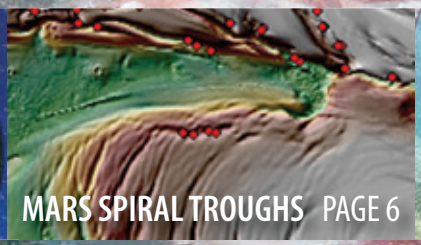
Planetary Science Institute

ANNUAL REPORT 2021

SCIENTIST AWARDS PAGE 5



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Dedicated to Solar System exploration,
PSI scientists are involved in NASA and international missions,
fieldwork around the world, education, and public outreach.

PLANETARY SCIENCE INSTITUTE

The Planetary Science Institute is a private, nonprofit 501(c)(3) corporation dedicated to Solar System exploration. It is headquartered in Tucson, Arizona, where it was founded in 1972.

PSI scientists are involved in NASA and international missions, the study of Mars and other planets, the Moon, asteroids, comets, interplanetary dust, impact physics, the origin of the Solar System, extra-solar planet formation, dynamic evolution of planetary systems, the rise of life, and other areas of research. They conduct fieldwork on all continents around the world. They are also actively involved in science education and public outreach through school programs, children's books, popular science books and art.

PSI scientists and educators are based in 30 states and the District of Columbia, and work from various international locations.

PSI BOARD OF TRUSTEES

ON THE COVER:
"A Rainstorm on Primordial Mars"

Painting by PSI Cofounder and Senior Scientist Emeritus William K. Hartmann

Current research at PSI and elsewhere has found increasing evidence for activity of liquid water in the very early history of Mars, including water flow from now-dry riverbeds that were mapped on Mars by the first Mars orbiter, Mariner 9, in 1971-72. Such work suggests a thicker atmosphere and greater water content in the early Martian atmosphere than today. The cover image is a 2007 painting by Hartmann (who was on the Mariner 9 imaging team), imagining early rainstorms that may have supplied water to the earliest Martian rivers.
(Painting in collection of Hartmann's Mars research coauthors, Nicolas Mangold and Veroniqué Ansan, University of Nantes, France.)

MESSAGE FROM THE DIRECTOR

IN 2021 THE COVID-19 PANDEMIC CONTINUED.

With the advent of COVID vaccines earlier in the year, we were ultimately able to open up our offices with masking requirements for the public areas once all employees at the offices were vaccinated.

Things got more interesting when in the Fall, federal guidelines were issued requiring all employees of federal contractors to be vaccinated. At PSI, this included off-site as well as on-site employees. We worked with a few employees to craft medical and religious exemptions that would stand up to third-party scrutiny (mandates on federal contractors cannot be taken lightly), but then in December a federal court intervened and suspended the new requirements pending further litigation.

Fortunately, for PSI it remained largely business as usual since NASA continued to operate and project partners continued to pay invoices. Families continued to be challenged, however, with the lack of child care and a need for in-home remote schooling. Communication among our employees continued to be key in the offers of mutual support and strategies.

For the second year in a row the PSI Annual Retreat was virtual, making use of Gathertown this time, augmented with Zoom. We had a lecture hall, a number of breakout rooms, a lounge area, poster facility and rooftop bar with a fireplace. Recorded presentations were run and live Q&A followed in the lecture hall. It was an interesting experience. The rooftop bar and fireplace were a hit and have continued to be used. I have greeted German students there from a class one of our scientists was teaching remotely at a German university. The world can indeed be a village!

SCIENCE ALSO CONTINUED APACE AT PSI

Mars is always a focus of major study by PSI scientists. Our SWIM team (Subsurface Water Ice Mapping), led by Senior Scientist Than Putzig, mapped out locations of subsurface ice down to lower Martian latitudes that might be a resource for future human exploration. Huge spiral troughs in the Martian polar caps were explained as an erosional process by Alexis Rodriguez (see the featured article on page 6). Senior Scientist Amanda Hendrix, co-chair of the Committee on Planetary Protection, identified large areas on Mars where spacecraft with relaxed sterilization requirements could be sent, making the access of the Mars surface simpler and less expensive. This recognizes the harsh UV environment, which is uninhabitable for Earth microbes.

Senior Scientist Grace Wolf-Chase led citizen scientists in the discovery of "stellar nurseries" before stars emerge from their birth clouds, which she named "yellowballs."

Senior Scientist Catherine Johnson and Research Associate Megan Russell discovered evidence of geologically recent volcanism on Venus (see the featured article on page 7).

A technique developed in part by Senior Scientist Nader Haghighipour was used to discover a planet orbiting two stars by the Transiting Exoplanet Survey Satellite.

Many other advances were made by PSI scientists for objects throughout the Solar System and beyond. Even in times of plague, we make advancements which inspire us to see better times ahead.

— Mark V. Sykes

PSI SCIENTISTS HONORED WITH PRESTIGIOUS AWARDS IN 2021

PSI SCIENTISTS, FROM LEFT:
Senior Scientists Alan Gillespie, David Grinspoon and Catherine Weitz

Senior Scientist Alan Gillespie Honored with 2021 Distinguished Career Award

Senior Scientist Alan Gillespie received the 2021 Distinguished Career Award from the Quaternary Geology and Geomorphology Division of the Geological Society of America.

The Distinguished Career Award is given to the Quaternary geologists and geomorphologists who have demonstrated excellence in their contributions to science.

The citation for the award read in part: "His passion for learning, knack for combining creativity and rigor, and dedication to his students never cease to inspire. Alan's fundamental contributions span an impressive range of research disciplines and advances in basic techniques and fundamental conceptions in remote sensing, geomorphology, glacial geology, planetary sciences, active tectonics, geochronology, and geoarchaeology. Notably, he contributed to developing or advancing thermal inertia imaging, exposure age dating, and recognition of global asynchronicity between mountain and continental glaciations. He also advanced both Martian geomorphology and knowledge of mega-floods in Asia and Alaska. He helped develop spectral mixing models, thermal inertia applications, and cosmogenic radionuclide dating methods that are now standard tools. His decades-long studies of Asian glaciations overturned once-conventional wisdom. His contributions to Martian geomorphology range from the origin of slope streaks to the formation of Valles Marineris and the role of wind erosion in crater-count chronologies."

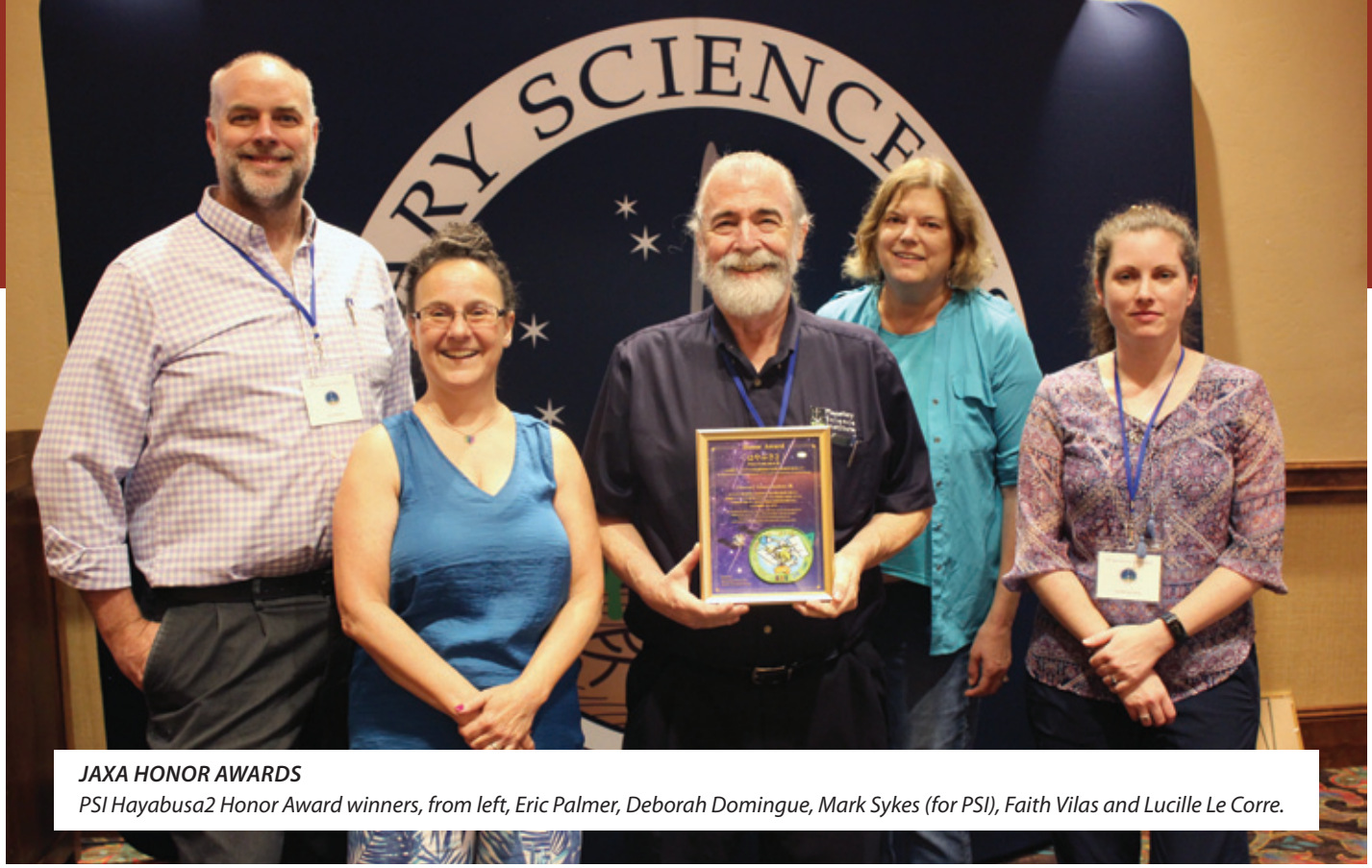
Senior Scientist David Grinspoon Named Fellow in Astronomy by American Association for the Advancement of Science

Senior Scientist David Grinspoon was named an American Association for the Advancement of Science (AAAS) Fellow in the field of astronomy. AAAS is the world's largest general scientific society and publisher of the Science family of journals.

Grinspoon was elected a class of 2021 Fellow by AAAS for distinguished scientific research in the field of comparative terrestrial atmospheres with a particular focus on Venus, and for prolific public science communication via books, articles, lectures, and other media.

"It's a great honor for me to be named as an AAAS fellow," Grinspoon said. "It's such an exciting and hopeful time to be involved in planetary exploration and astrobiology, and simultaneously a somewhat harrowing time to inhabit this rapidly changing planet where scientifically enlightened policy is both desperately needed and currently under threat. We need to serve society while advancing science, and I'm proud to be recognized by an organization of my peers which has as its mission to do both."

Grinspoon has served on the science teams of several interplanetary spacecraft and has published numerous papers on the evolution of the atmospheres, planets and potential



JAXA HONOR AWARDS
PSI Hayabusa2 Honor Award winners, from left, Eric Palmer, Deborah Domingue, Mark Sykes (for PSI), Faith Vilas and Lucille Le Corre.

biology of Earthlike planets, and has given invited keynote talks at conferences around the world. He has written and edited six books, including "Lonely Planets the Natural Philosophy of Alien Life" which won the PEN Literary award for nonfiction and "Earth in Human Hands: Shaping Our Planet's Future," named a Best Science Book of 2016 by NPR's Science Friday. His articles have been published in Slate, Scientific American, Natural History, The Atlantic, The Washington Post, the Los Angeles Times, and The New York Times, and he writes the regular "Cosmic Relief" column for Sky & Telescope Magazine. The American Astronomical Society awarded him the Carl Sagan Medal for Public Communication of Planetary Science. Asteroid 22410 Grinspoon, a main-belt asteroid, is named after him.

Senior Scientist Catherine Weitz Named Fellow of Geological Society of America

Senior Scientist Catherine Weitz was named a fellow of the Geological Society of America. GSA is a global professional society with a membership of more than 20,000 individuals in more than 100 countries. GSA provides access to elements that are essential to the professional growth of earth scientists at all levels of expertise and from all sectors: academic, government, business, and industry. The Society unites thousands of earth scientists from every corner of the globe in a common purpose to study the mysteries of our planet (and beyond) and share scientific findings.

Society Fellowship is an honor bestowed based on a sustained record of distinguished contributions to the geosciences and the Geological Society of America through such avenues as publications, applied research, teaching, administration of geological programs, contributing to the public awareness of geology, leadership of professional organizations, and taking on editorial, bibliographic, and library responsibilities.

Weitz was selected "…for her innovative, revolutionary, and influential discoveries on the geology of Mars, the Moon, and Venus, including work on missions, research, and publications, as well as for her support of GSA and contributions to the planetary science community."

PSI and Four Senior Scientists Receive Honor Awards for Hayabusa2 Mission to Asteroid

PSI and four of its senior scientists received honor awards from the Japan Aerospace Exploration Agency, the Japanese national air and space agency, to commemorate the amazing success of the Hayabusa2 mission's round-trip exploration to the asteroid Ryugu.

JAXA's award citation said, "The Hayabusa2 spacecraft completed a 2,195-day round-trip through space, explored the asteroid Ryugu, and successfully collected samples. We would like to express our heartfelt gratitude for your dedication and enthusiasm that made this venture possible."

Receiving the individual honor awards were Deborah Domingue, Lucille Le Corre, Eric Palmer and Faith Vilas. Mark Sykes accepted PSI's award.

HUGE SPIRAL TROUGHS ON MARS ARE YOUNG, FORMED BY EROSION

Spiral troughs found on the surface of Mars are in situ ice-excavated canyons with a total volume 10 times that of the Grand Canyon, making them one of the largest and youngest geologic mega-structures in the Solar System, according to research by Senior Scientist Alexis Palmero Rodriguez.

"Erosion formed a huge ice canyon system, and that erosion is a source of the long-known mid-latitude mantles on Mars," said Rodriguez, lead author of "North polar trough formation due to in situ erosion as a source of young ice in mid latitudinal mantles on Mars" (www.nature.com/articles/s41598-021-83329-3) that appears in Nature Scientific Reports.

"The troughs are arranged in a vast spiral pattern covering an area the size of Texas. We find that their growth lateral to katabatic wind (wind that carries high-density colder air from a higher elevation down a slope) directions produced widespread simple intersections, from which the highly complex spiral arrangement emerged," Rodriguez said.

"The spiral pattern seen in the troughs is basically an erosional byproduct," he said. "As the pits grow and intersect over a pre-existing dome-shaped polar cap, the spiral pattern emerges.

"It has long been proposed that sublimation of water ice from the north polar cap during high-obliquity cycles was an essential source of the planet's mid-latitude icy plains. Our finding identifies the troughs as direct evidence of those sublimation phases," Rodriguez said.

These spiral trough features formed very recently, in geologic terms: between a few million and 50,000 years ago, Rodriguez said.

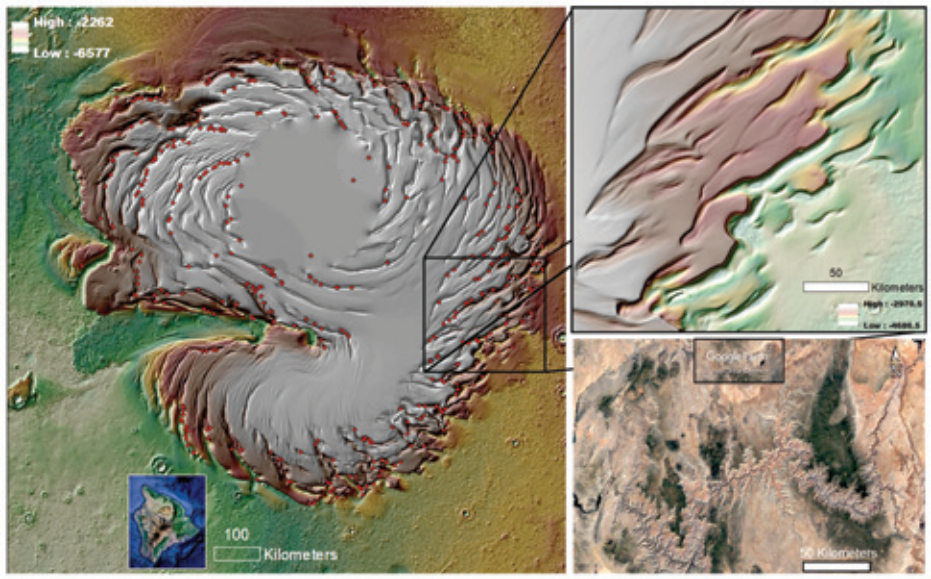
The presence of northern plains ice has long been known and has been recently suggested as a potential human resource. However, that ice could include frozen brines with compounds toxic to humans – for example, residues of ancient lakes, seas, and oceans.

"We estimated that about 25% of the northern plains icy substrates were derived from trough eroded ice. The ice was never liquid, so it never dissolved toxic compounds. We are looking at enormous volumes – equivalent to approximately 16 billion Olympic-sized swimming pools – of potentially pure clean water," Rodriguez said. "On the other hand, these icy layers, including those sampled by NASA's Phoenix Mars Lander, might not be the best places to look for life, for precisely the same reasons."

The age of the polar cap remains a subject of controversy, and numerous estimates exist. Based on detailed geologic mapping, a view is that most of its deposition happened during the last billion years. Consequently, while the troughs might be geologically young, the ice they exposed could be extremely ancient.

To provide perspective, the oldest ice cores on Earth are approximately 2.7 million years old, which has been very useful to reconstruct our planet's recent paleoclimatic evolution. The layers of Martian ice exposed within the troughs could enable in-depth paleoclimatic investigations potentially spanning several hundred million years into the past. An equivalent record on Earth would allow us to sample ice from when the dinosaurs roamed Earth and much more precisely understand the paleoenvironments under which they lived.

The project was funded by a grant to PSI from NASA's Mars Data Analysis program.



SPIRAL TROUGH ON MARS
Digital elevation model of Mars' north polar cap showing the spiraling trough. The red dots identify 424 locations of concentrically layered mounds and depressions, demonstrating that in-situ erosion was pervasive. The inset is a view of the island of Hawaii providing context for the polar cap's sheer size. The close-up view (upper right) shows an area equivalent to that of the Grand Canyon (bottom right). The left and upper right panels are MOLA-generated topography.
Credit: MOLA Science Team, MSS, JPL, NASA.

NEW EVIDENCE OF RECENT (GEOLOGICALLY SPEAKING) VENUSIAN VOLCANISM

New data analysis techniques allow evidence of recent volcanism to be found in old Magellan spacecraft data.

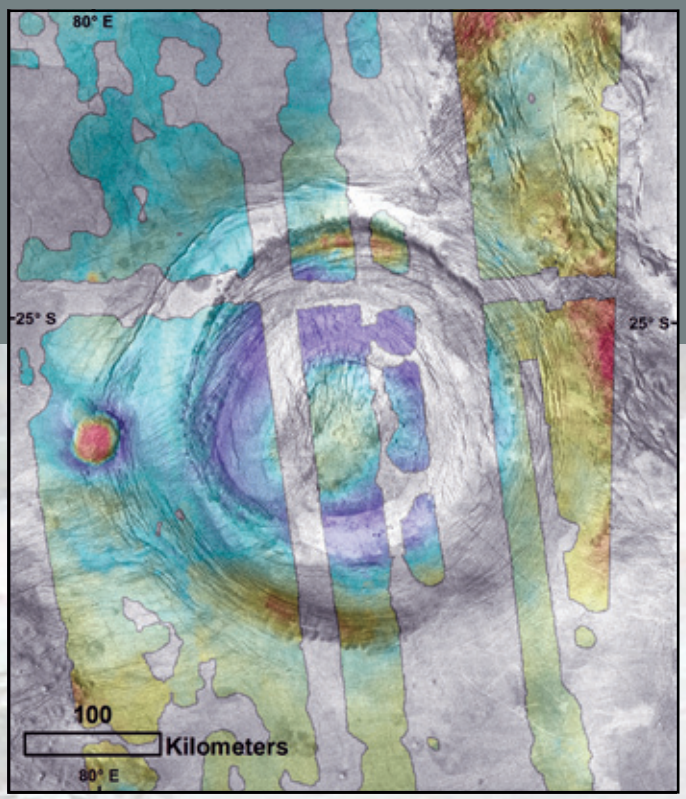
It is unclear if this activity is occurring today, or if it occurred within tens of million years, but geologically speaking, either case is recent. This adds to the growing body of evidence that volcanoes on Venus didn't go extinct as long ago as many had thought. This work was conducted by PSI researchers Megan Russell and Catherine Johnson.

In the 31 years since NASA's Magellan spacecraft entered orbit around Venus, researchers have been using the mission's radar images, topography and gravity mapping to understand the surface history of this cloud-covered world. Early results made it clear that Venus has significantly fewer impact craters on its surface than its cousins Mars and Mercury, and the craters that it does have are randomly scattered across the planet. Craters build up over time, and Venus' low number of craters means it has a surface that was somehow wiped clean roughly 300 million to 1 billion years ago. It is unclear if this was a catastrophic event that resurfaced the entire planet at once, or randomly distributed ongoing events that systematically resurfaced Venus over time, or some combination of both options. To understand what happened, it is necessary to understand when volcanoes have been active.

"The question of whether Venus has had geologically recent or ongoing volcanism has been an enduring enigma from the Magellan mission: we still have no smoking gun regarding this but more and more lines of evidence suggest a recently, and potentially currently, active planet," said Senior Scientist Catherine Johnson.

As computers have improved, it has become possible to do more and more with Magellan's finite data set. Russell and Johnson used a high-resolution stereo topography data set generated by other researchers to look at a volcano at the edge of the 350-kilometer across Aramaiti Corona.

Corona are roughly circular features, surrounded by a ring of cracks that appear roughly like a crown, and are thought to be large faults. At some coronae, like Aramaiti, volcanoes and/or lava flows are observed close to or on these fractures. The volcano studied by the PSI researchers was part of the lucky 20% of Venus' surface to be imaged in stereo with synthetic aperture radar (SAR), which revealed the elevations across the 3-D structure, providing a better view than a simple image.



OLD MAGELLAN DATA YIELDS NEW INFORMATION
Magellan SAR image of Aramaiti Corona. Narina Tholus (center left) appears as two adjacent domes that are superposed on the west outer fracture ring. Credit: NASA/PDS/Megan B. Russell PSI

"Instead of looking at the surface of the volcano or flows, we look at how the volcano deforms the ground around it. In response to the weight of the volcano, the ground around it bends, like flexing a plastic ruler," said Megan Russell, a PSI Research Associate and lead author of Evidence for a Locally Thinned Lithosphere Associated with Recent Volcanism at Aramaiti Corona, Venus that appears in Journal of Geophysical Research Planets. "The same kind of deformation is seen in the bending of the seafloor around the Hawaiian Islands. From this deformation, we can infer properties like heat flow local to the volcano."

To go beyond simply indicating younger versus older, it is necessary to use complex computer models to model the surface deformation. It is from this modeled deformation that properties like heat flow can be inferred.

Over time, these kinds of structures can evolve, and the degree of deformation that is observed hints at how old or young a feature might be and how much heat might be flowing under the surface.

Russell goes on to explain, "Modeling studies suggest that the shape and topography of this corona indicate that it is also geologically young, and would have similarly geologically young volcanism associated with it."

With three future missions planned for Venus, this team looks forward to exploring this question in greater detail in the future. "Happily, for those of us who were lucky enough to start our careers working on the Magellan mission, there are now three new missions slated to fly to Venus in the next decade or so," Johnson said.

CARBON DIOXIDE COLD TRAPS OFFER POTENTIAL LUNAR RESOURCE

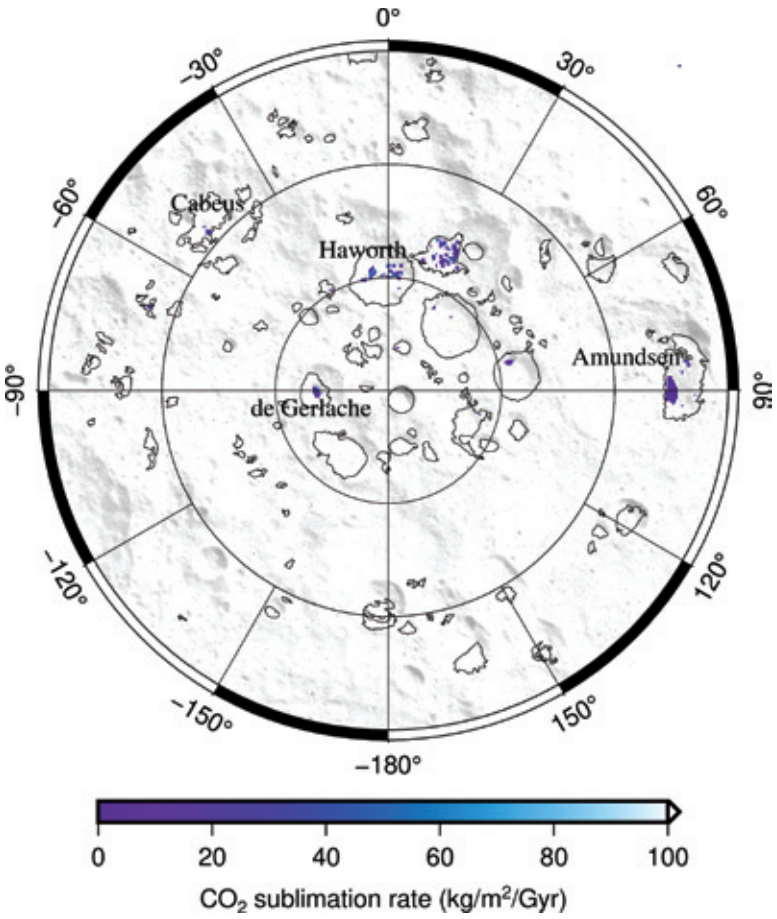
The existence of carbon dioxide (CO_2) cold traps on the Moon has been confirmed, offering a potential resource for future exploration of the lunar surface, according to a new paper by Senior Scientist Norbert Schorghofer.

"After water, carbon is probably the most important resource on the Moon. It can be used for the production of rocket fuel, but also for biomaterials and steel. If we have to bring carbon or fuel from Earth, it drives up the cost of sustained presence. It's part of 'living off the land,' or in-situ resource utilization," said Schorghofer, lead author of "Carbon Dioxide Cold Traps on the Moon" that appears in Geophysical Research Letters. PSI's Matthew A. Siegler is a co-author on the paper.

Various volatiles can be cold-trapped in permanently shadowed craters near the lunar poles. The existence of carbon dioxide cold traps has previously been surmised, but the required temperatures are near the lowest surface temperatures that have been reliably measured.

"Extensive and improved analysis of 11 years of orbital surface temperature measurements by the Diviner Lunar Radiometer Experiment on board NASA's Lunar Reconnaissance Orbiter establishes the existence of carbon dioxide cold traps on the Moon, which potentially host high concentrations of solid carbon dioxide, Schorghofer said. "Our work has established the existence of CO_2 cold traps, where theory predicts solid CO_2 should have accumulated. Our work does not show that there actually is CO_2 in these areas, but it is a reasonable expectation, especially since CO_2 was detected in the LCROSS (NASA's Lunar Crater Observation and Sensing Satellite) impact plume in 2009."

In the new study, many terabytes of Diviner data were processed to capture the full-time dependence of surface temperatures. The Moon actually has seasons; the lunar year is about 347 Earth days long, a period known as the "Draconic year." These seasons are not noticeable on most of the lunar surface, but they are important within the permanently shadowed areas where H_2O and CO_2 cold traps lie. Carbon dioxide ice is lost to space only during a short period in summer.

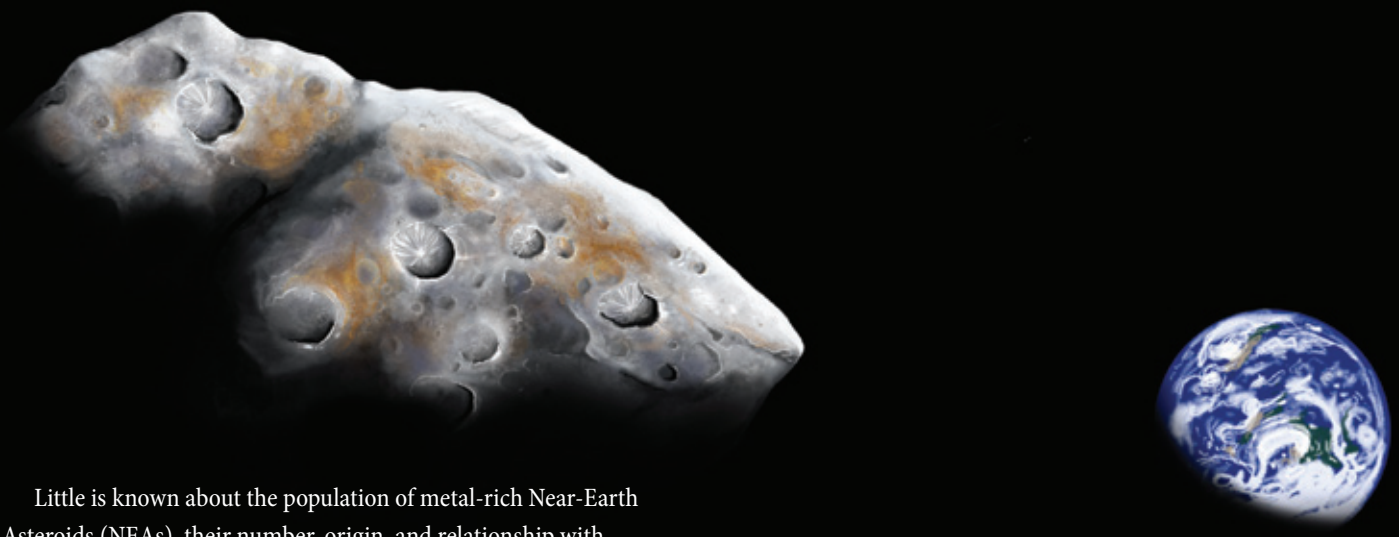


SOUTH POLAR REGION OF THE MOON
Areas that act as CO2 cold traps are colored. Black contours show the boundaries of H2O cold traps. The background map is shaded relief. Credit: Norbert Schorghofer

The total area of CO_2 cold traps in the south polar region of the Moon is about 200 square kilometers. For comparison, water ice cold traps cover nearly 14,000 square kilometers. Concentrated CO_2 is an extremely scarce resource, only found at a few places, and a large portion of its cold trap area resides on the floor of Amundsen Crater, which is relatively accessible, so it may be a promising exploration target. In this area, temperatures never exceed negative 350 degrees Fahrenheit, so it will definitely be a technological challenge to explore these extremely cold and permanently dark places.

Schorghofer's work was funded by grants to PSI from NASA's Lunar Data Analysis Program and Solar System Exploration Research Virtual Research Institute Geophysical Exploration of the Dynamics and Evolution of the Solar System program.

NEW STUDY FINDS EVIDENCE OF THE ORIGIN OF METAL-RICH NEAR-EARTH ASTEROIDS



ARTIST'S IMPRESSION OF NEAR-EARTH ASTEROID
An artist's impression of a close flyby of the metal-rich near-Earth asteroid 1986 DA. Astronomers using the NASA Infrared Telescope Facility have confirmed that the asteroid is made of 85% metal.
Credit: Addy Graham/University of Arizona

Little is known about the population of metal-rich Near-Earth Asteroids (NEAs), their number, origin, and relationship with meteorites found on Earth. A paper by Associate Research Scientist Juan Sanchez explains how near-infrared spectroscopic data of two NEAs reveals new information about the composition and physical properties of these bodies.

"We find that both NEAs are composed of mostly metal and a small fraction of silicate minerals, similar to mesosiderites, a rare type of stony-iron meteorites found on Earth," said Sanchez, lead author of the paper "Physical Characterization of Metal-rich Near-Earth Asteroids 6178 (1986 DA) and 2016 ED85" that appears in Planetary Science Journal. PSI Laboratory Technician Neil Pearson is also an author.

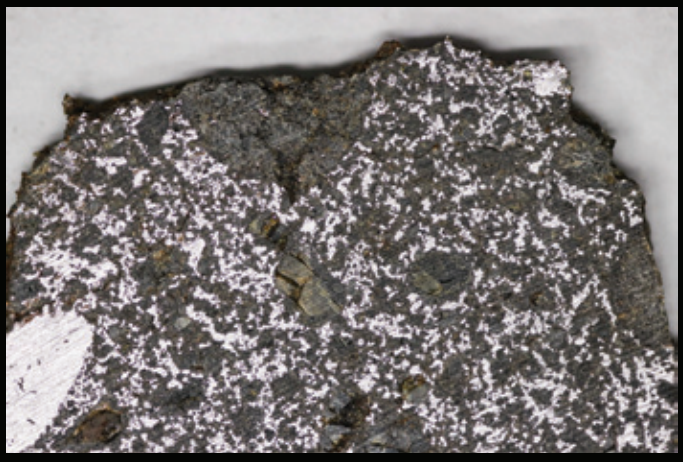
"Analysis of their orbits allows us to trace their origin to a region in the outer asteroid belt where the largest metal-rich asteroids reside," Sanchez said. The asteroid belt is located between the orbits of Mars and Jupiter.

"According to some studies, there are more than 60 parent bodies represented among iron meteorites found on Earth; however, those parent bodies have not been identified so far. There are also stony-iron meteorites and metal-rich carbonaceous chondrites whose origin is unknown," Sanchez said. "Because NEAs represent a direct link between meteorites found on Earth and their parent bodies throughout the Solar System, the identification of metal-rich NEAs gets us closer to determining the specific origin of the meteorites that derive from them."

The larger NEA, (1986 DA), is shown to be primarily metal by using radar data from an earlier study. Metal has a much higher radar reflectivity than rocky bodies composed of silicate minerals. The team's new near-infrared spectra of 1986 DA confirmed that the asteroid surface is a mixture of about 85% metal and 15% pyroxene, a rock-forming silicate mineral found in igneous and metamorphic rocks.

For the other NEA, 2016 ED85, there is no radar data available, but Sanchez finds that its near-infrared spectrum is almost identical to the spectrum of 1986 DA and other metal-rich asteroids, suggesting that this object has a similar composition.

The paper's findings are based on observations from the NASA Infrared Telescope Facility on the island of Hawaii. The work was funded by the NASA Near-Earth Object Observations Program, which also funds the NASA Infrared Telescope Facility.



STONY-IRON METEORITE
Photograph of stony-iron meteorite called mesosiderite showing iron-nickel metal mixed with silicate rocky material. Two metal-rich near-Earth asteroids observed by PSI astronomer Juan Sanchez are thought to be made of this rare class of meteorite.
Credit: University of Arizona

KASKES, MCINTOSH, MCNEIL AND NARAYANAN NAMED 2022 PIERAZZO AWARD WINNERS

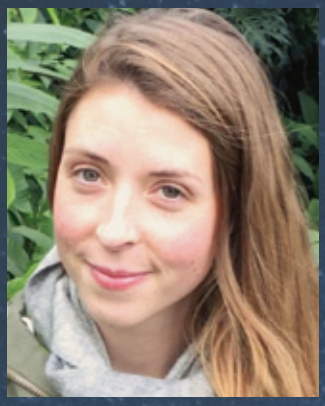
The winners of the 2022 Pierazzo International Student Travel Award established by the Planetary Science Institute have been selected. Four rather than two recipients were named as a consequence of the 2021 Pierazzo Awards being canceled due to COVID-19 travel restrictions.

The Pierazzo International Student Travel Award was established by PSI in memory of Senior Scientist Betty Pierazzo to support and encourage graduate students to build international collaborations and relationships in planetary science.

Pim Kaskes, Ophélie McIntosh and Joseph McNeil will receive awards for non-U.S.-based graduate students going to a planetary-related conference within the U.S., and Suchitra Narayanan will receive an award as a U.S.-based graduate student going to a planetary-related conference outside of the U.S.

A PSI representative will present each awardee with a certificate and check for $2,000 at their respective conferences.

Clockwise, from top left, the winners are:



Pim Kaskes

Pim Kaskes of the Vrije Universiteit Brussel (Brussels, Belgium) will attend the 53rd Lunar and Planetary Science Conference in The Woodlands, Texas, March 7-11, 2022. His research titles are "Suevite emplacement and impact melt dynamics within the Chicxulub impact structure" and "High-resolution chemostratigraphy across the Cretaceous-Paleogene boundary." Kaskes' work provides new evidence for physical parameters to use as input for impact, ejecta and climate models linked to the Chicxulub asteroid impact that resulted in a mass extinction event 66 million years ago that eliminated about 75 percent of life on Earth, including the (non-avian) dinosaurs. His research also provides knowledge for finetuning models of hypervelocity impacts elsewhere in the Solar System.

Ophélie McIntosh

Ophélie McIntosh of University Paris-Saclay will attend the Astrobiology Science Conference (AbSciCon) in Atlanta, Georgia, May 15-20, 2022. Her research title is "Thermal reactivity of organic molecules with chloride salts: consequences for the chemical composition of Mars samples analyzed in situ with the GCMS, SAM, and MOMA instruments." She will discuss the influence of chloride salts on the thermal degradation of organic molecules in Mars-like conditions and the meaning of these results in the search for biosignatures on the Martian surface and sub-surface. Her work could identify new organic compounds of astrobiological importance and optimize the Mars rover sampling locations.

Suchitra Narayanan

Suchitra Narayanan of the University of Hawaii at Manoa will attend the Protostars and Planets VII conference in Kyoto, Japan, this September 2022 (date TBD). Her research title is "Analyzing the Substructure and Dynamics and Sulfur Organics Inventory of Oph IRS43." She will discuss the first high-resolution look at the substructures and physical properties of this fascinating protoplanetary disk within which planets are expected to be in the earliest stages of formation.

Joseph McNeil

Joseph McNeil of Open University will attend the 53rd Lunar and Planetary Science Conference at The Woodlands, Texas, March 7-11, 2022. His research title is "Windows into Noachian Mars: Eroded landforms in Chryse Planitia and the ExoMars rover landing site." He will discuss his research into the geology of a population of kilometer-scale mounds, buttes, and mesas which exist around the margin of Chryse Planitia, Mars. These landforms have revealed crucial new information on the stratigraphy of this important and ancient region, and have significant consequences for the geology of Oxia Planum, the landing site of ESA's ExoMars 2022 Rover, Rosalind Franklin.

PSI FINANCIAL REPORT

Bruce Barnett Chief Financial Officer

PSI's revenues grew to more than $17.3 million for the fiscal year ended September 30, 2021. During the fiscal year, PSI was actively involved in 125 prime awards issued directly from federal agencies and 143 subawards/contracts issued through other institutions. 95 percent of PSI's revenues from grants and contracts originated from NASA.

REVENUES

Grants and Contracts	$ 15,371,970
Contributions	131,479
Other	1,835,387
Total Revenues	**$ 17,338,836**

ACTIVE PROJECTS BY PRIME AWARDING AGENCY

NASA	118
NSF	7
Non-Federal	143
Total Projects	**268**

Salaries and related fringe benefits represented 74 percent of PSI's total expenses. Operating expenses included $2.6 million from subawards issued to other institutions for collaborative efforts on PSI prime awards. Program Service expenses amounted to 90 percent of total expenses.

EXPENSES

Salaries and Benefits	$ 11,386,224
Operating	3,816,810
Depreciation	206,329
Interest	44,644
Total Expenses	**$ 15,454,007**

EXPENSES BY FUNCTION

Program Services	$ 13,895,763
Management & General	1,508,410
Fundraising	49,834
Total Expenses	**$ 15,454,007**

PSI's financial records are audited annually by independent auditors. A condensed Statement of Financial Position from PSI's audit report as of September 30, 2021, is reflected below.

Current Assets	$ 3,902,045
Property & Equipment, Net	1,373,050
Total Assets	**$ 5,275,095**

Current Liabilities	$ 1,878,460
Long-term Liabilities	751,596
Net Assets with Donor Restrictions	109,928
Net Assets without Donor Restrictions	2,535,111
Total Liabilities & Net Assets	**$ 5,275,095**

THANK YOU TO OUR 2021 BENEFACTORS

With deep appreciation the Planetary Science Institute acknowledges the following individual and organizational benefactors who made contributions between January 1, 2021, and December 31, 2021.

$2,000 and up

Dr. William K. Hartmann
Dr. Mark V. Sykes and Ms. Marilyn Guengerich

$1,000-$1,999

Anonymous
Ms. Anna Don
Mr. Scott D. Fouse
Dr. and Mrs. Tim and Carol Hunter
Mr. Rodney Petersen
National Bank of Arizona
Dr. Dorothy Oehler
Conoco Phillips

$500-$999

Mr. Bruce Barnett and Ms. Tammi Palmer
Echo Construction
Ms. Kimberly Foote
Ms. Atara Jacobson
Col. Pamela Melroy, Retired
Dr. Faith Vilas

$250-$499

Dr. Thea L. Canizo
Mr. and Mrs. Robert and Elisabeth Chrien
Dr. William Craig
Mrs. Madelyn Creedon
Mr. Larry East
Mr. and Mrs. Alan and Gina Fischer
Green Marble Group LLC
Mr. Richard Hendricks
Dr. Alan Howard
Dr. Robert McMillan
Dr. Thomas H. Prettyman
Dr. and Mrs. Robert and Maria Reedy
Dr. David Vaniman

$100-$249

Mr. and Mrs. Joe and Diana Alexander
Mr. Alex Berman
Dr. Christopher Chyba
Mr. Bruce L Dusenberry
Mr. Stephen Fleming
Mr. Bruce Gordon
Dr. Nader Haghighipour
Dr. Vicki Hansen
Mr. Charles Katzenmeyer
Dr. D. Terence Langendoen and Ms. Nancy Kelly
Dr. and Mrs. Larry and Nancy Lebofsky
Drs. Tod Lauer and Beatrice Mueller
Mr. Martin Lorin
Dr. and Mrs. Jonathan and Cynthia Lunine
Dr. and Mrs. Andrew and Anna Nelson
Dr. Nathaniel Putzig
Mr. and Mrs. Otto and Linda Rueger
Dr. Nalin Samarasinha
Mr. Mark Shalonis
Dr. Sugata Tan
Dr. Michelle Thomsen
Dr. and Mrs. Bryan J. and Gayle L. Travis
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Dr. Paul Weissman

$1-$99

Anonymous
Dr. Brent Archinal
Mr. Xakarus Alldredge
Dr. and Mrs. Victor and Pauline Baker
Mr. and Dr. William and Kathleen Bethel
Dr. Kunegunda Belle
Mr. Gary Bingham
Mr. and Mrs. Robert and Judith Breault
Mr. John Cerney
Ms. Stephanie Delgado
Mr. Paul Emmert
Mr. Ralph Gould
Mr. Terrence Greenwood
Ms. Sara Hammond
Mr. Pete Kasper and Ms. Chris Holmberg
Mr. Stephen D. Hopkins
Mr. William E. Houghton
Ms. Dianne Janis
Ms. Susan King
Dr. Candace Kohl
Mr. Boguslaw Malecki
Dr. Kurt Marti
Ms. Elaine Noel
Mr. and Mrs. John and Kathleen O'Brien
Mr. David Oesper
Dr. John Redwine
Mr. Jack Schaefer
Ms. Kathryn Schmoll
Dr. Anna Spitz
Dr. Sarah Sutton
Mr. and Mrs. Nelson and Caryl Tilden
Dr. Andrew Wheeler

PSI FUNDRAISING AND DEVELOPMENT

2021 PSI Challenge Campaign

The 2021 PSI Challenge Campaign was launched on November 1 and concluded on December 31, 2021. The target goal for the campaign was $10,000. The Institute is pleased to report that the total raised was $31,824.

PSI Education and Public Outreach

Education and Public Outreach Supports Teachers and the Public Across the U.S.

PSI continues to support many science education and public engagement projects that have a national and international reach. In 2021, PSI continued the program that supported Education and Public Outreach (EPO) through funding from the "Friends of PSI" program.

Programming in 2021 led by scientists and education and communication outreach specialists included both virtual and in person programming across the United States as the world transitioned to a new normal.

Here are a few of the EPO highlights of a busy year for PSI scientists, educators, and communicators:

Teacher Workshops

The PSI EPO team, led by Larry Lebofsky and Sanlyn Buxner, conducted two half-day virtual workshops for elementary, middle and high school teachers over the summer of 2021 in collaboration with the Arizona Science Teacher Association. In addition, the team attended the fall Arizona Science Teachers Association conference in Phoenix where they facilitated three in-person workshops for dozens of Arizona educators. Larry Lebofsky also attended the National Science Teachers Association regional conference in Los Angeles, California and provided a workshop for educators from across the U.S. All workshop participants were given kits of materials to conduct activities in their classrooms.

Virtual Presentations

Throughout 2021, scientists and educators provided virtual programming through public talks, star parties, training for educators and scientists, and classroom visits. Collectively, scientists and educations provided dozens of virtual presentations to astronomy clubs, museums, K-12 and university classrooms, camps, professional societies, and large public events.

HANDS-ON OUTREACH
Teachers engage in hands-on activities featuring classification and Solar System objects.
Credit: Larry Lebofsky

PSI Continues To Expand in 2021

For nearly 50 years, PSI's strength and advantage continue to be in its people.
Our culture of openness and high level of mutual support distinguishes us as an organization.
In 2021 PSI continued to grow, adding 24 new research and administrative staff members

Macey Brown
Research Assistant

Jean-Philippe Combe
Senior Scientist

Justin Cowart
Postdoctoral Research Scientist

Alan Gillespie
Senior Scientist

Nancy Graziano
Senior Communication Specialist

Jonathan Lilly
Senior Scientist

August Luna
Junior Research Assistant

Erik Madaus
Science Writer

Tom McCord
Senior Scientist

Ashley Murphy
Postdoctoral Research Scientist

Scott Robinson
Senior Research Associate

Megan Russell
Research Associate

Antoniya Savcheva
Research Scientist

Stephen Schwartz
Research Scientist

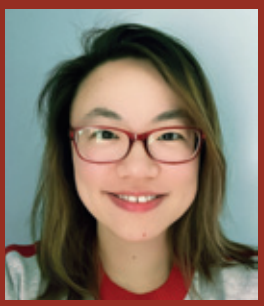
Zachary Smith
Research Assistant

Leslie Vittling
Senior Research Associate

Matthew Walker
Associate Research Scientist

Lucille Williamson
Research Assistant

David Woodard
Tech Support Analyst



Crystal Zhou
Senior Financial Analyst

NOT PICTURED:

Molly Crown
Research Intern

Karissa Herrera
Administrative Intern

Samara Imbeah
Research Assistant

Renee Summers
Administrative Associate

NEW PSI RESEARCH GRANTS

Oded Aharonson. Lunar topography and volatile stability from LOLA. NASA Lunar Reconnaissance Orbiter mission.

Peter Buhler. Do H_2O ice layers stabilize Mars' massive CO_2 ice deposit? NASA Mars Data Analysis program.

Sanlyn Buxner. Planetary resources and content heroes (ReaCH). NASA Science Activation program, Universities Space Research Association Subaward.

Matthew Chojnacki. Seasonal, annual, and multidirectional sand flux trends related to global or regional forcing factors. NASA Mars Data Analysis program.

Darby Dyar. Acquisition of a multi-parameter LIBS reference database of geological materials-PSI. NASA Planetary Data Archiving, Restoration, and Tools program.

Darby Dyar. Acquisition of a Raman microscope. NASA Planetary Major Equipment program.

Darby Dyar. VERITAS: Venus Emissivity, Radio Science, In SAR, Topography & Spectroscopy. NASA Discovery program. Jet Propulsion Laboratory subcontract.

Rebecca Ghent. The lunar rock-size frequency distribution: Implications for rock breakdown. NASA Lunar Data Analysis program. Jet Propulsion Laboratory subcontract.

Nader Haghighipour. Discovering circumbinary planets with TESS. NASA Transiting Exoplanet Survey Satellite program. SETI Institute subaward.

Nader Haghighipour. Dynamical evolution of circumbinary disks and embedded planets. NASA Exoplanets Research Program.

Nader Haghighipour. Discovering circumbinary planets with TESS. NASA Transiting Exoplanet Survey Satellite program. SETI Institute subaward.

Nader Haghighipour. Toward a realistic model of the formation of terrestrial planets and water delivery. National Science Foundation.

Candice Hansen. Trident: Mission to an exotic world mission phase A. NASA Discovery mission. Universities Space Research Association subcontract.

Candice Hansen. M2020 MastCam-Z support. NASA 2020 Mars Science Rover project. Arizona State University subcontract, Malin Space Science Systems subcontract.

Amanda Hendrix. HOLMS, Heterodyne OH Lunar Miniaturized Spectrometer. NASA Development and Advancement of Lunar Instrumentation program. Jet Propulsion Laboratory subcontract.

Amanda Hendrix. Detecting water on metallic M-type asteroids in the far-UV. NASA Hubble Space Telescope mission. Space Telescope Science Institute grant.

David Horvath. The climate, hydrology and limnology of Martian crater lakes: Implications for surface and subsurface habitability of Jezero crater and late Noachian/early Hesperian Mars. NASA Habitable Worlds program.

Elizabeth Jensen. MOST/FETCH antenna engineering design development software & hardware. NASA Multiview Observatory for Solar Terrestrial Science mission.

Catherine Johnson. InSight extended mission. NASA InSight mission. Jet Propulsion Laboratory subcontract.

Georgiana Kramer. CSA: Proposal/project consulting and color team review. ispace technologies U.S. inc.

Jian-Yang Li. The return of Rosetta's comet 67P/Churyumov-Gerasimenko. NASA Hubble Space Telescope mission. Space Telescope Science Institute grant.

Jian-Yang Li. The DART impact studied through characterization of the impact ejecta. NASA Double Asteroid Redirection Test mission.

Jian-Yang Li. Spectrophotometric modeling and mapping of young geological features on Ceres. NASA Discover Data Analysis program.

Jonathan Lilly. Global eddy-driven transport estimated from in situ Lagrangian observations. National Science Foundation.

Jonathan Lilly. Eddy dynamics from along-track altimetry. NASA Ocean Surface Topography Science Team program.

Scott Mest. The global geologic map of Ceres from Dawn. NASA Discovery Data Analysis program.

Alexander Morgan. Reconstructing basaltic sediment transport on Mars using terrestrial analogues. NASA Solar System Workings program.

Alexander Morgan. Do delta deposits around the crustal dichotomy record an ancient martian northern ocean? NASA Mars Data Analysis program. Dartmouth College subaward.

Alexander Morgan. Timing and spatial variability of post-Noachian fluvial erosion on Mars. NASA Ocean Surface Topography Science Team program. Smithsonian Institution subcontract.

Jeffrey Morgenthaler. Mass transport in Jupiter's magnetosphere–driven by internal or external processes? National Science Foundation.

Eric Palmer. Renewal for the Cooperative Agreement Notice–The Small Bodies Node of NASA's Planetary Data System with the Minor Planet Center. NASA Planetary Data System program.

Asmin Pathare. The modification of circumpolar craters in the Martian cryosphere. NASA Mars Data Analysis program.

Alex Patthoff. Europa's ice tectonics: First-principles and higher-order modeling. NASA Solar System Workings program. Jet Propulsion Laboratory subcontract.

Alex Patthoff. Unraveling Iapetus' tectonic and orbital history using polygonal impact craters. NASA Cassini Data Analysis Program. SETI Institute subaward.

Alex Patthoff. Building a global geologic map of Dione: Contributing to a comparative planetological framework for ocean worlds. NASA Planetary Data Archiving, Restoration, and Tools program.

Matthew Perry. Software Development Support Consulting Agreement. Space Hazards Applications, LLC.

Thomas Prettyman. Lunar polar hydrogen mapper–Part 2 (LunaH-Map) phase E and F. NASA Small Innovative Missions for Planetary Exploration program. Arizona State University subaward.

Nathaniel Putzig. Advance prospecting for the Mars Ice Mapper Mission. NASA Subsurface Water Ice Mapping On Mars program. Jet Propulsion Laboratory subcontract.

James Richardson. Using pit crater chains to probe regolith depth and development on asteroid 433 Eros. NASA Discovery Data Analysis program.

Alexis Rodriguez. Mars' mud volcanoes: Determining high-priority landing sites to search for evidence of life. NASA Advanced Rapid Imaging and Analysis program.

Alexis Rodriguez. Characterization of tsunami features and environments throughout the Martian northern plains. NASA Mars Data Analysis program.

Emilie Royer. Cassini ultraviolet visualization tool for satellites and rings. NASA Planetary Data Archiving, Restoration, and Tools program.

Nalin Samarasinha. Coma factory: A suite of tools to simulate, analyze, and interpret features in cometary comae. NASA Planetary Data Archiving, Restoration, and Tools program.

Norbert Schörghofer. Relation between cold traps and putative ice deposits. NASA Mars Data Analysis program.

Amanda Sickafoose. Studying small-body atmospheres through stellar occultations. NASA Solar System Observations program.

Matthew Siegler. Lunar Compact InfraRed Imaging System (LCIRiS). NASA

Lunar Surface Instrument and Technology Payloads program. University of Colorado subcontract.

Matthew Siegler. Passive radiometry for Martian subsurface temperatures and properties. NASA Mars 2020 mission.

Elizabeth Sklute. Reference database of ultraviolet through mid-infrared optical constants of minerals and glasses for planetary exploration. NASA Planetary Data Archiving, Restoration, and Tools program.

Sugata Tan. Habitability of hydrocarbon worlds: Titan and beyond. NASA Astrobiology Institute. Jet Propulsion Laboratory research support agreement.

Sugata Tan. Systematic study on the phase transition of confined fluid-mixture up to the critical region. U.S. Department of Energy. University of Wyoming subaward.

Matthew Walker. Technology for sending signals through the ice (STI Tech) on ocean worlds. NASA Concepts for Ocean Worlds Life Detection Technology program. John Hopkins Applied Physics Laboratory subaward.

John Weirich. Catalog of Saturnian satellite shape models. NASA Planetary Data Archiving, Restoration, and Tools program.

Catherine Weitz. Constraining the mineralogical, geochemical, and climatic history of Juventae Chasma. NASA Mars Data Analysis program. SETI Institute subaward.

Grace Wolf-Chase. Leveraging a Zooniverse discovery to diagnose a dominant mode of star formation and provide a CURE for introductory astronomy students. NASA Citizen Science Seed Funding program. The College of Idaho subaward.

Naoyuki Yamashita. Lunar geochemistry and prospecting with the KPLO Gamma-Ray Spectrometer. Korea Pathfinder Lunar Orbiter program.

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