XLVI*, abstract 2587.

Hughes, S. S. et al. (2015), King's Bowl, Idaho — A volcanic analog for fissure eruptions, pit craters, and dike injection along Rima Hyginus, Moon, and Cyane Fossae, Mars, *Lunar Planet. Sci. XLVI*, abstract 2846.***

Ito, G., A. D. Rogers, K. E. Young, J. E. Bleacher, C. S. Edwards, and T. D. Glotch (2015), Testing the incorporation of portable infrared imaging into a sampling workflow to enhance science return by astronauts, *Lunar Planet. Sci. XLVI*, abstract 1548.***

Ito, G., and T. D. Glotch (2015), Calculating the scattering properties of fine particulates of fine particulates on planetary surfaces, *Lunar Planet. Sci. XLVI*, abstract 1535.

Jaret, S. J., T. D. Glotch, B. L. Phillips, S. P. Wright, and D. T. King, Jr. (2015), Coesite at the Lonar Crater: The importance of pre-impact alteration and shock heterogeneity, *Lunar Planet. Sci. XLVI*, abstract 2086.

Jaret, S. J., T. D. Glotch, and J. R. Johnson (2015), Micro-Raman and micro-FTIR spectroscopy of experimentally shocked andesine, *Lunar Planet. Sci. XLVI*, abstract 2056.

Kaur, J., M. A. Schoonen, and D. Rickman (2015), Reactive oxygen species generation by lunar simulants, *Lunar Planet. Sci. XLVI*, abstract 1142.

Legett, C. IV, T. D. Glotch, and P. G. Lucey (2015), Modeling VNIR signatures of space weathering using the multiple sphere T-matrix model: Comparisons to observations and previous models, *Lunar Planet. Sci. XLVI*, abstract 2802.

McCanta, M. C., M. D. Dyar, C. Carey, S. Mahadevan, A. Lanzirotti, and S. Sutton (2015), Preliminary calibration for measuring ferric iron in silicate glasses: A Mössbauer and X-ray absorption spectroscopy study, *Lunar Planet. Sci. XLVI*, abstract 1388.

McCanta, M. C., M. D. Dyar, M. J. Rutherford, A. Lanzirotti, and S. Sutton (2015), In situ measurement of ferric iron in lunar glasses using Fe-XAS: Implications for lunar eruption mechanisms, *Lunar Planet. Sci. XLVI*, abstract 1500.

Nekvasil, H. N., N. J. Difrancesco, A. E. Coraor, and D. H. Lindsley (2015), A new mechanism for generating the calcium enrichment of lunar ferroan anorthosite, *Lunar Planet. Sci. XLVI*, abstract 1617.

Osinski, G. R. et al. (2015), Revisiting the West Clearwater Lake Impact Structure, Canada, *Lunar Planet. Sci. XLVI*, abstract 1621.***

Rucks, M. J., J. A. Arnold, and T. D. Glotch (2015), Mid-IR optical constants of triclinic minerals: A case study with labradorite, *Lunar Planet. Sci. XLVI*, abstract 2902.

Shirley, K. A., and T. D. Glotch (2015), First measurements from the Planetary and Asteroid Regolith Spectroscopy Environmental Chamber (PARSEC), *Lunar Planet. Sci. XLVI*, abstract 2025.

Shirley, K. A., T. D. Glotch, B. T. Greenhagen, M. White, and the Diviner Science Team (2015), A multiplicative approach to correcting the thermal channels for the Diviner Lunar Radiometer Experiment, *Lunar Planet. Sci. XLVI*, abstract 1992.

Sinclair, A., D. H. Lindsley, H. Nekvasil, and T. Glotch (2015), Synthesis of "large" pigeonite crystals for lunar spectroscopic and space weathering studies, *Lunar Planet. Sci. XLVI*, abstract 1494.

Stroud, R. M., N. D. Bassim, T. H. Brintlinger, B. T. De Gregorio, and K. D. Burgess (2015), PRISM: A new aberration-corrected scanning transmission electron microscope facility for planetary materials research, *Lunar Planet. Sci. XLVI*, abstract 2980.

Whelley, P. L., W. B. Garry, and J. E. Bleacher (2015), Lidar signatures of lava flow textures: Applications to planetary volcanism, *Lunar Planet. Sci. XLVI*, abstract 2140.

Young, K. E., J. E. Bleacher, C. A. Evans, A. D. Rogers, G. Ito, Z. Arzoumanian, and K. Gendreau (2015), Examining volcanic terrains using in situ geochemical technologies: Implications for planetary field geology, *Lunar Planet. Sci. XLVI*, abstract 1658.

6. Personnel

The RIS^{4}E team is committed to training the next generation of Solar System scientists and explorers. In the first year of funding, we have engaged 9 undergraduate students in high level research, fully or partially funded 7 graduate students, who have all contributed substantially to the RIS4E research mission, and funded 5 postdoctoral researchers, who are future leaders in NASA's Solar System exploration and research endeavors. In addition, Joel Hurowitz, formerly at JPL, and a RIS4E CO-I, was hired as an Assistant Professor in the Department of Geosciences at Stony Brook University. Details of undergraduate, graduate, postdoctoral, and new faculty personnel are listed below.

A. Undergraduate Students

1. Ramyaprabha Bondalapati,Stony Brook University ('15); SBU Pharmacology undergraduate researcher, (2014-present)

2. Sarah Byrne, Holyoke Community College ('14); RIS^{4}E summer intern; now Astronomy major at Mount Holyoke College (2014)

3. Joe Gardner, US Naval Academy ('15); RIS^{4}E summer intern (2014)

4. Jake Groh, US Naval Academy ('16); RIS4E summer intern (2014)

5. Julia Horne, Colgate University ('16); RIS^{4}E summer intern (2014)

6. Layton Neil, Kingsborough Community College ('15); RIS^{4}E summer intern (2014)

7. Valerie Pietrasz, California Institute of Technology ('16); RIS4E summer intern (2014)

8. Sara Port, Stony Brook University ('14); SBU Geology undergraduate researcher; now Ph.D. Geology student at University of Arkansas (2014)

9. Marco White, University of Vermont ('16); RIS^{4}E summer intern (2014)

B. Graduate Students

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

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

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

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

5. Jasmeet Kaur, Geosciences, Stony Brook University (2014-present)

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

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

C. Postdoctoral Researchers

1. Jessica Arnold, Geosciences, Stony Brook University (2014); now postdoctoral researcher with RIS^{4}E collaborator Neil Bowles at University of Oxford.

2. Katherine Burgess, Naval Research Laboratory (2014-present)

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

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

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

D. New Faculty

1. Joel Hurowitz, Geosciences, Stony Brook University

E. Publication Statistics

1. Total student- and postdoctoral-led publications: 3
2. Total publications with students as authors: 4
3. Total student- and postroctoral-led abstracts: 31
4. Total abstracts with students as authors: 36

WILLIAM FARRELL

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

NASA Goddard Space Flight Center, Greenbelt, MD

DREAM2 Annual Report Program Year #1: March 2014 to March 2015

DREAM2 PI team and Theme Leads: W. M. Farrell, R. M. Killen, G. T. Delory, J. S. Halekas, N. A. Schwadron, L. V. Bleacher

I. DREAM2 Team Progress Report

Airless bodies are exposed directly to the harsh space environment, including space plasmas, UV- and x-rays, micro-meteoroid impacts, and high energy charged particle radiation. In direct response to this energy, bodies react by emitting neutral and ion vapors, by altering the flow of the surrounding space plasma, and by creating high energy secondary radiation. To understand the connection between the space environment's coupled and dynamic interactions with exposed rocky bodies and human systems, SSERVI's center called the Dynamic Response of the Environment at Asteroids, the Moons and moons of Mars (DREAM2) advances key science environmental themes that seamlessly intertwine into exploration applications.

The DREAM2 center or space environment studies advances the understanding of the following question: **"How does the highly-variable environmental energy at an airless body affect volatiles, plasma, new chemistry, and surface micro-structure?".** To pursue this question DREAM2 has 6 themes that are common to exposed bodies: Plasma interaction, exosphere formation, radiation interaction, surface modification, effects from extreme events, and finally human interactions (in the form of missions and exploration). **Figure 1** illustrates the overlapping fundamental themes.

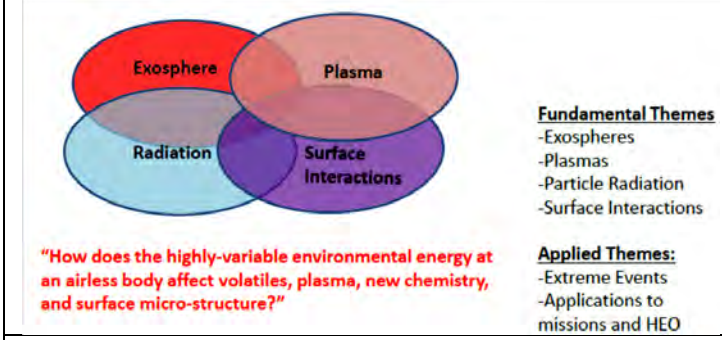


Figure 1- Overlapping DREAM2 themes

In the first year, the DREAM2 Program Office established 9 cooperative agreements with our expert partners and initiated funding. The Program Office also updated its webpage (http://ssed.gsfc.nasa.gov/dream/) and continued to fund support services of the DREAM2 Polycomm equipment located in the dedicated DREAM2 room at GSFC.

However, DREAM2's most critical element was the initiation of the team's science tasks, and this first year has been very successful with publication of numerous new findings, the inclusion of early career scientists, and successful demonstration on how science can support exploration – especially in the area of space environments.

Theme 1. Plasma Interactions at Small Bodies

The plasma provides the first interface to the surface of the Moon and other airless (or nearly airless) small bodies. Energy from plasma of solar and/or magnetospheric origin interacts directly with the surface, and also with exospheric gases derived from the surface. The result of this interaction is a bubbling cauldron of dynamic activity, with electrons, neutrals, and ions all blasted from the surface, charge layers built up on and above the surface, and nascent shocks and foreshock-like interactions developing as material derived from this interface feeds back on the incoming plasma. Understanding these interactions not only lays the groundwork for future exploration, but also strengthens our grasp of fundamental processes, with implications for other planetary bodies throughout our solar system and beyond.

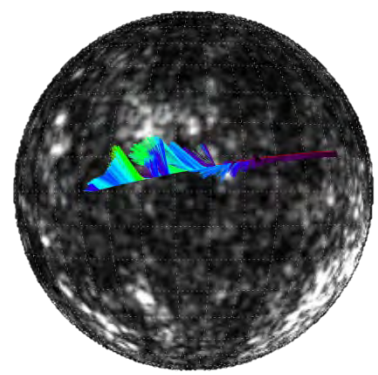


Figure 2: Solar wind magnetic field lines (color) distorted and shocked by their interaction with lunar crustal magnetic fields (grey-scale).

Only a few years ago, many researchers thought that the Moon merely provided a quiescent solid obstacle to the plasma flow, producing a downstream wake and little else. Then, in the late 2000's, high quality data from a host of new missions brought a revolution in our understanding of Moon-plasma interactions, showing that reflected and secondary particles from the Moon in fact significantly affect a region many tens of thousands of km in extent, with disturbances extending far upstream from the surface. A corresponding scientific surge awaits us at small bodies, and the DREAM2 team, with its combination of simulation experts and leading experimentalists, is poised to lead that surge. To fulfill this goal, DREAM2 proposed an investigation with the following topics, all of which we have made great progress on in the first year of performance.

Plasma Interactions Topic	Progress in Year One
Plasma Interaction vs. Body Size	Zimmerman and Fatemi et al. simulations of plasma interactions with small-scale magnetic fields, Halekas et al. observations of the smallest shocks in the solar system, Poppe et al. Phobos simulations and small-body interactions. Lipativ and Cooper have been developing hybrid models of pickup ions at the Moon.
Volatile/Plasma Connections and Exo-Ionosphere	Poppe and Sarantos anisotropic sputtering, Farrell and Hurly proton implantation studies, Halekas/Poppe/Sarantos LADEE plasma-exosphere coupling studies, Collier ROSAT X-Ray observations, Jordan & Stubbs breakdown weathering in lunar polar cold traps.
Plasma Grounding and Electrical Interaction	Jackson and Farrell human system-plasma electrical interaction modeling.
Effects of Composition, Conductivity, Magnetic Field	Poppe and Sarantos sputtering in crustal magnetic field regions, Collier & Newhart ALSEP magnetotail ion investigations, Halekas et al. mini-shock observations, Sarantos et al. exospheric modeling.
Special Regions around Small Bodies	Zimmerman et al. tree-code simulations of plasma and surface charging at small irregular bodies.
Dust Around Small Bodies	Hartzell and Zimmerman plasma and dust simulations around small bodies.

Key plasma highlights from DREAM2's Year One include the first resolved observations of shock-like structures (**Figure 2**) forming above magnetic anomalies at the Moon by DREAM2 researchers using ARTEMIS data (resolving a 40-year old debate about the existence of shocks at the Moon), arriving hand in hand with two first-of-kind simulations of these dynamic regions, both from DREAM2 researchers.

Other highlights include a model of astronaut charging as they push themselves around shadowed regions of an asteroid (Jackson et al, 2014) and the transport of lunar polar crater volatiles from crater floors to topside adjacent regions by impact vaporization and sputtering (Farrell et al., 2015).

Theme 2. Exospheres and Corona at Exposed Bodies

A rocky body expose directly to the space environment will emit atoms and molecules from its surface due to interactions with high-speed particulates, plasmas, and radiation. On larger bodies like the Moon and Mercury, these free atoms and molecules can become gravitationally bounded – never quite leaving the body's gravity pull- forming a surface bounded exosphere. However, on small bodies the gravitational forces are small thereby allowing the atoms/molecules to escape from the body, forming a corona of escaping gas about the body.

The topics studied by DREAM2's exospheres team fall into five broad categories: 1) To study the effects of body mass and size on the characteristics of its exosphere, 2) To examine drivers of dynamics as a function of distance from the sun. 3) To consider the corona as a medium to determine the underlying composition. 4) To determine water production and migration as a function of heliocentric distance. 5) To determine the nature of the exo-ionosphere vs. body size and heliocentric distance. 6) To determine the relative delivery of noble gases from the solar wind vs. the interior. 7) To determine the production and loss of hydrogen - bearing and carbon-bearing compounds.

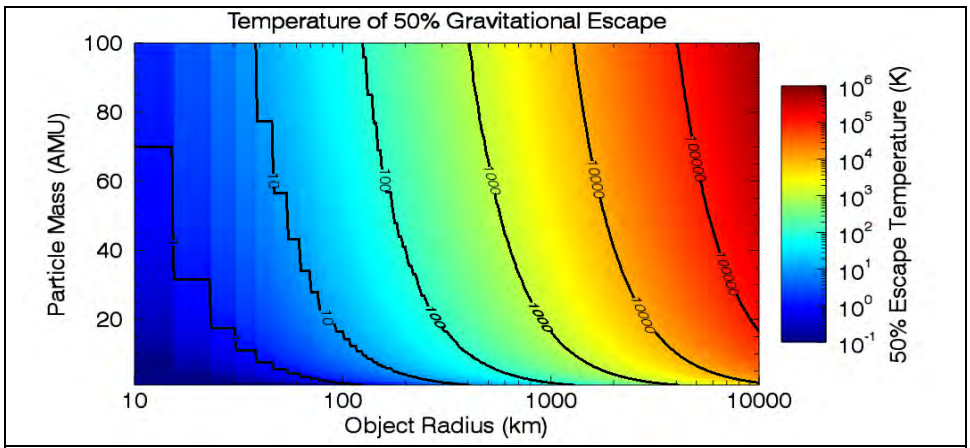


Figure 3 – Results from the generalized exosphere model showing the 50% escape energy as a function of atom mass and object size. The contours show where 50% of the gas in the Maxwellian distribution escapes into free space for a given temperature (on contour), AMU (y-axis) and body size (x-axis).

In DREAM2's first year of study significant advances in each of these topics were made. These include the following:

- Initiated a study of the universal exosphere character as a function of AMU, physical process energy, and exposed body size (from Mercury sized to 10 km). For example,

results of this 'Generalized Exosphere Model (GEM)' clearly show that ~50% of water molecules (AMU = 18) stay bounded to a Moon-sized body when released by impact vaporization (T~4000K), but completely escape for a small body (**Figure 3**). The study was presented at ASM2014 (Killen, Burger, et al. 2014)

- DREAM2 Co-Is Collier et al discovered that the lunar exosphere emits x-rays detectable by ROSAT. The x-ray emission profile at locations just nightside ot the terminator appeared to be consistent with model exosphere density profiles provided by Sarantos.
- DREAM2 and VORTICES team members examined the effect of Orion out gassing on a small body like that expected during the ARM mission. They concluded that Orion water should stick to the space weathered asteroid surface, but the amount that sticks depends on the number and nature of the defects which create more potent adsorption sites. \
- In anticipation of MAVEN's arrival, Poppe and Curry (2014) developed a model of surface sputtering from Phobos, and presented the concept that Phobos should have an exosphere/corona driven in part by the heavy O+ ions from Mars' own atmosphere. The moon-emitted atoms were shown to form a donut-like torus about Mars, similar to the Enceladus neutral torus about Saturn.
- Team members examined MESSENGER observations and found an effect in Mercury exospheric concentration in association with impacts from meteor streams (Killen and Hahn, 2014). In essence, as the stream passes the exospheric content should increase and is congruent with recent LADEE results (Colaprete et al., 2015, LPSC 2015, abstract 2364) where substantially greater exospheric content in O, OH, Ti and Fe was observed at the Moon during the Geminid shower.
- Continue ongoing work by Sarantos and Killen on improving the surface interaction of their exosphere code, including more advanced modeling of the effect of impacts and the surface-atom binding energy (i.e., activation energy). This work was presented at the DREAM F2F meeting on October 2014.
- DREAM2 co-I Hodges continues to apply his Lunar Exosphere Simulator (LExS) code to LADEE observations, especially in support of the NMS team.
- Co-I Hurley leads the Friends of Lunar Volatiles fosus group, and recently organized a special issue of Icarus devoted to lunar volatiles.

Theme 3. Radiation interactions at Exposed Surfaces

Airless bodies like the Moon, the moons of Mars, or near earth asteroids (NEAs), are exposed to an energetic particle radiation environment that can significantly affect their surfaces. This environment comprises slowly varying, yet highly energetic galactic cosmic rays (GCRs) and sporadic, lower energy solar energetic particles (SEPs). These particles are energetic enough to penetrate the regolith of airless bodies: GCRs down to ~1 m and SEPs to ~1 mm. GCRs can eject energetic protons from lunar regolith, which can then be detected and mapped. GCRs and SEPs both deep dielectrically charge the subsurface regolith. SEPs, in particular, may create electric fields strong enough to cause breakdown (i.e., sparking). Throughout the Moon's history, this breakdown may have weathered the regolith within permanently shadowed regions.

<u>Tools</u>

- **Lunar albedo proton map:** Co-I Wilson has developed techniques to map and analyze albedo protons spalled by GCRs from lunar regolith. These protons are detected by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on-board the Lunar Reconnaissance Orbiter (LRO).
- **Deep dielectric charging model:** Co-I's Jordan and Stubbs have created a time-dependent, data-driven, deep dielectric charging model to estimate the magnitudes of subsurface electric fields created by GCRs (detected by LRO/CRaTER) and SEPs (detected by LRO/CRaTER and the Electron, Proton and Alpha Monitor (EPAM) on-board the Advanced Composition Explorer, or ACE).
- **PREDICCS (Predictions of Radiation from REleASE, EMMREM, and Data Incorporating the CRaTER, COSTEP, and other SEP measurements):** Co-I Schwadron is leading the effort to continue developing this online system for now- and forecasting the GCR and SEP radiation environment at the Earth, Moon, and Mars.

Applying these tools, the radiation team have:

- *Completed:* A deep dielectric charging model to calculate the strength of electric fields created in the polar lunar regolith by the penetration of GCRs and SEPs. GCRs create a continuous electric field of ~700 V/m, and large SEP events can cause sporadic electric fields of $\geq 10^7$ V/m—large enough to cause dielectric breakdown [Jordan et al., 2014].
- *Completed:* An estimated the number of breakdown-causing SEP events experienced by the gardened regolith near the lunar poles. Regolith within PSRs may have experienced $>10^6$ events [Jordan et al., 2015].
- *Ongoing:* Currently working to predict the effects of "breakdown weathering" by estimating how sparking fragments lunar regolith grains in PSRs.
- *Ongoing:* Improving our deep dielectric charging model to better understand how the subsurface electric field varies with depth.
- *Ongoing:* Discover whether breakdown in PSRs may be observed from lunar orbit with LRO or ARTEMIS or with ground-based instruments. Post-doc Winslow is analyzing lunar surface charging detected using ARTEMIS data during large SEP events to find whether it could be affected by deep dielectric charging and/or breakdown.

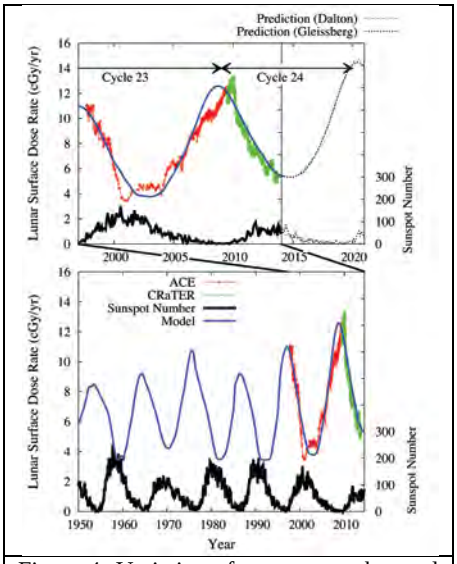


Figure 4- Variation of sunspot number and GCR dose, showing the increase of GCRs in the recent weakened solar cycle (Schwadron et al., 2014)

- *Ongoing:* Improving the statistics of our map of lunar albedo protons and have shown that the maria have a higher albedo than the highlands. We are attempting to establish whether possible albedo features correlation with geological features [Wilson et al., to be submitted to *J. Geophys. Res. Planets*].
- *Ongoing:* Schwadron et al. (2014) used results of PREDICCS to understand implications of the changing space environment for human exploration. Several key results are shown in **Figure 4**, which shows the evolution of GCR dose over time

based on modeling and data from CRaTER and ACE. The implication of the weakening heliospheric magnetic field is that the observed dose rates at successive solar minima and successive solar maxima have been increasing with time. It remains to be seen whether these changing conditions will persist. The latest trends demonstrate that the space environment at solar min is becoming increasingly hazardous and present a limiting factor for human exploration beyond LEO.

- *Ongoing:* Significant progress has been made with PREDICCS (Predictions of Radiation from REleASE, EMMREM, and Data Incorporating the CRaTER, COSTEP and other SEP measurements, http://prediccs.sr.unh.edu), which is an online system that utilizes data from various satellites in conjunction with numerical models to produce a near-real-time characterization of the radiation environment of the inner heliosphere. PREDICCS offers the community a valuable tool in forecasting events and improving risk assessment models for future space missions, providing up to date predictions for dose rate, dose equivalent rates and particle flux data at Earth, Moon and Mars. Joyce et al. [2014] presented a comparison between lunar dose rates and accumulated doses predicted by the PREDICCS system with those measured by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument aboard the Lunar Reconnaissance Orbiter (LRO) spacecraft during three major solar events in 2012.
- *Ongoing:* Co-I Zeitlin is examining energetic ion transport in lunar regolith using new 'Particle and Heavy Ion Transport System (PHITS) code to derive total (primary and secondary) dose rates and aid in understanding proton albedo.

Theme 4: Surface Response to the Space Environment

As the harsh elements of the space environment interact with the surface, the energy leaves a modifying signature on the surface structure. For example, space plasmas amorphize the regolith crystal structure in the first 100 nm, creating defects that can trap solar wind protons and and 'hopping' water or OH on the airless body. Radiation alters the surface by creating streaking defects and charge buildup which also may be sites for solar wind hydrogen trapping.

Figure 5- New high energy beam line at GSFC radiation facility

To test this, DREAM2 is building a lab experiment in GSFC's radiation facility to first irradiate a stimulant surface with high energy radiation (> 1 MeV) to create defects in the material, then perform (under the same vacuum) a second irradiation of the sample by 1 keV D_2 or protons that simulate the solar wind protons. We will determine if the additional defects from the high energy radiation affects the creation of OD or OH. A special beam line for the DREAM2 study is under construction (nearly complete) at GSFC **(Figure 5)** and the integration of the high and low energy beams is being designed. We anticipate to initiate the first tests in PY2 (Loeffler, Hudson, McClain, Keller).

Other surface interaction studies include:

- The publication of a model of solar wind hydrogen implantation in material of varying defect structure. The strength of the defects were modeled as a Gaussian distribution of activation energies, and the amount of H trapping as a function of specific distributions was quantified. It was found that solar wind implanted H's (and thus OHs) can display a diurnal effect when there are a modest amount of defects (Farrell, Hurley, Zimmerman).
- SETI institute investigators performed a set of lab studies on dust cohesion, including the testing of the fracture and stability of cohesive dust conglomerates that would be found at low gravity small body asteroids (Marshall). A theoretical model predicts the cone-shaped failure of dust masses above a trapdoor orifice is dependent on the thickness of the dust layer (**Figure 6**). Experiments confirm the model and are being used as a representation of the internal packing angle of grains in a dust mass. The experimental data are also being combined with dust 'balling' experiments in order to calculate van der Waals adhesion forces between dust grains.

- Poppe et al (2014) examined the solar wind inflow into magnetic anomalies and found that the solar wind ion speed to the surface can be slowed by an ambipolar Efield that form within the anomaly retards ion motion. As a consequence, the associated ion sputtering yields in magnetic anomalies are vastly reduced, possibly creating reduced weathering. This work connects plasma to the extended geological environment to the surface in a rich and unique way.
- In the lab, a GSFC team (McLain, Keller, Collier) are examining solar wind-like 1 keV proton interactions with lunar-like surface material, demonstrating that a surprisingly large fraction of the incoming ions convert and backscatter as energetic neutral hydrogen. They leave the surface at energy far greater than simple thermal energy –suggesting these H's do not dwell in the surface and undergo numerous collisions but instead are immediate scattered from the first nucleus they encounter.

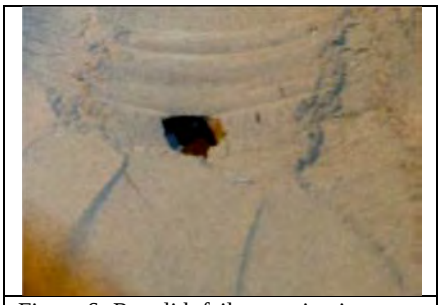


Figure 6- Regolith fails to maintain stability (creates a hole) when underlying surface has a hole. This effect does not occur if the regolith layer is thicker – due to more surrounding grains creating greater cohesion

- A model of the removal and transport of volatiles from lunar polar crater floors was developed, demonstrating that impact vaporization and sputtering are continually weathering and liberating volatiles to topside regions adjacent to the craters (Farrell, Hurley, Zimmerman).
- Tribochrging models: Human systems roving at the Moon and at asteroids will charge up via contact electrification between dusty surfaces and the human system. Jackson et al. (2014) has been developing these surface-dust charging models of wheel-regolith interactions, astronaut walking interactions and next drill-regolith interactions.

Theme 5: Integration and Extreme Events

In the upcoming last three years of DREAM2, the team plans to have a coordinated modeling effort on the effect of extreme environments at small bodies and the Moon. This effort is called the DREAM2 Extreme Environment Program (DEEP). In this program, our models

will be integrated to be run in a given sequence on a common event. This activity is similar to our 2010 SSLAM (Solar Storm- Lunar Atmosphere Model) effort under DREAM.

The three DEEP studies are 1) The effect of a solar storm at an exposed small body, 2) The space environment in Phobos' Stickney Crater, and 3) Human 'first contact' with a small body/NEA.

While these team-integration and coordinated efforts are planned for the last three years of DREAM2, we are currently developing and testing (and publishing) components of these models to be used. The components include:

- Laboratory studies at ORNL (Meyer) on the sputtering losses from heavy ions. This work will be integrated into the solar storm/small body DEEP study, since a passing CME is in fact rich in heavy ions, like He^{++}, O^{+7}, etc. Meyer's team lab study provided insight into these sputtering yields, which are many times greater than proton sputtering.
- Modeling of the Orion water gas and ion cloud in the vicinity of a small body. Both analytical and simulation work is ongoing to understand how the spacecraft-produced outgassing ater and new water ions may affect the surface of the small body. This work has been presented in past Exploration Science Forums and is a prelude to the DEEP workshop on 'first contact'.
- Continued modeling of solar wind flow in and around regional features like magnetic anomalies and craters by Zimmerman, Poppe, Fatemi and Lipativ. Such work feeds forward to the Stickney crater studies (see **Figure 7**).
- Glenar and Stubbs (2014) recently placed upper limits on electrostatically lofted dust based on the Clementine star camera light levels.
- Discussions are underway to merge CCMC magneto-hydrodynamic (MHD) models of the inner heliosphere during solar storms to local particle-in-cell codes to understand the solar storm/CME effect from its birth at the sun to its incidence at a small exposed body (Zheng, Pulkkinen)

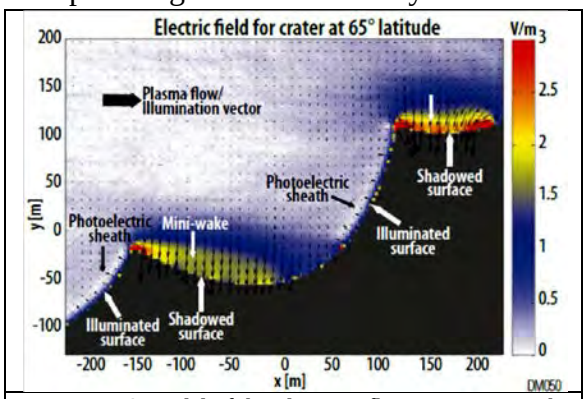


Figure 7 – A model of the plasma inflow at a crater with oblique orientation relative to the solar wind, from Zimmerman Tree Code model

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Theme 6: Mission and Exploration Applications

DREAM2's study of the space environment has direct and immediate applications to numerous SMD and HEOMD missions. The most active involvement includes:

The Lunar Atmosphere and Dust Environment Explorer (LADEE). DREAM2 Co-Is Colaprete, Delory, and Elphic all continue to be involved in the LADEE mission during its data analysis phase. Rick Elphic remains the project scientist, with Greg Delory the Deputy project

scientist, while A. Colaprete is the UVS instrument PI. Co-Is Delory and Elphic are currently overseeing the generation of revised datasets, including the generation of higher level derived data products, to the Planetary Data System. DREAM2 Co-Is Halekas, Poppe, Hurley, Stubbs, Sarantos, and Glenar continue to work with LADEE as Guest Investigators.

Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS). As LADEE Guest Investigaotrs, DREAM2 Co-Is Halekas and Poppe have sustained a productive collaboration between LADEE and ARTEMIS. Along the way they have pioneered unique methods to support the interpretation of LADEE data using coincident measurements of lunar pick-up ions and the lunar plasma environment. These measurements have had measurable impact on both LDEX and NMS data processing. Additional work by DREAM2 Co-I Delory is using two of the ARTEMIS spacecraft in a study of induced magnetic fields at the Moon. This work also involved significant graduate student involvement (H. Fuqua).

ARM Mission. As described above, DREAM2 team members have initiated a set of studies on the Orion and Astronaut interaction with a small body. These include the Orion outgassed water cloud with an exposed small body, the water ion cloud with the body, and astronaut/body charging studies. These have been presented at conferences like LPSC and ESF and were recently highlighted in the SSERVI's Director Seminar.

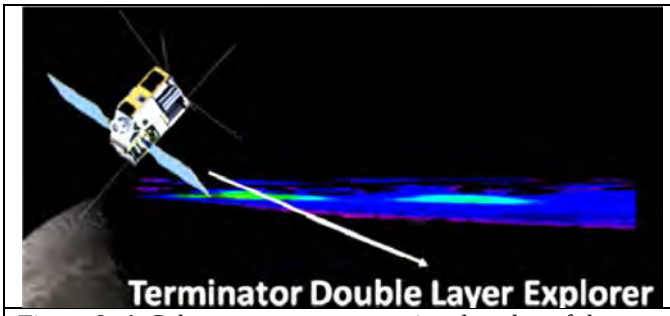


Figure 8: A Cubesat concept to examine the edge of the plasma wake, based on DREAM2 models of the plasma expansion process

Resource Prospector (RP). With FINESSE team members, DREAM2 co-is Elphic and Colaprete are instrument leaders of the HEOMD-funded RP mission to explore and prospect the lunar polar regions for volatiles. DREAM2 has contributes to this effort by provide models of volatile transport and redistribution that identify locations where RP might prospect. Models of rover wheel charging are also applicable to the RP rover system.

OSIRIS-REx. DREAM2 team Marshall is the leader of the OSIRIS Regolith Working Group (RWG) and his dust cohesion work (described above) has direct implications on regolith stability anticipated at any small asteroid, including Bennu.

LRO. DREAM2 team members continue to support LRO. DREAM2 co-is Keller and Vondrak are leads on the LRO Project Science team and there is continual DREAM2/LRO discussion on the latest finding especially on volatiles.

Additional Discovery and other mission proposals. Many DREAM2 Co-Is have had significant involvement in emerging mission proposals ranging from Discovery to cubesat-class that involve the physics of small-body/solar wind and plasma interactions. This participation has been significantly enhanced and strengthened by ongoing DREAM2 activities, which provide a deep knowledge base for the relevant science questions involved in these proposals (e.g., **Figure 8**). DREAM2 team members have submitted lunar cubesat proposal to both HSD's HTIDeS program and PSD's SIMPLEX program.

DREAM Co-I Clark continues the lead the community the Lunar Cubesat workshops which are has held annually over the last 4 years. These efforts are specifically designed to enable the

community in anticipation of planetary cubesat proposal calls, like the recent SIMPLEX solicitation.

II. Inter-team Collaborations

DREAM2 team members are in continual contact and collaboration with other SSERVI teams, science mission team, 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 like Zimmerman, Hurley, Bussey, Orlando, Hibbitts.

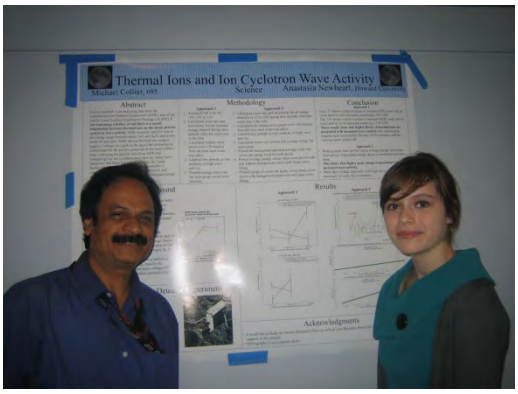
RISE4: Strong collaborating work on lunar pits, with the RISE4 field team providing lidar input to pit environment models shared by DREAM2 and VORTICES. Work with RISE4 team to pursue opportunities to architecture, design and build future exploration-oriented field instrumentation for astronaut use.

IMPACTS: 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.

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

III. E/PO Report (L. Bleacher, A Jones, P. Misra)

The keystone component of the DREAM2 E/PO program is a partnership with Howard University (HU), a Historically Black College and University located in D.C. The partnership spans higher education and formal education, and allows DREAM2 and SSERVI-related content to reach students and educators underrepresented in science. In Year 1, DREAM2 hosted two undergraduate students from the HU Physics and Astronomy Department as summer interns. In addition to their research, the students participated in monthly DREAM2 team meetings, met with other planetary scientists, and participated in tours and additional learning opportunities. They presented their completed projects through poster (**Figure 9**) and oral presentations that were open to the entire GSFC community. Both students elected to continue their research during the ensuing academic year and presented updates on their work at the DREAM2 science team meeting in October 2014.



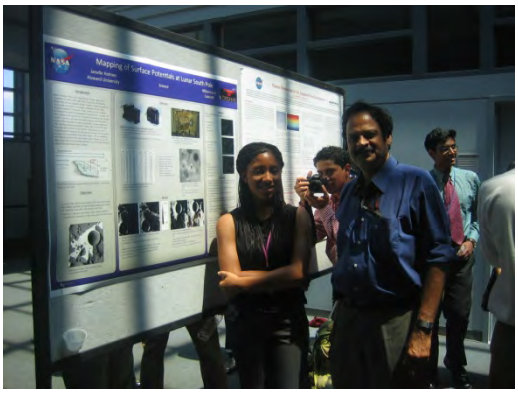


Figure 9- Students from Howard University displaying their project work as GSFC interns

The DREAM2 education team also began designing their DREAM2Explore workshop series for grade 6-9 pre- and in-service science teachers, the pilot of which will take place in Year 2. Team members visited the HU Middle School of Mathematics and Science to meet with the school's science teacher coordinator and professors in the HU Department of Curriculum and Instruction to discuss teachers' needs with respect to professional development and to begin recruiting participants. A draft of the workshop agenda was developed and is currently being refined. DREAM2 team members also led hands-on activities and shared information about DREAM2 and SSERVI at outreach events, such as the University of Maryland's annual Maryland Day event and International Observe the Moon Night.

IV. Publications

Davis, S, Marshall, J. Richard, D, Adler, D. Adler, B. (2014). Scattering properties of lunar dust analogs. Planet. Space Sci. , 90, 28-36 . **SSERVI-2014-008**

Stubbs, T. J., W. M. Farrell, J. S. Halekas, J. K. Burchill, M. R. Collier , M. I. Zimmerman , R. R. Vondrak , G. T. Delory , and R. F. Pfaff (2014), Dependence of lunar surface charging on solar wind plasma conditions and solar radiation, Planet. Space Sci., 90, 10-27, **SSERVI-2014-009**

Zimmerman, M. I., W. M. Farrell, and A. R. Poppe (2014), Grid-free plasma simulations of the complex interactions between the solar wind and small, near-Earth asteroids, Icarus, 238, 77-85. **SSERVI-2013-030**

Lipatov, A. S., J. F. Cooper, E. C. Sittler Jr., and R. E Hartle (2013), The light (H+, H2+, He+) and heavy (Na+) pickup ion dynamics in the lunar plasma environment: 3D hybrid kinetic modeling, Adv. Sp. Res. (Advances in Space Research) , 52, 1929-1938. **SSERVI-2013-031**

Poppe, A.R., J.S. Halekas, M. Sarantos, and G.T. Delory (2013), The self-sputtered contribution to the lunar exosphere, J. Geophys. Res.: Planets, 118, 1934-1944, DOI: 10.1002/jgre.20148 **SSERVI-2013-032**

Feldman, P. D., D. A. Glenar, T. J. Stubbs, K. D. Retherford, P. F. Miles, T. K. Greathouse, D. E. Kaufmann, J. W. Parker, and S. A. Stern (2014) , Upper limits for a lunar dust exosphere from far-ultraviolet spectroscopy by LRO/LAMP, Icarus, 233, 106-113. **SSERVI-2013-033**

Farrell, W. M., D. M. Hurley, R. R. Hodges, R. M. Killen, J. S. Halekas, M. I. Zimmerman, and G. T. Delory (2013), Redistribution of lunar polar water to mid-latitudes and its role in forming an OH veneer, Planet. Space Sci, 89, 15, **SSERVI-2013-029**

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Fatemi, S., M. Holmström, Y. Futaana,C. Lue, M. R. Collier, S. Barabash, and G. Stenberg (2014), Effects of protons reflected by lunar crustal magnetic fields on the global lunar plasma environment, *J. Geophys. Res. Space Physics*, *119*, doi:10.1002/2014JA019900. **SSERVI-2014-500/Student**

Schwadron, N. A., S. Smith and H. E. Spence (2013), The CRaTER Special Issue of Space Weather: Building the observational foundation to deduce biological effects of space radiation, *Space Weather*, *11*, 47, doi:10.1002/20026. **SSERVI-2014-221**

Jordan, A.P., T. J. Stubbs, C. J. Joyce, N.A. Schwadron, H. E. Spence, J. K. Wilson (2013), "The formation of molecular hydrogen from water ice in the lunar regolith by energetic charged particles", JGR: Planets, vol. 118, 1-8, DOI: 10.1002/jgre.20095. **SSERVI-2014-222/Student**

Halekas, J. S., A. R. Poppe, J. P. McFadden, V. Angelopoulos, K.-H. Glassmeier, and D. A. Brain (2014), Evidence for small-scale collisionless shocks at the Moon from ARTEMIS, Geophys. Res. Lett., 41, 7436-7443. **SSERVI-2014-225**

Schwadron, N. A., J. B. Blake, A. W. Case, C. J. Joyce, J. Kasper, J. Mazur, N. Petro, M. Quinn, J. A. Porter, C. W. Smith, S. Smith, H. E. Spence, L. W. Townsend, R. Turner, J. K. Wilson, and C. Zeitlin (2014), Does the worsening galactic cosmic radiation environment observed by CRaTER preclude future manned deep-space exploration?, Space Weather, 12, 622-632. **SSERVI-2014-239**

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Fatemi, Shahab, Charles Lue, Mats Holmstrom, Andrew R. Poppe, Martin Wieser, Stas Barabash, and Gregory T. Delory (2015), Solar wind plasma interaction with Gerasimovich lunar magnetic anomaly, J. Geophys. Res, submitted. **SSERVI-2015-026**

Lipatov, A. S., W. M. Farrell, J. F. Cooper, E. C. Sittler, and R. E. Hartle, 3-D hybrid kinetic modeling of the interaction between the solar wind and lunar-like exospheric pickup ions in the case of oblique/quasi-parallel/parallel upstream magnetic field, Adv. Space Res., submitted, **SSERVI-2015-041**

Farrell, W. M., D. M. Hurley, and M. I. Zimmerman, Spillage of lunar polar crater volatiles onto adjacent terrains: The case for dynamic processes, Geophys. Res. Lett., submitted, **SSERVI-2015-042**

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V. Conference papers, extended abstracts, posters and presentations.

Total Number:~35

Recent DREAM2 LPSC 2015 Abstract Titles:

THE FEASIBILITY OF ELECTROSTATIC DUST LEVITATION IN SMALL BODY PLASMA WAKES.
C.M. Hartzell1 and M. Zimmerman2, 1Department of Aerospace Engineering, University of Maryland (hartzell@umd.edu), 2Johns Hopkins University Applied Physics Laboratory (Michael.Zimmerman@jhuapl.edu)

LUNAR PROTON ALBEDO ANOMALIES: SOIL, SURVEYORS, AND STATISTICS
J. K. Wilson et al.

Dielectric breakdown weathering of the Moon's polar regolith, A. P. Jordan et al.

Modeling the Phobos and Deimos Neutral Gas Tori: Implications for Detection by MAVEN, A. R. Poppe, S. M. Curry, S. Fatemi, J. P. McFadden, and G. T. Delory.

LRO/CRATER DISCOVERIES OF THE LUNAR RADIATION ENVIRONMENT AND LUNAR REGOLITH ALTERATION BY RADIATION
N. A. Schwadron1, H. E. Spence1, J. K. Wilson1, A. P. Jordan1, R. Winslow1, C. Joyce1, M. D. Looper2, A. W. Case3,N. E. Petro4, M. S. Robinson5, T. J. Stubbs4, C. Zeitlin6, J. B. Blake3, J. Kasper3,7, J. E. Mazur3, S. S. Smith1, L. W.Townsend8,

ROVER WHEEL CHARGING ON THE MOON AND THE EFFECTS OF ADHERING DUST. T. L. Jackson[1] , W. M. Farrell[1] , M. I. Zimmerman[2], [1]NASA Goddard Space Flight Center (Telana.L.Jackson@nasa.gov), Greenbelt, MD 20771, [2]Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723.

VI. Students, Postdocs, New Faculty

2014 Undergrad Interns/Students
Ana Newheart, St. Marys
Janelle Holmes, Howard U
Robin Leiter, U. Virginia

Graduate Students
Heidi Fuqua, UCBerkeley
Colin Joyce, U. New Hampshire

DREAM2 Post-Docs
Shahab Fatemi, UCBerkeley
Reka Wilson, U. New Hamphire

Enabling New Faculty
Jasper Halekas has moved from a research scientist at UCB to a tenure track faculty position at Iowa. His strong activity in DREAM and DREAM2 were cited as evidence of his outstanding capabilities.

ANDY RIVKIN

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

Johns Hopkins Univ. Applied Physics Laboratory, Laurel, MD

VORTICES Report: Year 1

The VORTICES team has made significant progress in Year 1 of funding. Due to space limitations, the following includes highlights from tasks rather than an exhaustive accounting. In addition to the strictly research results discussed below, VORTICES had a team meeting at APL on 17-18 November 2014. All tasks gave presentations, 20 team members from Maine to JPL to Alaska attended in person, with 7 callers from Hawaii and elsewhere.

Looking ahead, four of five requests for Apollo rock and soil samples were successful. Fifth request will be resubmitted. We attempted to make the sample requests common (i.e., requesting the same material) when possible so that the results of different experiments could be compared for the same materials. We are working on a request for meteorite samples to do the same work. VORTICES members have also obtained several nights of observing time at various telescopes. The observations themselves will fall under next year's report.

Significant progress on the task studying the hydrogen distribution on the Moon and small bodies was made in three primary areas: 1) Studies of hydrogen and associated measurements on small bodies; 2) Studies of hydrogen and associated measurements on the Moon (See Fig 1.); and 3) Studies of future hydrogen measurements that can be made at the Moon. This work has been documented in 5 papers either accepted or submitted to peer-reviewed journals and 17 abstracts and/or presentations made at national or international scientific conferences. Siegler & Miller have been examining the possibility of lunar polar wander being recorded in the epithermal neutron data (aka H concentration), to be presented at the 2015 LPSC.

Work on modeling of volatile formation and deposition has centered on modeling the 2-D distribution of water ice in lunar polar regions. Hurley has implemented her impact gardening model to produce a statistical representation of the heterogeneity of ice deposits in lunar permanently shadowed regions. The model produces a distribution of observable quantities as a function of the age and thickness of the original ice deposit. She compared the distribution of observables to data from neutrons, radar, and FUV to look for a consistent scenario. The data are consistent with a deposit that is 400-700 Myr old that was initially about 10-20 cm thick.

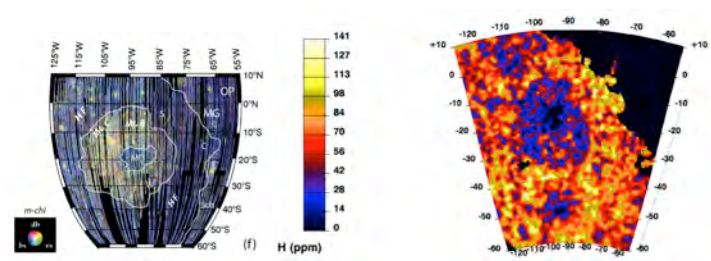


Figure 1: While Orientale basin is thought to have a relatively mature regolith by optical maturity and block abundance measures, its radar circular polarization ratio (left) and neutron spectrometer-derived hydrogen abundance (right) both indicate an immature regolith. Cahill et al. are investigating the cause of this apparent disagreement, currently thought to be due to different sampling depths of the various techniques.

Experimental analysis and modeling of volatile/regolith interactions is being conducted by Orlando and his team at Georgia Tech. They have modified and calibrated their temperature programmed desorption (TPD) experiment. New results from the group confirm that water has stronger sticking to highlands vs. mare materials. Initial runs of solar wind bombardment of regolith grains using CouPI were conducted. These simulations will be used to get a depth distribution of solar wind implanted material. Then looking at the orientation of the implanted surface, we will interpret the results in terms of what is visible to remote sensing

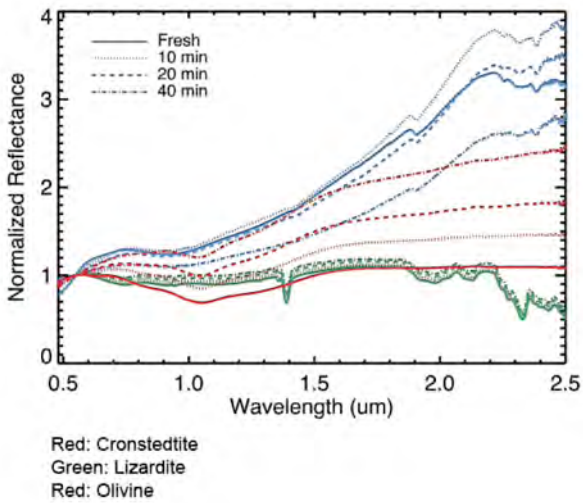


Figure 2: Space Weathering: Kaluna and Gillis-Davis (2015) Previous space weathering experiments on carbonaceous chondrites show a range of effects: darkening, brightening, reddening, blueing. Samples were laser irradiated as uncompressed powders in vacuum. Olivine and Cronstedtite became darker with exposure and water was released. Reddening and blueing observed suggesting can be expected for C-type asteroids. Darkening of surfaces may not all be due to nano-phase iron formation.

The thermal characterization of the surface and near-surface of airless bodies is being studied by Greenhagen et al., who are examining Diviner lunar eclipse data vis-a-vis model of regolith thermal physical properties structure. This will be presented at LPSC. Kaluna and Gillis-Davis (2015) have been addressing the question of space weathering on airless surfaces, particularly with respect to hydrated minerals (Figure 2). Previous space weathering experiments on carbonaceous chondrites show a range of effects: darkening, brightening, reddening, blueing. Samples were laser irradiated as uncompressed powders in vacuum. Olivine and Cronstedtite became darker with exposure and water was released. Reddening and blueing observed suggesting can be expected for C-type asteroids. Darkening of surfaces may not all be due to nano-phase iron formation

Work on regolith generation has pursued three paths: 1) The direct measurement of crack growth in meteoritic material as a consequence of thermal cycling. 2) The computation of the interacting stress states around multiple cracks within rocky bodies undergoing thermal loads, and 3) The characterization of a lunar simulant material in terms of dynamic strength and particle size distribution.

Hazeli and Hogan are conducting thermal fatigue cycling experiments on an ordinary chondrite (GRO 85209), showing that microstructure and contacts between different mineral phases localizes the thermal strain. impact experiments illustrate the same phenomena with microstructure controlling fragmentation. This ties into wory by Collaborators Delbo and Wilkerson, who recently used thermal cycling experiments to show that the time to fragment a rock due to thermal fatigue is of the order 10^3-10^4 years compared with micrometeorite time scales of 10^7 years. Team members identified the mechanisms associated with crack initiation and propagation as a result of thermal

stresses governed by coefficient thermal mismatches in the microstructure. This measurement consisted of hybrid experimental setup combining digital image correlation (DIC) with infrared thermography that enabled us to measure strain field and CTE values and also to quantify local strain as a function of the temperature increments. It is observed that the maximum principal strain evolves heterogeneously in the microstructure and it drives fatigue crack with temperature.

The group has also focused on the mechanical behavior of lunar simulant materials during dynamic uniaxial compression. This has involved: (1) developing techniques and methodologies to quantify brittle fragmentation sizes and shapes before and after testing, (2) developing a test setup to encapsulate the material in a steel cylinder (assumed rigid), and (3) performing experiments to evaluate the strength of the fragmented material using a compression Kolsky bar apparatus. Thus far, experiments have been performed on the JSC1A lunar simulant. So far, we have achieved a peak stress of 60 MPa at a corresponding strain of 0.15. Eventually, these techniques will be applied to lunar materials, where we are interested in strength and further fragmentation. These mechanical fragmentation results will be linked with on-going efforts in thermal fragmentation within this project.

The VORTICES team is continuing its work on illumination characterization for surface operations. We have been working on a Rover Traverse tool that minimizes rover's exposure to darkness and continued work on identifying safe landing sites near the north pole that have maximum amount of sunlight as well as manageable slopes in to permanently shadowed regions.

Beyond the work done in research, VORTICES has also taken part in larger community efforts. Two VORTICES team members, Dana Hurley and Matthew Siegler, are serving as guest editors for an Icarus special Issue on Lunar volatiles, with Table 1 showing its current status.

TABLE 1: Icarus Special Issue on Lunar Volatiles

Total Submissions	Accepted	In Review	No Resubmission	Rejections
20	13	3	2	2

Hurley also served as an ESF SOC Co-Chair along with Nancy Chabot, with VORTICES team members Angela Stickle and Jeff Plescia serving on the SOC. The Lunar/NEO Volatiles Focus Group is chaired by VORTICES member Dana Hurley, and Andy Rivkin is serving on the SBAG committee writing the Human Exploration Goals document. VORTICES team members Plescia and Sanders participated in a HEOMD SAT on the lunar polar landing sites

Inter-team Collaborations

- Hibbitts: Gave talk at ASU "The nomadic life of water on the Moon"
- Working on collaboration with ASU on water transport in lunar pits.
- Friends of Lunar / NEO Volatiles teleconference run by Hurley.
- Team members supported Resource Prospector Mojave desert field test,
- Ran simulations of vapor release from the Schrodinger vent in support of CLSE
- Planetary Science Institute (M. Siegler: Non-SSERVI)
- NASA Ames Research Center (L. Teodoro: Non-SSERVI)

EPO Report

In our first year, the EPO effort for VORTICES engaged a variety of audiences with lunar and small body science, as well as other research topics supported by the SSERVI. This included activities targeting formal education (K-12 and Higher Education) and informal education audiences. The largest effort this first year included the 2014 Solar System Exploration Pre-Service Teacher Institute (SSEPTI) which targeted students getting their education degrees at Minority Serving Institutions around the country. This first workshop took place at LPI in Houston, TX, so most students were from MSIs in the Texas and Southwest areas. Leveraging the success of the previous NLSI's Unknown Moon Institute (UMI) for educators, APL partnered with LPI to offer this professional development for pre-service educators while also providing mentoring opportunities for current in-service STEM teachers during the workshops. Sixteen teachers participated in this workshop, with eleven of them being pre-service teachers. A review of our evaluation survey shows that participants enjoyed the sharing and interactive aspect of being with other pre-service teachers from different universities as well as the interaction and mentoring from in-service teachers. Participants also valued the interaction with practicing scientists and sharing their teaching techniques and experiences with scientists. We feel – based on feedback from this SSEPTI workshop as well as feedback from our previous UMI workshops – the interaction between the educators and the SSERVI scientists are among the most effective and popular activities in our workshop. The workshop concluded with a Family Day, where over 60 children, parents and grandparents were invited to LPI so that the SSEPTI participants could practice what they learned during the workshop. This was a new activity that proved to be very valuable as it allowed the workshop participants an opportunity to implement what they had learned during the workshop and find areas where modifications may be needed for use in their own classrooms. In the Spring of 2015, the VORTICES EPO team will also be utilizing the Magic Planet for future student-targetted events including Take Your Child to Work Day and Girl Power at APL. Magic Planet is a spherical display that is very popular to young crowds, and especially useful in displaying global data and generating discussions on comparative planetology as they are taken through an interactive tour of the Solar System. In the fall, the VORTICES team will again partner with other SSERVI EPO teams and the Maryland Science Center to celebrate International Observe the Moon Night as part of its informal education activities. VORTICES scientists will be present at the event and VORTICES research will be displayed on posters to facilitate discussions on what SSERVI and VORTICES are and how they contribute to lunar and small body science.

Publications

1. Lawrence, David J., Patrick N. Peplowski, Jeffrey B. Plescia, Benjamin T. Greenhagen, Sylvestre Maurice, Thomas H. Prettyman, Bulk Hydrogen Abundances in the Lunar Highlands: Measurements from Orbital Neutron Data, *Icarus*, 10.1016/j.icarus.2015.01.005, 2015.
2. McCubbin, Francis M., Kathleen E. Vander Kaaden, Romain Tartèse, Rachel L. Klima, Yang Liu, James Mortimer, Jessica J. Barnes, Charles K. Shearer, Allan H. Treiman, David J. Lawrence, Stephen M. Elardo, Dana M. Hurley, Jeremy W. Boyce, Mahesh Anand, Volatiles (H, C, N, F, S, Cl) in the lunar mantle, crust, and regolith: Distribution, processes, sources, and significance, *American Mineralogist*, in press, 2015.
3. Peplowski, Patrick N., David Bazell, John O. Goldsten, David J. Lawrence, Hydrogen and major-element concentrations on 433 Eros: Evidence for an L- or LL-chondrite-like surface composition, *Meteoritics and Planetary Science*, 10.1111/maps.12434, 2015.
4. Teodoro, Luis F. A., David J. Lawrence, Vincent R. Eke, Richard C. Elphic, William C. Feldman, Sylvestre Maurice, Matthew A. Siegler, David A. Paige, Local-time Variations of Lunar Prospector Epithermal Neutron Data, *Icarus*, in review, 2015.
5. Wilson, J. T., V. R. Eke, RJ. Massey, R. C. Elphic, B. L. Jolliff, D. J. Lawrence, E. W. Llewellin, J. N. McElwaine, L. F. A. Teodoro, Evidence for explosive silicic volcanism on the Moon from the extended distribution of thorium near the Compton-Belkovich Volcanic Complex, *J. Geophys. Res. Planets*, in press, 2015.
6. Cahill, J. T. S., B. J. Thomson, G. W. Patterson, D. B. J. Bussey, C. D. Neish, N. R. Lopez, F. S. Turner, T. Aldridge, M. McAdam, H. M. Meyer, R. K. Raney, L. M. Carter, P. D. Spudis, H. Hiesinger, J. H. Pasckert. The Miniature Radio Frequency Instrument's (Mini-RF) global observations of Earth's Moon, *Icarus*, doi: 10.1016/j.icarus.2014.1007.1018.
7. Farrell, W. M., D. M. Hurley, and M. I. Zimmerman. Solar wind implantation into lunar regolith: H retention in a surface with defects, *Icarus*, in press, 2015.
8. Grava, C., J.-Y. Chaufray, K. D. Retherford, R. Gladstone, T. K. Greathouse, D. M. Hurley, R. R. Hodges, A. J. Bayless, J. C. Cook, and A. Stern. Lunar Exospheric Argon Modeling, *Icarus*, in press, 2015.
9. Hurley, D. M., M. Sarantos, C. Grava, J.-P. Williams, K. D. Retherford, M. Siegler, B. Greenhagen, and D. Paige. An analytic function of lunar surface temperature for exospheric modeling, *Icarus*, in press, 2015.
10. Hogan, J. D., C. El Mir, J. B. Plescia, KT Ramesh. Dynamic brittle fragmentation: Probing the byproducts of hypervelocity impact in space, Procedia Engineering (13th Hypervelocity Impact Symposium), 2015.
11. *Accepted*: "Discrete Element Method Simulations of Mars Exploration Rover Wheel High-Slip Mobility Tests." by Jerome B. Johnson et al., (SSERVI- 2014-172), Earth and Space 2014 Conference Proceedings.
12. *Accepted:* "Discrete Element Method Simulation of a Boulder Extraction from an Asteroid" by Anton V. Kulchitsky et al., (SSERVI-2014-169) Earth and Space 2014 Conference Proceedings.
13. *Submitted: "Laser Space Weathering of Allende Reveals Change In Visible Continuum", Gillis et al.*

14. *In Revision*: Icarus-13537. Poston et al., "Water chemisorption interactions with Apollo lunar samples 12001 and 72501 by ultrahigh vacuum temperature programmed desorption experiments"
15. *Submitted*: GRL Grieves et al., "Solar wind origin and the evolution of hydroxyl on the Moon"
16. Members of the VORTICES team provided content for several chapters in the Asteroids IV book, though lineage to SSERVI is unfortunately somewhat obscure.

Conference papers/extended abstracts/posters/presentations by VORTICES members:

1. J. T. S. Cahill, D. J. Lawrence, O. Delen, A. Stickle, and R.K. Raney, The Maturely, Immature Orientale Impact Basin, *46th Lunar and Planetary Science Conference*, Abstract #2981, 2015.
2. V. R. Eke, L. F. A. Teodoro, R. C. Elphic, W. C. Feldman and D. J. Lawrence, The polar water ice inventory – what do we know and how?, *European Lunar Science Symposium*, London, United Kingdom, 2014.
3. V. R. Eke, K. E. Bower, S. Diserens, M. Ryder, P. E. L. Yeomans, L. F. A. Teodoro, R. C. Elphic, W. C. Feldman, B. Hermalyn, C. M. Lavelle, D. J. Lawrence and S. Maurice, The Impact Of Craters On Neutron Fluxes, *46th Lunar and Planetary Science Conference*, Abstract #1905, 2015.
4. David J. Lawrence, Patrick N. Peplowski, Martin Ozimek, Christopher Scott, Lunar PLANE: Lunar Polar Low-Altitude Neutron Experiment for High-Spatial Resolution Hydrogen Measurements, *European Lunar Science Symposium*, London, United Kingdom, 2014.
5. David J. Lawrence, Patrick N. Peplowski, Jeffrey B. Plescia, Benjamin T. Greenhagen, Sylvestre Maurice, Thomas H. Prettyman, Lunar Highlands Bulk Hydrogen Concentrations, *Annual Meeting of the Lunar Exploration Analysis Group, Abstract #3038*, 2014.
6. David J. Lawrence, Richard S. Miller, Patrick N. Peplowski, Martin Ozimek, Christopher Scott, Lunar PLANE: Lunar Polar Low-Altitude Neutron Experiment for High-Spatial Resolution Hydrogen Con-centration and Depth Measurements, *Annual Meeting of the Lunar Exploration Analysis Group, Abstract #3042*, 2014.
7. David J. Lawrence, Richard C. Elphic, Richard S. Miller, Patrick N. Peplowski, Resolving the Spatial and Depth Hydrogen Distribution within Lunar Permanently Shaded Regions with the Lunar Polar Low-Altitude Neutron Experiment, *46th Lunar and Planetary Science Conference*, Abstract #2235, 2015.
8. Richard S. Miller and David J. Lawrence, New Insights Into the Depth Distribution of Hydrogen at the Lunar Poles, *NASA SSERVI Exploration Science Forum*, NASA Ames Research Center, 2014.
9. Patrick N. Peplowski, David Bazell, John O. Goldsten, Larry G. Evans, David J. Lawrence, and Larry R. Nittler, Abundances of H and Major-elements on Asteroid 433 Eros: Revisiting the In-situ Measurements of the NEAR Gamma-Ray Spectrometer, *NASA SSERVI Exploration Science Forum*, NASA Ames Research Center, 2014.

10. Patrick N. Peplowski, David J. Lawrence, Dave Bazell, Composition Of The Lunar Highlands As Revealed By Lunar Prospector Thermal Neutron Measurements, *46th Lunar and Planetary Science Conference*, Abstract #2545, 2015.
11. Patrick N. Peplowski, David Bazell, Larry G. Evans, John O. Goldsten, David J. Lawrence, Larry R. Nittler, Hydrogen And Major_Element Concentrations On Asteroid 433 Eros: Evidence For An L- Or Ll-Chondrite Like Surface Composition, *46th Lunar and Planetary Science Conference*, Abstract #2283, 2015.
12. M. A. Siegler, R. S. Miller, J. T. Keane, I. Matsuyama, D. A. Paige, M. J. Poston, D. J. Lawrence, Hidden in the Neutrons: Physical Evidence for Lunar True Polar Wander, *46th Lunar and Planetary Science Conference*, Abstract #2675, 2015.
13. Luis F.A. Teodoro, David J. Lawrence, Richard C. Elphic, Vincent R. Eke, William C. Feldman, Sylvestre Maurice, The Search for a Diurnal Effect in Lunar Hydrogen Abundance, *Annual Meeting of the Lunar Exploration Analysis Group, Abstract #3023*, 2014.
14. Luis A. Teodoro, David J. Lawrence, Richard C. Elphic, Vincent R. Eke, William C. Feldman, Sylvestre Maurice, The search for a diurnal effect in lunar hydrogen abundance, *Fall 2014 Meeting of the American Geophysical Union*, San Francisco, CA, 2014.
15. Luis F.A. Teodoro, David J. Lawrence, Richard C. Elphic, Vincent R. Eke, William C. Feldman, Sylvestre Maurice, Matthew Siegler, and David Paige, The Quest For A Diurnal Effect In Lunar Hydrogen Abundance, *46th Lunar and Planetary Science Conference*, Abstract #1786, 2015.
16. J.T. Wilson, V.R. Eke, R.J. Massey, R.C. Elphic, B.L. Jolliff, D.J. Lawrence, L.F.A. Teodoro, On the extended distribution of thorium near the lunar Compton-Belkovich volcanic complex, *European Lunar Science Symposium*, London, United Kingdom, 2014.
17. J. T. Wilson, V. R. Eke, R. J. Massey, R. C. Elphic, B. L. Jolliff, D. J. Lawrence, E. W. Llewellin, J. N. McElwaine, L. F. A. Teodoro, Evidence for explosive silicic volcanism on the Moon from the extended distribution of thorium near the Compton-Belkovich Volcanic Complex, *46th Lunar and Planetary Science Conference*, Abstract #2081, 2015.
18. Hurley, D M, Lunar Volatiles, Global Exploration Roadmap Workshop, APL, April 2014
19. Hurley, et al. Distribution of H2 in the Lunar Exosphere from LAMP Observations, DPS meeting Tuscon AZ, #306.03, November 2014.
20. Hurley et al., Simulations of Water in the Lunar Exosphere, AGU Fall Meeting, P23-3996, December 2014.
21. Farrell, W., D. Hurley, M. Zimmerman. Solar Wind Implantation into Lunar Regolith: Hydrogen Retention in a Surface with Defects, LEAG Meeting, 3021, Laurel MD, October 2014.
22. Hurley, D., M. Benna, P. Mahaffy, R. Elphic, and D. Goldstein. Water Interactions with Lunar Regolith from LADEE Observations, LEAG Meeting, 3044, Laurel MD, October 2014.
23. *Zimmerman, M., B. Bussey, D. Hurley, Can Solar Wind Volatiles Survive the Day Inside a Lunar Pit? LEAG Meeting, 3012, Laurel MD, October 2014.
24. *Kring, D. A., G. Y. Kramer, D. B. J. Bussey, and D. M. Hurley. Prominent Volcanic Soure of Volatiles in the South Polar Region of the Moon, LEAG Meeting, 3057, Laurel MD, October 2014.

25. American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 15-19, 2014. "A new mechanism for the formation of regolith on asteroids." M. Delbo, G. Libourel, J. Wilkerson, N. Murdoch, P. Michel, C. Ganino, C. Verati, S. Marchi, K.T. Ramesh.
26. The Division on Planetary Sciences Annual Meeting, Tucson, AZ, Nov. 9-14, 2014. "Thermal Fatigue on Asteroids." M. Delbo, J. Wilkerson, P. Michel, G. Libourel, N. Murdoch, S. Marchi, C. Ganino, V. Chrystele, K.T. Ramesh.
27. European Planetary Science Congress, Cascais, Portugal, Sept. 7-12, 2014. "Thermal cracking as a source of regolith on asteroids." M. Delbo, G. Libourel, J. Wilkerson, N. Murdoch, P. Michel, C. Ganino, C. Verati, S. Marchi, K.T. Ramesh.
28. Asteroids, Comets and Meteors, Helsinki, Finland, Jun. 30 – Jul. 4, 2014. "Effects of Solar Heating on Asteroids." M. Delbo, G. Libourel, J. Wilkerson, N. Murdoch, P. Michel, C. Ganino, C. Verati, S. Marchi, K.T. Ramesh.
29. Asteroids, Comets and Meteors, Helsinki, Finland, Jun. 30 – Jul. 4, 2014. "Regolith production on asteroid surfaces via thermal fatigue fragmentation. N. Murdoch, M. Delbo, G. Libourel, J. Wilkerson, P. Michel, C. Ganino, C. Verati, S. Marchi, K.T. Ramesh.
30. Jamie Kimberly, James D. Hogan, K.T. Ramesh (Jan 2015). Strength of Meteorites and Terrestrial Rock Samples Subjected to Various Loading States. AstroRecon2015, Phoenix, Az.
31. James D. Hogan, Jamie Kimberley, Kavan Hazeli, Jeff Plescia, K.T. Ramesh (March 2015). On the Role of Defects in the Dynamic Failure of an Ordinary Chondrite. LPSC 2015. Houston, Texas.
32. K. Hazeli, J. Wilkerson, C. El Mir, M. Delbo and K. T. Ramesh (March 2015). Regolith Formation On Airless Bodies. LPSC 2015. Houston, Texas.
33. James D. Hogan, Charles El Mir, Jeff Plescia, K.T. Ramesh (April 2015). Dynamic Brittle Fragmentation: Probing the Byproducts of Hypervelocity Impact in Space. Hypervelocity Impact Symposium. Boulder, Co.

- Attended The Low-Cost Lunar Settlement Workshop, Menlo Park CA, August 23, 2014
- Attended KISS workshop entitled "Mapping and Assaying the Near-Earth Object Population Affordably on a Decadal Timescale"
- Abstracts submitted to LEAG, October 2014
- Team presenting at Earth & Space Conference, Oct 2014
- Two presentations at Lunar Workshop in London
- Submitted abstracts to ACM meeting
- Early Solar System Bombardment III 4-5 February
- DPS meeting in Tucson
    - Abstracts with 11 team members/collaborators
    - 37 distinct abstracts with VORTICES members (some with several)

DANIEL BRITT

Center for Lunar and Asteroid Surface Science (CLASS)

University of Central Florida, Orlando, FL

Center for Lunar and Asteroid Surface Science (CLASS)

Annual Report for 2014

Note: CLASS was selected in 2013 and started work in 2014 so this report covers only the first year of CLASS operations rather than the 4 years requested by the SSERVI annual report template.

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, particularly since they are recorded by survey central and available broadly to remote collaborators. Typically we find that the audience for the recorded seminars is 4 to 10 times larger than the live audience. In addition to seminars the CLASS PI Dr. Britt participated in the NASA/SSERVI Asteroid Grand Challenge Virtual Seminar Series with a talk entitled "Physical properties of NEAs".

CLASS Student Exchange: this program was initiated in the summer of 2014 and provides travel funding for exchanges of students between CLASS investigators. The objective was to broaden the research and intellectual scope of CLASS-sponsored students and to foster close collaboration between CLASS investigators. CLASS supported 4 exchanges that included:

- Akbar Whizin: Exchanged with Jürgen Blum (Institut für Geophysik und extraterrestrische Physik, TU Braunschweig). Topic Microgravity experiments of colliding dust aggregates and the formation of proto-planetesimals.
- Jenna Jones: Exchanged with Mike Nolan of Arecibo Observatory (and the CLSE team). Topic: Radar observations of near-Earth Asteroids.
- Daniel Heißelmann exchanged with Josh Colwell of UCF. Topic: Microgravity and Regolith on NEAs
- Christine Comfort exchange with Marco Delbo of Observatoire de la Cote d'Azur. Topic: Thermophysical models of NEAs.

CLASS Sponsorship of Workshops: CLASS is proactive in creating dynamic intellectual environments that allow the maximum interchange of ideas and approaches across interdisciplinary lines. This sand we are provided modest funding to help sponsor several workshops that are typically led by our CLASS co-I's or collaborators. CLASS sponsored the workshop "Internal structure of carbonaceous chondrite parent bodies and their link with primitive asteroids" at the Observatoire de la Côte d'Azur, Nice. June 2-4 and is a sponsor of an upcoming workshop on the "Thermal Properties of Asteroids".

Dr. Peter Brown giving a public lecture as a CLASS Visiting Scientist

CLASS Visiting Scientists: CLASS sponsored a series of visiting Scientists at UCF to foster a deeper collaboration and exchange between CLASS team members. These included Peter Brown (Western University, shown in the adjacent picture), Dan Durda (SWRI), and Cyril Opiel (Boston College). Typically a visiting scientists gives a CLASS seminar, leads a local discussion group with graduate students, and consults

with CLASS faculty at UCF.

CLASS Directed Brainstorming: We take advantage of the AdobeConnect capabilities provided by SSERVI by assembling CLASS team members to support addressing critical exploration science questions for our NASA partners. We ran two directed brainstorming sessions for the NASA-JSC Swamp Works group to address science questions related to the proposed Asteroid Redirect mission.

CLASS Support for HEOMD Activities: CLASS is proactive in providing science support when requested for NASA HEOMD exploration needs. During 2014 CLASS supported a HEOMD program of Boulder Pull Tests with science background and physical properties parameters to make the tests as realistic as possible. We also supported a SBAG special action group that addressed HEOMD questions on the strength, cohesion, chemistry, structure, and surface properties of small asteroids. CLASS supported experiments in asteroid ISRU by JPL and plume interactions on asteroids. CLASS is also conduction a range of research programs that will support HEOMD exploration priorities. These are listed below under the individual CLASS scientists.

The CLASS PI in the Infrared. Note SSERVI and CLASS pins.

CLASS Science:

- Dr. Dan Britt (CLASS PI): Investigations included: (1) Research into the space weathering products of volatile-rich asteroids including the possibility that the precursors of life can generated on small bodies. (2) The strength of asteroidal materials. (3) Structure of small asteroids. (4) The potential of asteroidal for radiation shielding. (5) Measurement of the density and porosity of meteorites. (6) Developing recipes for terrestrial analogs for meteoritic materials.
- Dr. Humberto Campins: We have been working on identifying the main belt sources of NEOs using their spectra and albedo. Three NEOs currently targeted by spacecraft have low albedos; more specifically their geometric albedos are near 5%. Most low-albedo asteroids in the inner-belt belong to one of four families (Calrissa, Erigone, Polana and Sulamitis) or to a background population outside these families. We are conducting a near-infrared spectroscopic study of low-albedo inner-belt asteroids in order to test the proposed hypothesis that the three current sample-return spacecraft targets and the parent of the Almahata Sitta meteorite originated in this region.
- Drs. Barb Cohen and Robert Coker: Have developed a two-dimensional model that focused on specifying the temperature and duration of the liquid water phase in asteroids' interiors, where the majority of heating and fluid flow occur. Calculations using an updated version of the code solves the one-dimensional, radially symmetric, heat conduction equation for a model asteroid consisting of an initial mixture of rock and ice. We have made upgrades to several expressions, but the major new aspects of our code are the rigorous treatment of fluid flow through a porous medium in microgravity and improved treatment and estimation of porosity and permeability. We are exploring the use of the COMSOL Multiphysics modeling package. The goal is to characterize the heat budget of 20-100-km bodies and determine what types of mineral alteration are likely in such an aqueous environment.

- Dr. Josh Colwell: Has been model near-surface electrostatic dust transport on asteroids and the Moon using a fully three-dimensional numerical model to explore differences in dust transport phenomena near craters, boulders, and other topographic features. This incorporates the latest measurements on the lunar plasma environment for lunar simulations and will incorporate results on cohesion between grains and our experimental results on ejecta production for initial conditions. Our lunar results will predict variations in the local distribution of fine regolith grains (and their size distributions) on asteroids based on their topographical, plasma, and geophysical environments. Other work includes experiments on the microgravity environment effects on small particle adhesion and accretion.

CLASS Co-I Dr. Guy Consolmagno SJ explaining meteorite density measurments to another Jesuit.

- Drs. Guy Consolmagno and Bob Macke: Continued work on the density and porosity of meteorites and lunar samples. Macke developed a new method of determining bulk volume of samples using laser cad-cam scanning. This has increased the accuracy of the determination by a factor of 5.
- Dr. Dan Durda: We used numerical modeling techniques to reproduce the outcomes of a set of selected impact experiments representing a range of resulting morphological features. Numerical modeling will provide quantitative constraints on the role of material strength and regolith cohesion in low-speed secondary crater and boulder landing track formation. Our goal is to produce geologically accurate and mechanically valid simulations of secondary crater and track formation processes and to use these models, calibrated against the impact experiment outcomes, to extend our study to size scales not attainable with our flight experiments and to further our understanding of regolith material properties..
- Dr. Marco Delbo: Continues his collaboration in 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 of the European Space Agency (ESA) will survey the entire sky with a limiting magnitude of about 20 in the V-band. Gaia will observe about 400,000 asteroids and produce high precision astrometry and photometry. Delbo is in charge of Gaia spectrophotometric observations of asteroids in the wavelength range between 0.35 and 0.95 microns. He has also made significant contributions to thermal modeling and analysis of NEAs.
- Dr. Yan Fernandez: Worked on radar observations of NEAs including the characterization of their highly complex shapes in order to apply thermal modeling techniques. He is mentoring grad student Jenna Jones who had a very successful summer research experience at Arecibo funded by the CLASS student exchange program.
- Dr.Tom Kehoe: To better understand the evolution of the regolith on the surface of these bodies, we used dynamical simulations to model the orbital evolution of regolith particles liberated from their surfaces by impacts. This involves tracking the trajectories of the particles following an impact to determine which particles do not attain escape velocity, causing them to be re-deposited elsewhere on the body's surface, and which particles escape

the body and join the interplanetary flux. We considered bombardment of small bodies by particles at low impact speeds (on the order of the escape velocity of the asteroid or moon, typically on the order of m/s) in addition to the high-speed impacts from the flux of interplanetary meteoroids (on the order of km/s).

- Dr. Phil Metzger: Investigated how rocket exhaust plume effects and soil compaction. We have been working on extending the analytical Soil Mixing Model of Gault, et al. to include compaction beneath the mixing layer via impact shock propagation. Metzger is also working with Britt to develop asteroid simulants. This has included characterizing asteroid physical properties and matching them with appropriate terrestrial materials on geotechnical properties, particle size and shape distributions, and flowability characteristics.
- Dr. Cyril Opeil: Leads research into the Thermal Conductivity, Stress-Strain, and Specific Heat Capacity of meteorites at realistic thermal conditions for asteroids. CLASS has funded an upgrade to his Quantum Design system to enable measurements of specific heat over the same temperature range of 2-400 K. He has measured 5 meteorites over the past year while installing the upgrade.
- Dr. Cass Runyon: Leads the CLASS EPO program. Her report is included in Section III.
- Dr. Dan Scheeres: We have been working on the following aspects of microgravity environment around small bodies. (1) YORP spin-up using a realistic range of small body sizes for possible exploration targets; (2) the effects of planetary flybys including close approaches and more distant complex approaches such as gravitationally interacting with both the Earth and the Moon on a single pass; (3) the effects of impacts using a range of impact velocities, sizes, and material strengths; (4) the effects direct human or robotic exploration activity using a range of realistic exploration scenarios. This investigation includes Phobos and Deimos, with their unique gravitational environment of being a microgravity environment being within the gravity well of the larger Mars system.
- Dr. Larry Taylor: Investigated the development of the real Np-Fe texture through precipitation of metallic Fe from a vapor phase consisting of supersaturated Fe in a silica-rich gas formed by flash melting of appropriate compositions. This is conducted in a lab at Oak Ridge National Laboratory. We performed additional studies on the particle size fraction of the soils <1 μm, in particular the shape parameters and the arrays of np-Fe on rims and in the agglutinitic glass.
- Dr. Faith Vilas: We have been observing surface reflectance attributes of both near-Earth and main belt asteroids and small planetary satellites selected to address the presence of aqueous alteration and levels of space weathering that are apparent on different sizes and types of asteroids. Target selection is directed by the current state of the knowledge about the surface reflectance attributes of these objects at the start of CLASS. Larger diameter telescopes (e.g., the MMT 6.5-m telescope) are targeted to observe small-diameter (therefore usually low magnitude) objects.
- Dr. Melissa Strait: Leads research into the form and morphology of porosity in meteorites. This work pins down the nature of how porosity is retained in meteorites and thus asteroids.

II. Inter-team Collaborations

With the Institute for the Science of Exploration Targets: Mini-Moon Exploration. Observational and theoretical work indicate that small asteroids are often temporarily captured in the Earth-Moon gravitational system. These objects, also known as mini-moons, are typically on the order of a few meters in diameter, are captured for periods of several months to a year, and represent a sampling of the small asteroidal material in near Earth space. As such mini-moons, represent a uniquely accessible resource for robotic missions, ISRU, and human exploration. CLASS and Institute for the Science of Exploration Targets are working together to explore the possibilities of min-moon exploration including work on their number, frequency, dynamics, surface properties, micro-gravity environment, rubble-pile structure, and exploration risks.

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT): Regolith Processes on Volatile-Rich Small Bodies. CLASS PI, Prof. D. Britt visited IMPACT in the summer of 2014, and in February 2015 for a LASP seminar, and to discuss and plan 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. CLASS worked with IMPACT on a White Paper on observations of comet dust impacts on Phobos during the recent Siding Spring encounter with Mars.

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 the reduce 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 has collaborated from the beginning of CLASS selection in their EPO activities, 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. In addition SEEED and CLASS are collaborating on formal education courses with a joint graduate seminar scheduled for the Fall of 2015 on the Exploration of Phobos and Deimos.

III. EPO Report

Throughout the first year of the SSERVI grant, the SEEED and CLASS SSERVI Education Public Engagement (EPE) team was very busy training pre-service and in-service educators from both formal and informal institutions, working with students and engaging the public on SSERVI-related topics such as how our teams are exploring and working to understand the formation and evolution of the Moon and small bodies in our solar system.

To facilitate inspiring and engaging both students and the public, we have pulled together a dynamic team of science educators, authors, artists and storytellers from around the country – all

of whom are committed to working on the project through its entirety. Our EPE team is focusing on three areas: 1) infusing arts into traditional science, technology, engineering and mathematics (STEM) lessons; 2) integrating formal, informal and out-of-school experiences to foster content retention; and 3) broaden audience reach to include ALL learners, especially those with disabilities. We continue to work closely with the core group of educators trained during our first workshop as we identify gaps and redundancy in curricula and activities related to SSERVI science and technology.

We are currently working with two students and one part-time staff member who are blind. They are helping to review existing SSERVI – related curricula and activities vetted by our EPE Core Team that may become part of the final educator guide. As we progress, we are building a list of modifications and / or adaptations needed to ensure that we address Universal or Inclusive Design.

Educator Professional Development Events that included SSERVI STEM content

Event / Activity	Date	Location	# Educators	Grades	Underserved*
Space Science for Teachers Course	06.05-07.03.2014	Charleston, SC + online	10	6 - 14	Yes
SSERVI Workshop – Core TEAM	09.05-07.2014	Columbia, SC	20	4 -16 / informal	Yes
National Federation of the Blind Workshop for Educators of the Blind	10.14-17.2014	Baltimore, MD	40	4 – 16	Yes
Geology of the Moon - Online course for in-service teachers	Fall 2014	18 states + military	20	4 - 16	Yes

*Underserved participants include Deaf/Hearing Impaired, Blind / Visually impaired and underserved populations

Student- and Public - Centered Events

Event / Activity	Date	Location	# Participants	Grades / Public	Underserved*
Charleston STEM Festival	02.08 2014	Charleston, SC	1500	Public	Yes
Cougars Basketball STEM Day	02.18.14	Charleston, SC	1600	4 – 8	Yes
Grand Opening – SC State Museum	08.13-14.2014	Columbia, SC	5000+	Public	Yes
InOMN	09.06.2014	Columbia, SC	6000	Public	Yes
Riverdogs	04.09.14	Charleston, SC	5000	K-12	Yes

*Underserved participants include Deaf/Hearing Impaired, Blind / Visually impaired and underserved populations

Upcoming EPE activities

- Quarterly telecon with the Core EPE Team; planning for upcoming Summer 2015 workshop
- Poster presentation at LPSC, Houston, TX

IV. Publications (partial list and only for 2014)

Murchie S., Britt D., and Pieters C. (2014) The Case for Phobos Sample Return. In Phobos J. Oberst Ed., Planetary and Space Science 102, 176-182.

Britt D.T., Consolmagno G.J., and Lebofsky L.A. (2014) Asteroids. In: *The Encyclopedia of the Solar System*. T. Spohn Ed., Academic Press

Kohout T., Havrila K., Toth J., Husárik M., Gritsevich M., Britt D.,l and 18 others (2014) Density, porosity and magnetic susceptibility of the Košice shower and homogeneity of its parent body. Planetary and Space Science, 93-94, 96-100.

Pieters C. M., Murchie S., Thomas N., and Britt D. (2014) Composition of Surface Materials on the Moons of Mars. In Phobos J. Oberst Ed., Planetary and Space Science 102, 144-151.

Kohout T., Cuda J, Filip J, Britt D.,l and 8 others (2014) Space weathering simulations through controlled growth of iron nanoparticles on olivine. Icarus 237, 75-83.

E. A. Kramer et al., 2014. A dynamical analysis of the dust tail of Comet C/1995 O1 (Hale-Bopp) at high heliocentric distances. Icarus 236, 136-145.

J. P. Emery et al., 2014. Thermal infrared observations and thermophysical characterization of OSIRIS-REx target asteroid (101955) Bennu. Icarus 234, 17-35.

Lauretta, D.~S., and 28 colleagues 2014. The OSIRIS-REx target asteroid (101955) Bennu: Constraints on its physical, geological, and dynamical nature from astronomical observations. Meteoritics and Planetary Science 113.

Delbo, M., Libourel, G., Wilkerson, J., Murdoch, N., Michel, P., Ramesh, K.~T., Ganino, C., Verati, C., Marchi, S. 2014. Thermal fatigue as the origin of regolith on small asteroids.\ Nature 508, 233-236.

Cellino, A., Bagnulo, S., Tanga, P., Novakovi, B., Delbo, M. 2014. A successful search for hidden Barbarians in the Watsonia asteroid family.\ Monthly Notices of the Royal Astronomical Society 439, L75-L79.

Thomas, C.~A., Emery, J.~P., Trilling, D.~E., Delbo, M., Hora, J.~L., Mueller, M.\ 2014.\ Physical characterization of Warm Spitzer-observed near-Earth objects.\ Icarus 228, 217-246.

Mommert, M., and 10 colleagues 2014.\ The Discovery of Cometary Activity in Near-Earth Asteroid (3552) Don Quixote.\ The Astrophysical Journal 781, 25.

Bridgestock, L. J.; Williams, H.; Rehkämper, M.; Larner, F.; Giscard, M. D.; Hammond, S.; Coles, B.; Andreasen, R.; Wood, B. J.; Theis, K. J.; Smith, C. L.; Benedix, G. K.; Schönbächler, M.Unlocking the zinc isotope systematics of iron meteorites. Earth and Planetary Science Letters, Volume 400, p. 153-164

Moreno, F., Licandro, J., {\'A}lvarez-Iglesias, C., Cabrera-Lavers, A., Pozuelos, F.\ 2014.\ Intermittent Dust Mass Loss from Activated Asteroid P/2013 P5 (PANSTARRS).\ The Astrophysical Journal 781, 118.

Alexander, C.M.O'D., G.D. Cody, Y. Kebukawa, R. Bowden, M.L. Fogel, A.L.D. Kilcoyne, L.R. Nittler, and C.D.K. Herd (2014). Elemental, Isotopic and Structural Changes in Tagish Lake Insoluble Organic Matter Produced by Parent Body Processes. Meteoritics and Planetary Science, v. 49, 503-525.

Blinova, A., C.D.K. Herd, and M.J.M. Duke (2014). Testing Variations within the Tagish Lake Meteorite – II: Whole-Rock Chemistry of Pristine Samples. Meteoritics and Planetary Science, v. 49, 1100-1118.

Blinova, A., T.J. Zega, C.D.K. Herd, and R.M. Stroud (2014). Testing Variations within the Tagish Lake Meteorite – I: Mineralogy and Petrology of Pristine Samples. Meteoritics and Planetary Science, v. 49, 473-502.

Hilts, R.W., C.D.K. Herd, D.N. Simkus, and G.F. Slater (2014). Soluble Organic Compounds in the Tagish Lake Meteorite. Meteoritics and Planetary Science, v. 49, 526-549.

Metzger, Philip T., "Plume Interactions with Asteroid Regolith during Proximity Operations," NASA report to Asteroid Return Mission (ARM) Alternative Study (October 2014).

Metzger, Philip T., "Estimation of Regolith Backscatter during OSIRIS-REx Sample Capture," NASA report to OSIRIS-REx Project (2014).

Lane, John E., Takis Kasparis, Philip T. Metzger, and W. Linwood Jones, "In Situ Disdrometer Calibration Using Multiple DSD Moments," Acta Geophysica 62 (6), 1450-1477 (2014).

M.D. Campbell-Brown and P. Brown (2014) A 13-year radar study of the η-Aquariid meteor shower, MNRAS, 446, 3669-3675

J.S. Bruzzone, P. Brown, R.J. Weryk, D.K. Wong and M.D. Campbell-Brown (2014) A decadal survey of the Daytime Arietid meteor shower using the Canadian Meteor Orbit Radar, MNRAS, 446, 1625-1640.

Silber, E. A., Brown, P.G., (2014) Optical observations of meteors generating infrasound—II: Weak shock Model Theory and Validation, accepted JGR, Jan 7, 2014

Silber, E. A., Brown, P.G., (2014) Optical observations of meteors generating infrasound—I: Acoustic signal identification and phenomenology. J. Atmos. Solar-Terrestrial Phys. 119, 116–128.

Jenniskens, P., Rubin, A.E., Yin, Q.-Z., Sears, D.W.G., Sandford, S. a., Zolensky, M.E., Krot, A.N., Blair, L., Kane, D., Utas, J., Verish, R., Friedrich, J.M., Wimpenny, J., Eppich, G.R., Ziegler, K., Verosub, K.L., Rowland, D.J., Albers, J., Gural, P.S., Grigsby, B., Fries, M.D., Matson, R., Johnston, M., Silber, E., Brown, P., Yamakawa, A., Sanborn, M.E., Laubenstein, M., Welten, K.C., Nishiizumi, K., Meier, M.M.M., Busemann, H., Clay, P., Caffee, M.W., Schmitt-Kopplin, P., Hertkorn, N., Glavin, D.P., Callahan, M.P., Dworkin, J.P., Wu, Q., Zare, R.N., Grady, M., Verchovsky, S., Emel'Yanenko, V., Naroenkov, S., Clark, D.L., Girten, B., Worden, P.S., (2014) Fall, recovery, and characterization of the Novato L6 chondrite breccia. Meteorit. Planet. Sci. 49, 1388–1425. (**This paper was also the feature cover for this MAPS issue**)

Stober, G., Matthias, V., Brown, P., Chau, J.L., (2014) Neutral density variation from specular meteor echo observations spanning one solar cycle. Geophys. Res. Lett. 41, 6919–6925.

Pokorný, P., Vokrouhlický, D., Nesvorný, D., Campbell-Brown, M.D., Brown, P., (2014) Dynamical Model for the Toroidal Sporadic Meteors. Astrophys. J. 789, 25.

Bolin, B., Jedicke, R., Granvik, M., Brown, P., Howell, E., Nolan, M.C., Jenniskens, P., Chyba, M., Patterson, G., Wainscoat, R., (2014) Detecting Earth's Temporarily-Captured Natural Satellites - Minimoons. Icarus 241, 280–297.

Ye Q., Wiegert, P.A., Brown P. G., Campbell-Brown M. D., and Weryk R. J. (2014) The unexpected 2012 Draconid Meteor Storm. Monthly Notices of the Royal Astronomical Society, 437, 3812-3823

V. Conference papers, extended abstracts, posters and presentations

Total number of CLASS Team Conference Papers, extended abstracts, poster presentations and oral presentations for 2014 is 267. More details will be available on the CLASS website.

VI. List of undergrad students, grad students, postdocs, and new faculty added to CLASS

- Adrienne Dove: New tenure-track Faculty added by CLASS
- Philip Metzer: New Research Faculty
- Gal Sarid: New Research Faculty
- Julie Brisset: Postdoc
- Daniel Johnson: Undergrad
- Ackbar Whizin: Graduate Student
- Jenna Jones: Graduate Student
- George Hatcher: Graduate Student
- Leos Pohl : Graduate Student
- Nate Lust: Postdoc
- Tracy Becker: Graduate Student
- Zoe Landsman: Graduate Student
- Christine Comfort (Undergrad)

WILLIAM BOTTKE

Institute for the Science of Exploration Targets: Origin, Evolution and Discovery (ISET)

Southwest Research Institute, Boulder, CO

SSERVI Year 1 Progress Report
Institute for the Science of Exploration Targets (ISET)
P.I. Bill Bottke

1) Research activities

Kevin Walsh has performed a large number of Terrestrial Planet Formation simulations using our new Lagrangian Integrator for Planetary Accretion and Dynamics (LIPAD) code. LIPAD is unique in its ability to accurately follow the coupled collisional, accretional, and dynamical evolution of a population consisting of objects ranging from sizes as small as a few centimeters to fully formed planets. LIPAD has allowed Kevin to model growth from planetesimals to planets. This work is uncovering major issues in many of the assumptions built into previous classical models of planet formation. While the modes of growth are similar, they are happening at vastly different times in different places in the proto-planetary disk.

Along similar lines, Katherine Kretke and Hal Levison have developed a new model of planetesimal and planet formation called "slow pebble accretion with viscous stirring" that has been implemented into LIPAD. Using their new model, they can explain the formation of the terrestrial planets and gas giants, for the first time, within a single integrated scenario. This model envisions that the cores of the giant planets formed from 100 to 1000 km bodies that directly accreted a population of pebbles (really boulders) – centimeter- to meter-sized objects – that slowly grew in the protoplanetary disk. They have applied this model to the terrestrial planet region and found that it can reproduce the basic structure of the inner Solar System, including a small Mars and a low-mass asteroid belt. Their models show that for an initial population of planetesimals with sizes similar to those of the main belt asteroids, slow pebble accretion becomes inefficient beyond ~1.5 AU. As a result, Mars's growth is stunted and nothing large in the asteroid belt can accumulate. This work was submitted as two papers for Nature.

Bill Bottke has been working on earliest bombardment of the Moon (and inner Solar System worlds). It is known that the inner Solar System's biggest and most recent known collision was the Moon-forming giant impact between a large protoplanet and the proto-Earth. Not only did this event create a disk near Earth that formed the Moon, but it also ejected several percent of an Earth mass out of the Earth-Moon system. Bottke et al. argued that numerous kilometer-sized ejecta fragments from that event struck main belt asteroids at velocities exceeding 10 km/s, enough to heat and degas target rock. Such impacts produce ~1,000 times more highly heated material by volume than typical main belt collisions at ~5 km/s. By modeling their temporal evolution, and fitting the results to ancient impact heating signatures in stony meteorites, we infer the Moon formed ~4.47 billion years ago, in agreement with previous estimates. This work is in press for Science. In closely related work, we find that giant impact ejecta may produce most of the Pre-Nectarian basins and craters on the Moon. We can also now show that our "E-belt" model of the late heavy bombardment that started 4.1-4.2 Ga can reproduce constrains from Earth, Moon, Mars, and the asteroid belt, a major and novel

accomplishment. Bottke has also been heavily involved in a project to derive the current orbit and size distribution of the NEO population. Bottke has also submitted 4 different chapter for the Asteroids IV book and has served as an editor.

Simone Marchi has been working on several projects over the last year. First, Marchi used lunar and meteoritic data, as well as recent dynamical models, to constrain the early collisional history of the Earth, focusing on the first ~1 Gyr of its evolution (this work is a collaboration with the SSERVI teams lead by Dr. Dave Kring and Prof. Carle Pieters). This work was published in Nature. Here we fostered new collaborations on a number of interesting follow-up projects, such as the outgassing of large melt pools (with Dr. Black, Harvard University) and the effects of giant impacts on mantle dynamics (with Dr. O'Neill, Macquarie University).

Second, Marchi was involved in the first papers dedicated to the analysis of the morphology of 67P/Churyumov-Gerasimenko from Rosetta data, recently published in Science. Moreover, Marchi provided support for several follow-up manuscripts that have been submitted to an Astronomy and Astrophysics special issue. Marchi is also leading a manuscript in preparation about the origin of 67P C-G. Finally, he was involved in a numbers of abstracts submitted to AGU 2014 and LPSC 2015, and gave several presentations at Rosetta team meetings.

Third, Marchi continued his analysis of the cratering on Vesta and Ceres as a member of the Dawn science team. In particular, Marchi refined some of the work done over the last few years, and included these new data in a review chapter "Cratering on Asteroids" for "Asteroids IV". Marchi regularly participated to Dawn team meetings and presented new work.

Clark Chapman worked in close collaboration with Simone Marchi on a chapter for the "Asteroids IV" book on cratering of asteroids. He has also worked with several other researchers, including Drs. Paul Schenk, Stuart Robbins, Zhiyong Xiao, and Michelle Kirchoff on various cratering issues such as saturation. And he has refereed papers for several journals dealing with topics like the crater populations on Toutatis. He spent a couple of days trying to locate a long-missing lunar crater catalog by searching recently found archives at the University of Arizona; he found many relevant items, but neither the card decks, print-out, or transferred-to-tape versions of the catalog. Recently, Dr. Chapman has started writing a paper for peer-review publication based on the talk he gave at the "Asteroids Comets Meteors" meeting in Helsinki in July concerning methodology of studying size-frequency distributions of craters, including mistakes in a widely used "black box" program called CraterStats, which calculates error bars for cumulative distributions incorrectly.

Michelle Kirchoff has been counting very small craters (D < 1 km) superposed on the floors on some of the youngest lunar craters with diameters greater than 50 km from LROC NAC images. This work has been supported by Marchi and Chapman. They intend to use these counts along with the Model Production Function (Marchi et al., 2009) to compute the formation ages of these craters. Once the ages are determined, they will infer how the rate for larger impacts varied during the most recent epoch on the Moon. In a closely related project, several ISET members led by Bottke are working with Prof. Becky Ghent (U. Toronto) on using Diviner data from LRO on using rock abundance as a proxy for crater ages – this work may allow us to date all young lunar craters > 10 km that formed over the last 1 Gyr. This project was discussed at the 3rd Bombardment workshop.

Julien Salmon has been collaborating with Robin Canup on the study of the accretion of the Moon from disks produced by non-canonical impacts, an alternative type of impacts that leave the Earth-Moon system with an excess of angular momentum. They found that forming a lunar-mass object requires a very massive disk of 3 lunar masses or more, which may only be achieved by some of these non-canonical impacts. To test and calibrate their model against additional constraints, they have been studying the accretion of Phobos, Deimos from an impact-generated rocky debris disk around Mars, and Mimas, Enceladus and Tethys from a massive ice-rich primordial ring around Saturn. This work was presented at the DPS.

Robin Canup has been involved in 2 main projects. First, Canup and Bill Ward are investigating the ability of the evection resonance to remove large amounts of angular momentum from the Earth-Moon system soon after the Moon formed. Such a process is needed in new Moon-forming impact scenarios, which can directly produce a planet and disk with equal silicate compositions (in agreement with the Earth and Moon) but leave a very rapidly spinning Earth. A paper is in preparation.

Second, Canup, with Channon Visscher (Dordt College), Julien Salmon and Bruce Fegley (Wash. U.), have been studying the volatile depletion of the Moon. The Moon is depleted in volatile elements relative to the silicate Earth. It has been suggested that volatiles were evaporatively lost prior to the Moon's accumulation. However, thermal escape may have been minimal for expected conditions. They explore whether depletion could have instead resulted by volatiles being preferentially accreted by the Earth rather than by the Moon. Models suggest that approximately tens to 60% of the Moon's mass is derived from melt clumps that form near the Roche limit as inner disk material spreads outward. The disk begins in a silicate two-phase (vapor-melt) state with high temperatures. Once the silicate vapor has entirely condensed, the disk cools and increasingly volatile elements can be incorporated into the melt. They combined results of lunar accretion simulations with estimates of the disk's thermal state and predictions from a chemical equilibrium code. They find that potassium, sodium, and zinc condense late in the disk's evolution after the Moon has essentially completed its accretion. This implies that the portion of the Moon derived from the inner disk would be substantially depleted in these elements even in the absence of escape processes. A paper is in preparation.

The CU team led by Dan Scheeres has focused on the mechanics of asteroids held together by weakly cohesive bonds that may exist in the regolith that mantles and exists throughout these bodies. This work has included the stress and failure analysis of observed active asteroids which have had catastrophic break-ups, the analysis of the fast-spinning asteroid 1950 DA which provided unique insight into the manner in which these asteroids fail, and has entailed working through detailed predictions of how a cohesionless asteroid may evolve geophysically to provide a counter-point to the cohesive theories. In addition to this, the implications of cohesive strength for the end-of-life scenarios of rubble pile bodies are also being studied. This work has involved support from post-docs Paul Sanchez and Toshi Hirabayashi, and support from graduate student Travis Gabriel.

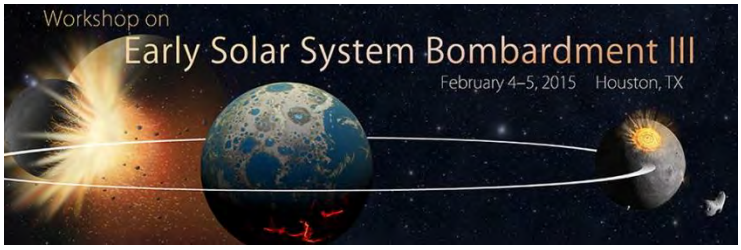
2) Inter-team collaborations

Marchi and Bottke have been interacting with David Kring's team (*Center for Lunar Science and Exploration)* and Carle Pieters' team (SSERVI Evolution and Environment of Exploration Destinations) on several topics related to the bombardment history of the Moon and the Solar System.

- Marchi et al. (2014; Nature) discussed the bombardment of hadean Earth with Lindy-Elkins Tanton of SEEED and Dave Kring of CLSE.
- Marchi et al. (2014; PSS) discusses the main belt asteroid crater records with Dave Kring (CLSE).
- Bottke et al. (2015; Science) discussed ejecta from the Moon-forming impact hitting main belt asteroids and making ancient impact ages in meteorites with Tim Swindle from CLSE.

Bottke was also involved with several additional projects with other SSERVI teams:

- Hopkins et al. (2015; Icarus) discussed "Micrometer-scale U-Pb age domains in eucrite zircons, impact re-setting, and the thermal history of the HED parent body" with O. Abromov from CLSE.
- Rivkin et al. (2015; Icarus) discussed the missing asteroid family for Ceres with A. Rivkin of VORTICES.
- Reddy et al. (2014; Icarus) discussed how the "Chelyabinsk meteorite explains unusual spectral properties of Baptistina Asteroid Family" with V. Reddy of CLASS
- Elkins-Tanton et al. (2014; LPSC) wrote an abstract on "Journey to a Metal World: Concept for a Discovery Mission to Psyche" with L. Elkins-Tanton and Rick Binzel (SEEED)
- Bottke is an editor for the Asteroids IV book with supervising editor of the Space Science Series R. Binzel (SEEED).



CLSE (Kring) and ISET (Canup) served as co-conveners for the 3rd Workshop on Early Solar System Bombardment, held in February 2015 at LPI. Bottke, Marchi, and Minton from ISET participated. Many members of SEEED also attended and participated.

The U. Colorado team led by Co-I D. Scheeres has collaborations on-going with the CLASS team from UCF, specifically Scheeres presented remotely at a SSERVI meeting at the end of January and will present at an upcoming seminar. Collaboration also continues with the CU team led by Horanyi.

3) EPO activities

Summer Science Program. Levison/Dones/Nesvorny/Kretke/Krichoff served as science lecturers for the Summer Science Program in New Mexico and California in July 2014. This program offers SSERVI-rich participatory science experiences to ~250 high-performing high-school students in a continuing partnership with Summer Science Program, Inc. (SSPI). They are bringing their program to Boulder for July 2015.

Engaging the Public Through the Moons MOOC.
The ISET education team at the Lunar and Planetary Institute (LPI) has been working in partnership with the Open University to support their second run of the "Moons" MOOC, which began on February 2, 2015. LPI Education Specialist Dalton completed a facilitator's course with the Open University team, and she will interact with students through discussion forums to support their learning. The free course draws from students, educators, and the interested public and has over 9000 registered participants. An invitation to participate in the course was disseminated to the Afterschool Alliance, the SSERVI Center for Lunar Science and Exploration high school research program participants, and the broader SMD education community.

Helping Librarians Bring Science to Their Patrons.
Training. Thirty-five public librarians from across the U.S. will attend a one-day professional training session on the Explore! Marvel Moon module at the LPI on February 25, 2015. Staff scientist Kirchoff will provide content expertise and Suzanne Foxworth (Astromaterials Research and Exploration Science at the NASA Johnson Space Center) will certify participants to use the lunar and meteorite sample disks. Participants will tour the LPI library, view of the Moon through telescopes with the Johnson Space Center Astronomical Society, and receive related materials for serving preschool-aged children and learn about the Night Sky Network through the Astronomical Society of the Pacific.

Activities. Open content produced from the initial run of the Moons MOOC will be incorporated into revisions of the Explore! Marvel Moon module, created with the ISET team through the previous NLSI grant. Training participants will provide feedback on possible meteor/meteorite/asteroid activities to adapt for use in libraries, that can broaden the content of the module.

Sharing Results.
LPI Education Specialist Shaner is working with a participant in the 2014 NLSI-CLOE/Earth to Sky Interagency Partnership joint webinar to contribute an article about the International Observe the Moon Night — including the participant's use of CLOE resources — for Legacy magazine.

Walsh participated in "Beyond Boulder", a Colorado University event to discuss career with Physics Undergrads (Feb 2). Kirchoff filmed a lecture and participated in a Q&A session for The Open University's Massive Open Online Course on Moons of the Solar System (Spring & Fall 2014). She also was a science advisor for the Academy High School LPI ExMASS team (Fall 2014-Spring 2015).

4) Publications

Bottke, W. F., Vokrouhlický, D., Marchi, S., Swindle, T., Scott, E. R. D., Weirich, J. R. , Levison, H. F. *Dating the Moon-Forming Impact Event with Asteroidal Meteorites*. Science, in press.***

Bottke, W. F., Vokrouhlický, D., Walsh, K. J., Delbo, M., Michel, P., Lauretta, D. S., Campins, H., Connolly, H. C., Scheeres, D. J., Chelsey, S. R. (2015). *In search of the source of asteroid (101955) Bennu: Applications of the stochastic YORP model*. Icarus 247, 191-217.

Bottke, W. F., et al. (2015). *The Collisional Evolution of the Asteroid Belt.* In Asteroids IV (P. Michel, F. DeMeo, and W. F. Bottke, Eds). U. Arizona Press, in press.

Canup, R. M. (2013). *Lunar conspiracies*. Nature, Vol. 504, Issue 7478, p. 27

Canup, R. M. (2014). *Lunar-forming impacts: processes and alternatives*. Phil. Trans. R. Soc. A 372:20130175.

Delbo, M., Libourel, G., Wilkerson, J., Murdoch, N., Michel, P., Ramesh, K. T., Ganino, C., Verati, C. and Marchi, S. (2014). *Thermal fatigue as the origin of regolith on small asteroids.* Nature 508, 233-236, 2014.

De Sanctis, M. C., Frigeri, A., Ammannito, E., Tosi, F., Marchi, S., Zambon, F., Raymond, C. A. and Russell, C. T. (2015). *Mineralogy of Marcia, the youngest large crater of Vesta: Character and distribution of pyroxenes and hydrated material.* Icarus 248, 392-406, 2014.

Fieber-Beyer, S. K., Gaffey, M. J., Bottke, W. F., Hardersen, P. S. (2015). *Potentially hazardous Asteroid 2007 LE: Compositional link to the black chondrite Rose City and Asteroid (6) Hebe*. Icarus 250, 430-437.

Golubov, O., Scheeres, D. J. and Krugly, Yu. N. (2014). *A 3-dimensional model of tangential YORP*. Astrophysical Journal 794:22.

Hirabayashi, M. and Scheeres, D. J. (2015). *Stress and Failure Analysis of Rapidly Rotating Asteroid (29075) 1950 DA.* Astrophysical Journal Letters 798:L8.

Hirabayashi, M., Scheeres, D. J., Sanchez, P. and Gabriel, T. (2014). *Constraints on the Physical Properties of Main Belt Comet P/2013 R3 from its Breakup Event.* Astrophysical Journal Letters 789:L12 (5pp).

Hopkins, M. D., Mojzsis, S. J., Bottke, W. F., Abramov, O. (2015). *Micrometer-scale U-Pb age domains in eucrite zircons, impact re-setting, and the thermal history of the HED parent body.* Icarus 245, 367-378.***

Levison, H. F., Kretke, K., Duncan, M. *Growing Gas Giant Planets from the Slow Accumulation of Centimeter- to Meter-Size Objects*. Submitted to Nature.

Levison, H. F., Kretke, K., Walsh, K. J., Bottke, W. F. *Growing the Terrestrial Planets from the Slow Accumulation of Centimeter- to Meter-Size Objects*. Submitted to Nature.

Marchi, S., Bottke, W. F., Elkins-Tanton, L. T., Bierhaus, M., Wuennemann, K., Morbidelli, A. and Kring, D. A. (2014). *Widespread mixing and burial of Earth's Hadean crust by asteroid impacts*. Nature 511, 578-582.***

Marchi, S., Bottke, W. F., O'Brien, D. P., Schenk P., Mottola S., De Sanctis, M. C., Kring, D. A., Williams, D. A., Raymond, C. A. and Russell, C. T. (2014) *Small crater populations on Vesta*. Planetary and Space Science 103, 96-103.***

Melosh, H. J. (2014). *New approaches to the Moon's isotopic crisis*. Phil. Trans. R. Soc. A 372:20130168.

Morbidelli, A., Walsh, K. J., O'Brien, D.P., Minton, D. A., Bottke, W. F. (2015). *The Dynamical Evolution of the Asteroid Belt.* In Asteroids IV (P. Michel, F. DeMeo, and W. F. Bottke, Eds). U. Arizona Press, in press.

Nesvorný, D., Vokrouhlický, D., Deienno, R. and Walsh, K. J. (2014). *Excitation of the Orbital Inclination of Iapetus during Planetary Encounters*. The Astronomonical Journal, 148, 52.

O'Brien, D. P., Marchi, S., Morbidelli, A., Bottke, W. F., Schenk, P. M., Russell, C. T. and Raymond, C. A. (2014). *Constraining the Cratering Chronology of Vesta*. Planetary and Space Science 103, 131-142.

Reddy, V., Sanchez, J. A., Bottke, W. F., et al. (2014). *Chelyabinsk meteorite explains unusual spectral properties of Baptistina Asteroid Family*. Icarus 237, 116-130.***

Rivkin, A. S., Asphaug, E., Bottke, W. F. (2014). *The case of the missing Ceres family.* Icarus 243, 429-439.***

Salmon, J. and Canup, R. M. (2014). *Accretion of the Moon from the protolunar disc*. Phil. Trans. R. Soc. A 372:20130256.

Scheeres, D. J. (2015). *Landslides and Mass Shedding on Spinning Spheroidal Asteroids*. Icarus 247: 1-17.

Scott, E., Keil, K., Goldstein, J. I., Bottke, W. F., Moskovitz, N., Asphaug, E. *Early Impact History and Dynamical Origin of Differentiated Meteorites and Asteroids*. In Asteroids IV (P. Michel, F. DeMeo, and W. F. Bottke, Eds). U. Arizona Press, in press.

Sierks, H., (45 authors), Marchi, S., et al. (2015). *On the nucleus structure and activity of comet 67P/Churyumov - Gerasimenko.* Science 347, aaa1044 1-5.

Stephan, K., Jaumann, R., De Sanctis, M. C., Tosi, F., Ammannito, E., Krohn, K., Zambon, F., Marchi, S. et al. (2014). *Small fresh impact craters on asteroid 4 Vesta: A compositional and geological fingerprint.* Journal of Geophysical Research 119, 771-797, 2014.

Thomas, N., (41 authors), Marchi, S., et al. *The morphological diversity of comet 67P/Churyumov - Gerasimenko.* Science 347, aaa0440 1-6, 2015.

Vincent, J.-B., Schenk, P., Nathues, A., Sierks, H., Hoffmann, M., Gaskell, R. W., Marchi S. et al. (2014). *Crater depth-to-diameter distribution and surface properties of (4) Vesta.* Planetary and Space Science 103, 57-65.

Vokrouhlický, D., Bottke, W. F., Chesley, S. R., Scheeres, D. J., Statler, T. S. *The Yarkovsky and YORP Effects*. Asteroids IV, in press.

Ward, W. R. (2014). *On the evolution of the protolunar disc*. Phil. Trans. R. Soc. A 372:20130250.

Williams, D. A., Jaumann, R., McSween, H. Y., Marchi, S., Schmedemann, N., Raymond, C. A. and Russell, C. T. (2014). *The chronostratigraphy of protoplanet Vesta*. Icarus 244, 158-165.

Williams, D. A., (19 authors), Marchi, S., et al. (2014). *The geology of the Marcia quadrangle of asteroid Vesta: Assessing the effects of large, young craters.* Icarus 244, 74-88.

Williams, D. A., O'Brien, D. P., Schenk, P. M., Denevi, B. W., Carsenty, U., Marchi, S. et al. (2014). *Lobate and flow-like features on asteroid Vesta.* Planetary and Space Science 103, 24-35.

5) Abstracts

A total of 39 abstracts have been submitted to conferences.

Details are available in the attached spreadsheet.

6) Students and Post-docs.

Our ISET team has supported a number of young scientists:

- Graduate student Travis Gabriel and Post-docs Paul Sanchez & Toshi Hirabayashi, have been collaborating with Dan Scheeres (2 papers, 4 abstracts)
- Post-doc Katherine Kretke and Kevin Walsh have been collaborating with Hal Levison (3 papers, 3 abstracts).
- Post-doc Julien Salmon has been collaborating with Robin Canup (1 paper, 3 abstracts)

INTERNATIONAL PARTNERSHIPS

SSERVI has an international partnership program that provides collaborative opportunities for the global science community. Proposals that demonstrate collaborative intentions and clear goals aligned with the U.S. teams can be accepted for Affiliate or Associate partnerships, allowing participation in SSERVI programs on a no-exchange-of-funds basis. Contact the Central Office for additional information.

CANADA

Dr. Gordon Osinski
University of Western Ontario
Partnership signed July 2008

GERMANY

Prof. Ralf Jaumann
German Aerospace Center
Partnership signed December 2010

ISRAEL

Prof. Shlomi Arnon
Ben-Gurion University at the Negev
Partnership signed January 2010

ITALY

Simone Dell'Agnello
National Institute of Nuclear Physics
Partnership signed December 2014

NETHERLANDS

Dr. Win van Westrenen,
VU University Amsterdam
Partnership signed August 2010

SAUDI ARABIA

Dr. Abdulaziz O. Alothman
King Abdulaziz City for Science & Technology
Partnership signed December 2009

SOUTH KOREA

Dr. Gwanghyeok Ju
Korea Aerospace Research Institute

Dr. Kyeong Kim
Korea Institute of Geoscience and Mineral Resources
Partnership signed November 2008

UNITED KINGDOM

Dr. Mahesh Anand
Open University
Partnership signed January 2009