Planetary Science Institute

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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 also are 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 31 states and the District of Columbia, and work from various international locations.

PSI BOARD OF TRUSTEES

ON THE COVER:
"Solar Prominences Seen from the Moon"

Acrylic painting by William K. Hartmann, co-founder and Senior Scientist Emeritus at the Planetary Science Institute. Hartmann reports that he got the idea for the painting by thinking about ways to add color to lunar landscapes.

During solar storms, red-glowing flame-like "prominences" extend outward from the Sun, as often seen during solar total eclipses. These would be visible from the Moon simply by stepping into the shadow of a mountain so as to block the overwhelmingly bright disk of the Sun. Since the Sun moves through the lunar sky about 28 times slower than it moves across the Earth's sky, large prominences, could be observed at your leisure!

MESSAGE FROM THE DIRECTOR: Challenges, Discoveries & Recognitions

2019 OPENED IN THE MIDST OF THE LONGEST GOVERNMENT SHUTDOWN IN HISTORY. Other organizations were having to shut down. Many NASA officials were furloughed. PSI gets half of its funding from grants, for which expenses are drawn down as they are incurred from a financial system managed the Department of Health and Human Services. During an earlier shutdown this system was suspended. This time it remained open. The other half of PSI funding comes from mission support, expenses which are recovered through invoicing. Fortunately, these invoices generally were still being paid (we were able to work around the exceptions). In anticipation of the shutdown, PSI had ensured it had the financial reserves and access to bank loans in the event regular funding mechanisms were interrupted.

This cannot go on forever, of course. At some point, further grant awards would have to be made, but those officials were no longer around. JPL announced that if the shutdown continued past January, it would have to reduce support for active missions. The ability to pay invoices would decline across these and other missions. American Solar System exploration would grind down and face the prospect of long-term damage. At that point, I traveled to Washington, D.C. for most of a week and met with numerous Senate delegations to explain to them the impact of a government shutdown on our national space efforts. The most common response was that they had no idea of the consequences to space exploration. Fortunately, in the middle of my last meeting, the shutdown came to an end.

EVERY YEAR, PSI SCIENTISTS MAKE REMARKABLE DISCOVERIES AND OTHERWISE IMPROVE OUR UNDERSTANDING OF THE SOLAR SYSTEM AND PLANET ON WHICH WE LIVE, its history and evolution, and the opening universe of thousands of Solar Systems around other stars. Given the fundamental instability of support for what we do, these advances in our knowledge are to be cherished and celebrated. A sample includes:

Senior Scientist Jeff Morgenthaler discovered that sodium emissions from Jupiter's moon Io provided a means of detecting volcanic eruptions that were otherwise undetectable using standard thermal emission techniques. Senior Scientist Julie Rathbun discovered a periodicity in Io eruptions that was previously unknown – understandable since the period is 540 days! These are all pieces to the puzzle of understanding how volcanism works on another world.

Senior Scientist Alexis Rodriguez has been constructing a dynamic model of early Mars, determining that the coast line of the ancient polar ocean on Mars was sculpted by tsunamis arising from asteroid impacts in the early Solar System. He also determined that the 1997 Mars Pathfinder landed on the spillway of an ancient sea that experienced catastrophic floods released from the planet's subsurface and its sediments. This could potentially yield evidence of habitability at that time.

Research Scientist Jamie Molaro, working with data from the OSIRIS-REx mission, helped make the first observations of thermal fracturing breaking down rocks on the asteroid Bennu. This is fundamental to interpreting both photometric and spectra reflectance of objects throughout the Solar System.

The future of human exploration of Mars will depend upon knowing the location of reliable sources of water. Two teams, led by Senior Scientists Than Putzig and Gareth Morgan, are combining radar, thermal, neutron, altimetry, and image data from several Mars-orbiting spacecraft to undertake a joint "Subsurface Water Ice Mapping" effort on Mars – yes, they are a "SWIM" team…

IT IS ALSO IMPORTANT TO ENGAGE THE PUBLIC IN WHAT WE DO. Senior Scientist Pamela Gay's CosmoQuest program provided a means by which the public was able to participate in mapping out the location of millions of rocks, boulders and craters on the surface of asteroid Bennu, to help identify a safe location for the OSIRIS-REx mission to collect a sample to return to Earth.

LOOKING TO THE FUTURE, Senior Scientist Aileen Yingst was awarded NASA funding to develop a new spacecraft-mounted camera system to return the first high-resolution video of landing plumes for upcoming missions to the Moon. She has named the system "Heimdall," who in Norse mythology was the watchman of the gods. Research Scientist Ryan Watkins is part of the team, bringing her experience studying the effects of rocket exhaust on planetary surfaces.

WE TAKE DEEP PRIDE WHEN OUR SCIENTISTS ARE RECOGNIZED FOR THEIR RESEARCH AND OTHER CONTRIBUTIONS TO SOLAR SYSTEM EXPLORATION. This year, Senior Scientist Michelle Thomsen was awarded the Arctowski Medal by the National Academy of Sciences and the American Geophysical Union's John Adam Fleming Medal. Senior Scientist Faith Vilas was honored with the American Geophysical Union Fred Whipple Award. Senior Scientist Catherine Johnson received the Royal Astronomical Society Price Medal and the Shen Kuo Award by the International Association of Geomagnetism and Aeronomy. Senior Scientist Pamela Gay was honored with the Isaac Asimov Science Award by the American Humanist Association. Their work stands as an inspiration to all of us.

— Mark V. Sykes

PSI SCIENTISTS GARNERED MANY PRESTIGIOUS AWARDS DURING 2019

Thomsen Honored with Two Major Awards

Michelle Thomsen was honored with two major awards in 2019: the American Geophysical Union's John Adam Fleming Medal and the National Academy of Sciences Arctowski Medal.

The Fleming Medal was for her seminal contributions to the understanding of collisionless shocks and the dynamics of the magnetospheres of Earth and the outer planets, and for selfless mentoring of a generation of scientists.

Thomsen's work includes the study of how shock waves operate in space plasmas, as well as the study of the ways in which material from the Sun, the upper atmosphere, and planetary moons is transported and accelerated within planetary magnetospheres. She is particularly interested in comparative magnetospheric studies, which address the relative importance of the same physical process operating in different magnetospheric environments.

Thomsen received the Arctowski Medal for her outstanding contributions to the study of solar physics and solar terrestrial relationships. She was cited for her "fundamental contributions to our understanding of the relationships between the Sun and its planetary bodies, with a particular emphasis on the physics of collisionless shocks and the dynamics of the planetary magnetospheres of Earth, Jupiter, and Saturn," the Academy said. Thomsen will receive a bronze medal, a $100,000 prize, and $100,000 to support research in solar physics and solar terrestrial relationships at an institution of her choice.

Vilas Receives Fred Whipple Award

Faith Vilas has been named the 2019 recipient of the Fred Whipple Award, the highest honor given by the Planetary Sciences section of the American Geophysical Union.

Vilas has during her more than 40-year career pioneered remote sensing of the Solar System, pushing its capabilities through instrument design and expert telescopic observations of a variety of Solar System targets. Vilas studies the surface composition of airless bodies including asteroids, the Moon, planetary satellites, and the planet Mercury. She has made ground-based visible wavelength spectroscopy her focus, and has excelled in pulling out small but telling spectral features in the spectra of these airless bodies.

Her groundbreaking work includes her discovery and analysis of subtle absorption features in reflectance spectra of darker – presumed primitive – asteroids. In particular, this includes a spectral feature centered near 0.7 μm, which is caused by light reflected from minerals created by water altering the structure and composition of underlying rocks – evidence of water's action throughout history in the asteroid belt.

Gay Recognized for Science Communications

Pamela Gay was honored with the American Humanist Association Isaac Asimov Science Award for her work in astronomy and technology, and for playing an important role in creating a more informed and progressive society by communicating science to the public.

Gay is an astronomer, writer, and podcaster focused on using new media to engage people in science and technology.

Gay is co-host of the Astronomy Cast podcast and one of the streamers for the CosmoQuestX Twitch channel, which are now programs at PSI. She leverages these platforms to educate people and invite them to do science on CosmoQuest.org. This website allows everyday people to map out other worlds and find the safe places to land a spacecraft and the scientifically interesting places to explore.

Sykes and Vilas Named AAS Legacy Fellows

Mark Sykes and **Faith Vilas** were made Legacy Fellows of the American Astronomical Society. The AAS Fellows program was established in 2019 to recognize AAS members for their contributions toward the Society's mission of enhancing and sharing humanity's scientific understanding of the universe. Fellows may be cited for original research and publication, innovative contributions to astronomical techniques or instrumentation, significant contributions to education and public outreach, and noteworthy service to astronomy and to the Society itself.

Johnson Receives Price Medal and Shen Kuo Award

Catherine Johnson received the Royal Astronomical Society's Price Medal. The Price Medal is awarded for single investigations or a series of closely-linked investigations of outstanding merit into the formation and composition of the Earth and/or planets in areas including seismology, tectonics, geodesy, geomagnetism, Solar System dynamics and meteoritics. Johnson was cited for outstanding research into the magnetism and geodynamics of Earth, the Moon, Venus, Mars and Mercury.

Johnson was also honored with the Shen Kuo Award by the International Association of Geomagnetism and Aeronomy, IAGA, for her outstanding interdisciplinary contributions to IAGA science. The Shen Kuo Award acknowledges outstanding scientists whose activities and achievements include fields of research covered by IAGA. Johnson was cited for her interdisciplinary contributions

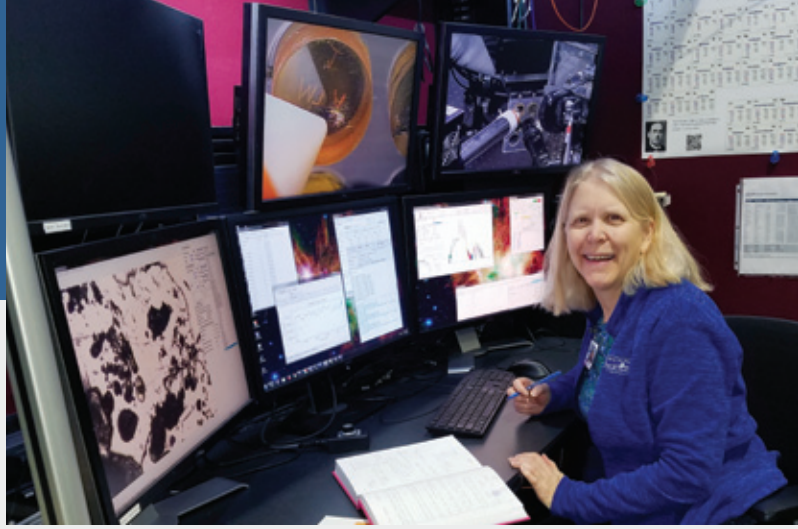
DYER TO INVESTIGATE PRISTINE LUNAR MATERIAL

Senior Scientist M. Darby Dyar has been selected by NASA to lead a team in the study of previously untouched lunar samples returned to Earth by NASA's Apollo spacecraft almost 50 years ago.

"This project brings massive state-of-the-art synchrotron and infrared analysis to bear on tiny lunar samples to unlock the secrets of the lunar interior," said Dyar, the principal investigator for the Spectroscopy Consortium Addressing Redox Acquired by Beads (SCARAB) project selected for funding by NASA. Dyar's team includes Steve Sutton and Antonio Lanzarotti of the University of Chicago, Molly McCanta at the University of Tennessee, and Sheila Seaman at the University of Massachusetts in Amherst.

"SCARAB will use tiny glass beads found in the lunar soil to turn the Moon inside out," said Dyar, who received the 2018 Eugene Shoemaker Distinguished Science Medal from NASA's Solar System Exploration Research Virtual Institute. "We will study the interior processes that lead to volcanism on the lunar surface. We will use state-of-the-art synchrotron technology and a mapping FTIR spectrometer to measure gradients of volatiles – hydrogen and oxygen – preserved in lunar glass beads.

"The beads are formed by rapid cooling of droplets from explosive lunar fire fountains, like those seen in Hawaii," she said. "We will map changes from core to rim that reveal hydrogen and oxygen pressures in the lunar interior and before, during, and after eruption."



DARBY DYER SELECTED BY NASA TO STUDY LUNAR MATERIAL
Senior Scientist Darby Dyar at the X-ray microprobe instrument at Beamline 13 IDE, Advanced Photon Source, Argonne National Laboratory, where she will study pristine lunar material. Photo credit: Molly McCanta.

The team will study pristine lunar volcanic glass beads in specially curated materials from Apollo 15, 16, and 17 that will be released by the Apollo Next Generation Sample Analysis (ANGSA) program. These samples have been locked up untouched since they were returned to Earth in 1971-72.

Results will be compared to previously studied samples, some of which have been exposed to air in the time since the 1970s, which will be analyzed using the same methods. Results will determine if chemical changes have taken place under terrestrial conditions despite our most careful curation procedures.

"I first studied lunar glasses as part of my Ph.D. thesis 40 years ago," Dyar said. "It's so exciting to return to this problem with new technologies I could never have imagined then. I'm thrilled and honored to be part of this new effort to analyze these specially curated samples."

that target a holistic understanding of bodies throughout the Solar System, particularly the magnetic field of the planet Mercury, and the Earth's magnetic field within the past 5 million years.

Hendrix Served as 2019 Global Scholar in Residence

Amanda Hendrix was named, and served as, the 2019 Global Scholar in Residence, at Holy Innocents' Episcopal School in Atlanta, Georgia.

PSI Scientists Receive NASA Honors Awards

A number of our scientists received NASA Honors Awards in 2019.

Rebecca M.E. Williams was a member of the MSL Extended Mission-1 Science and Operations Team cited for exceptional technical innovations and execution of rover surface operations leading to numerous, profound new discoveries about the ancient climate and habitability of Mars.

D. Alex Patthoff was honored as a member of the Europa Geologic Mapping Group for the production of a geologic map of Europa, which will provide a touchstone for planning, implementing and enhancing the scientific return from the Europa Clipper Mission.

The Dawn Science Team, which included **William C. Feldman, Margaret E. Landis, Lucille Le Corre, Jian-Yang Li, Scott Mest, David P. O'Brien, Thomas H. Prettyman, Norbert Schorghofer, Hanna G. Sizemore, Mark V. Sykes, Pasquale Tricarico, Naoyuki Yamashita** and **R. Aileen Yingst**, was honored for exceptional work in analyzing and interpreting Dawn's science data from the Ceres mission, breaking new ground in dwarf planet science, and rapid dissemination of results.

Candice Hansen was on the Enceladus Life Signatures and Habitability Team that received a NASA Group Achievement Award for outstanding achievements advancing life detection capabilities for Planetary Science, displaying technical and science expertise to enable a successful mission.

LUNAR WATER MOLECULES HOP AS SURFACE TEMPERATURE INCREASES

Small amounts of water are attached to lunar grains on the dayside of the Moon and migrate around depending on surface temperature, Senior Scientist Amanda Hendrix found.

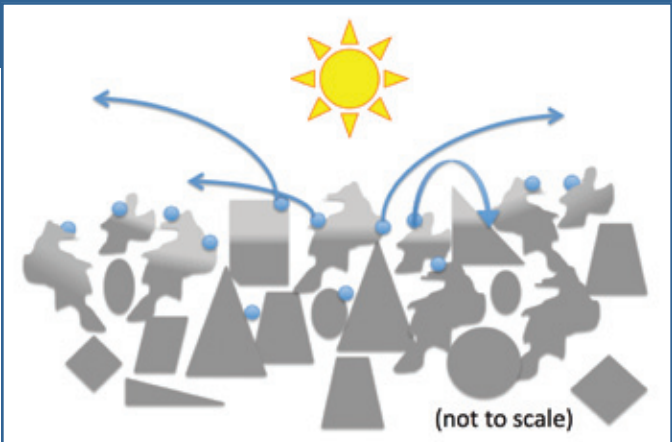
Data from NASA's Lunar Reconnaissance Orbiter (LRO) show that lunar water molecules can adhere to surface grains at night and through much of the day, and migrate around when the temperature reaches its peak at midday, says a paper in Geophysical Research Letters titled "Diurnally-Migrating Lunar Water: Evidence from Ultraviolet Data" on which Hendrix is lead author. Senior Scientist Faith Vilas is a co-author on the paper.

Data from the Lyman Alpha Mapping Project (LAMP) instrument aboard LRO are consistent with surface water on the Moon, varying with both terrain type and the local time and temperature, Hendrix said. LAMP is a far-ultraviolet (FUV) imaging spectrograph.

Data from the FUV spectrograph are used to measure the signature of a partial monolayer of water on the top surface of the lunar regolith. The diurnally-varying signature is interpreted as water molecules thermally desorbing close to local noon each day, when the surface temperature reaches a maximum value. These measurements represent the first time the UV absorption signature has been used to detect water at low latitudes on a rocky airless body, and are the only set of data currently providing diurnal coverage of lunar hydration.

"Variations in FUV spectra are attributed to a partial monolayer of water thermally absorbing and desorbing, controlled mainly by temperature," Hendrix said. "Lunar highlands regions are more hydrated than mare regions, likely due to the greater numbers of activation sites on the grains – these are locations on the lunar grains that can really hold on tightly to a water molecule."

A major source of water on the Moon is considered to be protons (hydrogen ions) in the solar wind. When the Moon passes through the magnetotail of the Earth – a region where the Moon is shielded from the solar wind – it is expected that this source of water essentially turns off. However, the new results show that the water observed by LAMP does not change when the Moon is in the magnetotail, suggesting that the water observed by LAMP is not being produced immediately by the solar wind, but rather builds up over time.



LUNAR SURFACE WATER MOLECULES
This cartoon representation shows how water molecules are sparsely attached to some grains at the top of the lunar surface. The molecules are tightly bound to the grains until surface temperatures reach their peak near local noon. At this poinr, the molecules thermally desorb and can move to a nearby location that is cold enough for the molecule to be stable, perhaps into the small shadow cast by a neighboring grain. The lunar grains are rough (and shaped irregularly), which may be related to how the molecules can remain tightly bound for much of the lunar day. Credit: Amanda Hendrix, PSI

"These results aid in understanding the lunar water cycle and will ultimately help us learn about accessibility of water that can be used by humans in future missions to the Moon," Hendrix said. "A source of water on the Moon could help make future crewed missions more sustainable and affordable. Lunar water can potentially be used by humans to make fuel or to use for radiation shielding or thermal management; if these materials do not need to be launched from Earth, that makes these future missions more affordable.

"But first we need to understand more about where the lunar water is and how accessible it is," Hendrix said. "We know that there is water frost in the permanently shadowed regions near the lunar poles. Does the water that LAMP observes at lower latitudes on the Moon bounce around and eventually make it to the cold polar regions?"

"This is an important new result about lunar water, a hot topic as our nation's space program returns a focus on lunar exploration," said Southwest Research Institute's Kurt Retherford, the principal investigator of the LRO LAMP instrument. "We recently converted the LAMP's light collection mode to measure reflected signals on the lunar dayside with more precision, allowing us to track more accurately where the water is and how much is present."

SODIUM, NOT HEAT, REVEALS VOLCANIC ACTIVITY ON JUPITER'S MOON IO

A large volcanic event was detected on Jupiter's moon Io using Jovian sodium nebula brightness variation, according to research by Senior Scientist Jeff Morgenthaler.

"These results highlight the growing body of evidence that the traditional way of monitoring Io's volcanism – by looking for temperature changes on its surface caused by hot lava – is not able to reliably find these large gas release events," said Morgenthaler, lead author on the Astrophysical Journal Letters paper "Large Volcanic Event on Io Inferred from Jovian Sodium Nebula Brightening." Senior Scientist Julie Rathbun is a co-author on the paper.

"Lack of a strong infrared counterpart to this event tells us something about the geology of Io. To use some well-known Earth analogies, this volcanic event may have been from an eruption more like that of Mount St. Helens in 1980, which released lots of gas and dust, rather than Kilauea's recent eruptions in Hawaii, which produced lots of hot lava," Morgenthaler said.

"The Io volcanic event occurred sometime between mid-December 2017 and early January 2018. Gas from the event filled Jupiter's magnetosphere, the region of space dominated by Jupiter's magnetic field, with excess material until early June," Morgenthaler said. "Io is the most volcanic body in the Solar System, so its volcanism is the ultimate source of the material. Interestingly, this event, which was the longest recorded by this technique, was not independently reported by any other Io volcanic monitoring technique, despite a significant number of observations in support of NASA's Juno mission."

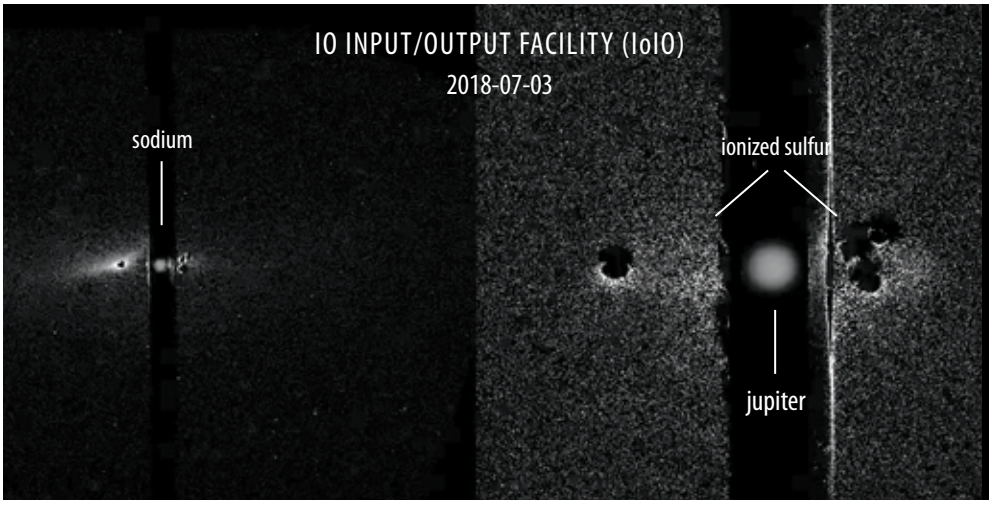
A small telescope popular with amateur astronomers, a 14-inch (35 cm) Celestron Schmidt-Cassegrain telescope, was used to detect the volcanic event. PSI's Io Input/Output facility (IoIO), hosted at the

SMALL TELESCOPE DETECTS VOLCANIC EVENT ON IO
IoIO consists of a 14-inch (35 cm) Celestron Schmidt-Cassegrain telescope feeding a custom-built coronagraph. An Astro-Physics 1100 mount, 80 mm offset guide scope, and associated software enable the system to acquire and guide on Solar System targets robotically.

San Pedro Observatory in Benson, Arizona, 40 miles east of Tucson is outfitted with a coronagraph, which reduces the intensity of the light from Jupiter and allows light coming from clouds of gas around Jupiter to be imaged through special filters.

"The immediate goal of the research is to better understand how ionized material moves in a rapidly rotating planetary magnetosphere," Morgenthaler said. "Ultimately, this project will help us understand all magnetospheres better. Since the Earth's magnetosphere protects us from some of the harmful effects of living relatively close to a star, this research does have some 'down home' applications."

By using equipment popular with high-end amateur astronomers, the project was able to take advantage of the low cost of mass-produced equipment. The project is funded by a National Science Foundation grant to PSI.



SCREEN SHOT OF PSI VIDEO ANIMATION
Visit https://www.psi.edu/sites/default/files/ftp/Na_SII_best_0.mp4 to see a video animation of sodium and ionized sulfur emission around Jupiter recorded by PSI's Io Input/Output facility (IoIO) over a three-month period. The animation shows the dynamic nature of the system: Io orbits Jupiter every 1.5 days and Jupiter rotates every 10 hours. The strong magnetic field of Jupiter traps the ring of sulfur ions, known as the Io plasma torus, shown in the right panel.

CITIZEN SCIENTISTS HELP MAP ASTEROID BENNU

When NASA's OSIRIS-REx mission spacecraft arrived at the asteroid Bennu, it discovered more rocks and boulders than envisioned. Mapping all these potential hazards was necessary to select a location to collect a sample of the surface for return to Earth. This effort was the work of multiple teams around the globe. One of those teams consisted of more than 3,500 citizen scientists who used CosmoQuest's Bennu Mappers project to mark rocks, measure boulders, and map craters. Together, they made more than 14 million annotations of features on a global map of Bennu. CosmoQuest is a project that is based at the Planetary Science Institute's Tucson, Ariz. headquarters (CosmoQuest.org).

These volunteers had no way of knowing in advance if the sites they studied and mapped would be the one selected as the final sampling site for the OSIRIS-REx spacecraft. Folks who saw images with fewer rocks could hope "This is it!" But first, they had to mark all the photos with hundreds of rocks and dozens of boulders so mission scientists could choose the images critical to site selection.

"It is amazing that more than 3,500 citizen scientists participated in CosmoQuest's project to map Bennu and help mission scientists find the best place for OSIRIS-REx to collect a sample," said Pamela L. Gay, Senior Scientist and Senior Education and Communication Specialist at PSI. "This kind of a volunteer effort makes it easier to find safe places to sample and scientifically interesting places to explore."

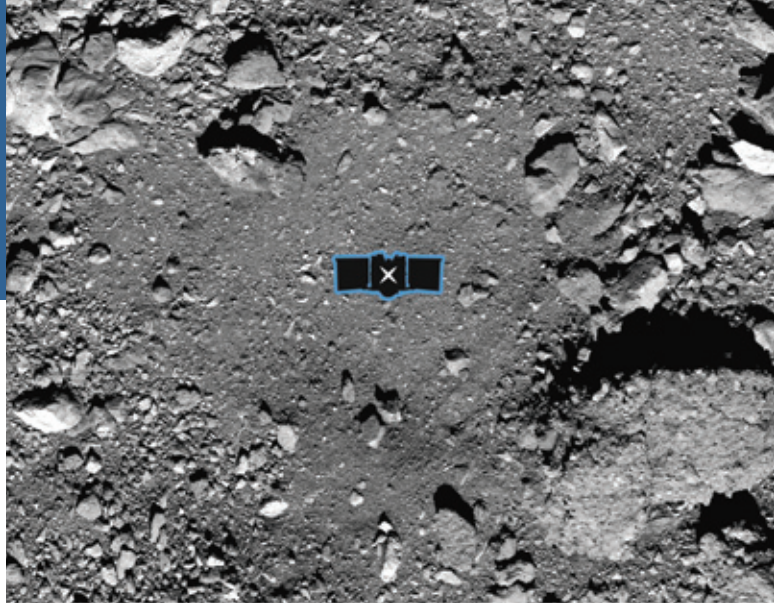
While the majority of people marked fewer than 10 images from the global mosaic, 68 volunteers marked 100 to 500 images, and 23 marked more than 500 pictures! Each image took as much as 45 minutes to complete, and these people put in weeks of individual effort during the four months it took to map this world.

Boulder Breakup Studied

In other Bennu activity, Research Scientist Jamie Molaro used high-resolution Bennu images from OSIRIS-REx to analyze the processes that break down boulders on the surfaces of airless bodies.

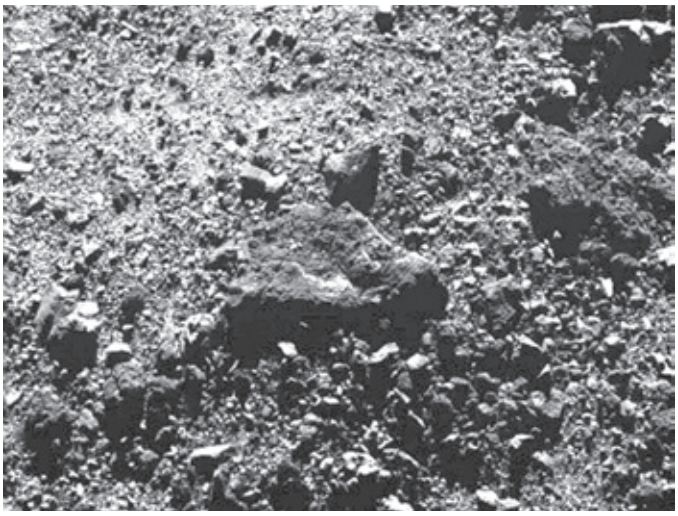
Breakdown can occur due to impacts on the surface, movement of boulders in landslides, and thermal fracturing. Thermal fracturing is a process where cracks can form in boulders due to heating and cooling from the Sun over time. This process is believed to be very important on certain objects in the Solar System. However, it is hard to observe because it happens at small scales.

"Based on what we're seeing in these images, we believe rock breakdown due to thermal fracturing is happening on Bennu. What is really exciting is that this is the first time we're observing direct evidence for this process on a planetary surface," Molaro said.



BENNU'S SAMPLE COLLECTION SITE NIGHTINGALE
This image shows sample site Nightingale, OSIRIS-REx's primary sample collection site on asteroid Bennu. The image is overlaid with a graphic of the OSIRIS-REx spacecraft to illustrate the scale of the site. Credit: NASA/Goddard/University of Arizona

Until OSIRIS-REx arrived at Bennu, scientists relied primarily on numerical models and laboratory studies to understand the nature of this process. They have learned that boulder size and composition play a big role in how thermal fracturing operates because it changes the boulder's response to heating and cooling. Now, the results from these computer models and laboratory studies can be compared directly to observations from the spacecraft, allowing scientists to better understand how it works to break down rocks and produce dust on asteroid surfaces.



BOULDER BREAKUP ON BENNU
The large boulder in the image center is approximately 28 meters across and has a somewhat round shape, though many smaller boulders surrounding it are very angular. Some of these appear to be fragments that may have disaggregated from the central boulder. Other boulders show signs of surface exfoliation and fractures that may have been caused by impacts, mechanical weathering, and other forms of rock breakdown. Credit: NASA/Goddard/University of Arizona

NASA DRAGONFLY MISSION TO STUDY TITAN FOR ORIGINS, SIGNS OF LIFE

Senior Scientists R. Aileen Yingst and Catherine Neish will be co-investigators on NASA's Dragonfly mission that will feature a drone-like rotorcraft lander to explore the prebiotic chemistry and habitability of dozens of sites on Saturn's moon Titan.

The Dragonfly mission, part of NASA's New Frontiers program, will sample materials and determine surface composition to investigate Titan's organic chemistry and habitability, monitor atmospheric and surface conditions, image landforms to investigate geological processes, and perform seismic studies.

Neish will study Titan's geology, with a particular focus on impact cratering, volcanism, and aqueous surface chemistry. Yingst will research what geologic processes have been – and currently are – active on Titan.

"Unlike other worlds we've landed on, Titan really has an otherworldly feel," Yingst said. "For a geologist, being able to study and remotely move around on the surface of a planet where water ice is as hard as rock, and liquid water would be considered a lava, is tremendously challenging and exciting."

"My Ph.D. dissertation investigated the creation of biological molecules on Titan's surface. Titan is a natural laboratory for the study of prebiotic molecules," Neish said. "I am thrilled to have the opportunity to 'collect the results' of these natural experiments as a part of the Dragonfly team."

Elizabeth Turtle, lead investigator on Dragonfly, worked at PSI from 2002-2006 and is now at the Johns Hopkins Applied Physics Laboratory, which manages the mission for NASA.

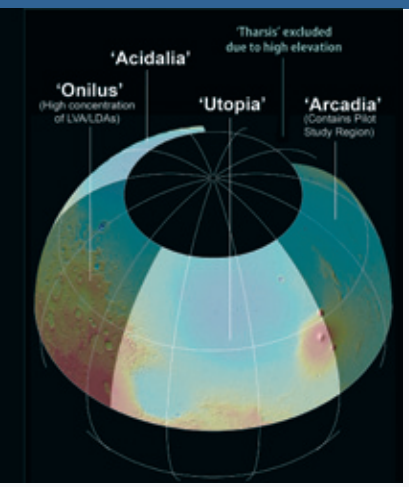
The mission is slated to launch in 2026 and reach Titan in 2034. Dragonfly is a drone the size of a rover used to investigate Mars. Rotors allow it to move about the surface of Titan.

Titan features water ice, methane, carbon-based molecules and energy needed for life. Dragonfly will investigate organic chemistry, habitability and the presence of past or current life.

New Frontiers is NASA's largest program of competitively selected planetary science missions. The program calls for a mission cost limit of $850 million for development, excluding launch and operation cost.

ARTIST 'S RENDERING OF NASA'S DRAGONFLY TITAN MISSION
Dragonfly is a dual-quadcopter lander that would take advantage of the environment on Titan to fly to multiple locations, some hundreds of miles apart, to sample materials and determine surface composition to investigate Titan's organic chemistry and habitability, monitor atmospheric and surface conditions, image landforms to investigate geological processes, and perform seismic studies. Credit: NASA/Johns Hopkins Applied Physics Laboratory

MARS EXPLORATION CONTINUES



SWIM Project Maps Potential Sources of Mars Water

Missions carrying humans to Mars will require on-site resources, and a project led by Senior Scientist Nathaniel Putzig and Research Scientist Gareth Morgan is mapping the availability of potential shallow water-ice sources across the surface of the Red Planet.

Two teams led by Putzig and Morgan mapping subsurface ice deposits in Arcadia Planitia were combined in a joint project called "Subsurface Water Ice Mapping (SWIM) on Mars," which extends the coverage of the mapping project from an experimental swath over Arcadia Planitia to all other low elevation regions across the Martian Northern Hemisphere. In addition to an expanded 'Arcadia' study region, the SWIM team has been contracted to map three other study regions: 'Acidalia,' 'Onilus,' and 'Utopia' regions shown in the accompanying figure.

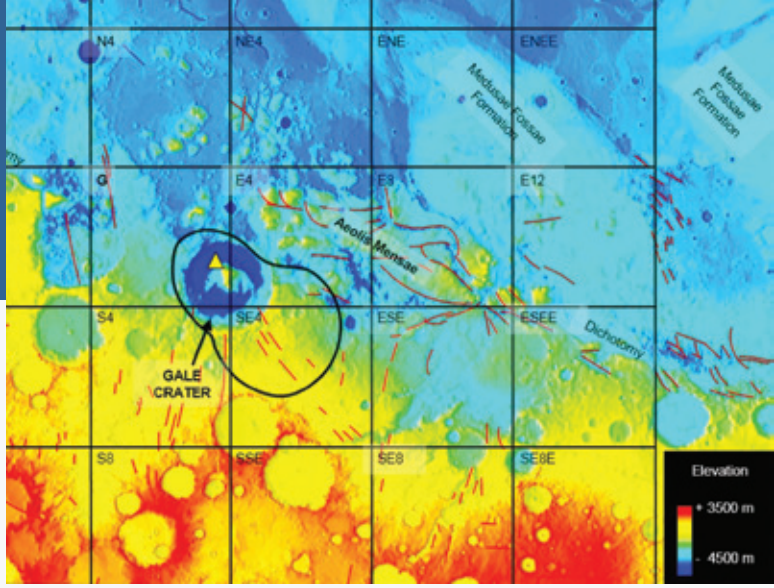
"Water ice will be a critical resource for human explorers on Mars, not only for life support but also for generating fuel to power equipment on the ground and rockets for the return journey to Earth," said Putzig. "Maps that identify the nature and availability of potential water resources will help determine where humanity will establish its first outposts on Mars."

Mysterious Mars Methane Bursts Confirmed

Martian methane releases are rare, episodic, and often debated, but Senior Scientist Dorothy Z. Oehler is involved in research that has discovered evidence of a methane emission in June 2013, which constitutes the first confirmation of a methane release on Mars.

Oehler is an author on two papers on methane detections in the Martian atmosphere: "Methane spikes, background seasonality and non-detections on Mars: A geological perspective" and "Independent confirmation of a methane spike on Mars and a source region east of Gale Crater."

Methane on Mars is of great interest, as subsurface accumulations could provide a resource for future exploration activities and it can enhance habitability. Methane could also be a signature of microbial, methane-generating life, though life is not required to explain these detections because methane can also be produced by abiotic processes.



LEFT: SUBSURFACE WATER ICE MAPPING PROJECT

The Subsurface Water Ice Mapping project is currently studying large expanses of the northern hemisphere of Mars to identify potential shallow water-ice resources. Work is focused in the four outlined regions, all of which exhibit evidence of ice such as Lineated Valley Fill (LVF) and Lobate Debris Aprons (LDA). Credit: Gareth Morgan

ABOVE: AREA OF METHANE DETECTIONS

Location map and regional setting of area of methane detections and potential source. Basemap of Mars Orbiter Laser Altimeter (MOLA) elevation on MOLA Hillshade. The black grid is the area of interest from atmospheric modelling. Red lines are extensional faults; blue lines are compressional faults. The black outline around Gale Crater is the envelope of Planetary Fourier Spectrometer footprints for orbit 12025. The yellow triangle is the location of the Curiosity rover. (Adapted from Giuranna et al., 2019.)

NASA Spacecraft May Have Explored the Edges of an Early Mars Sea in 1997

NASA's first rover mission to Mars, the Pathfinder, imaged an extraterrestrial marine spillover landscape 22 years ago, Senior Scientist Alexis Rodriguez said.

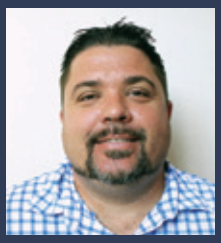
The landing site is on the spillway of an ancient sea that experienced catastrophic floods released from the planet's subsurface and its sediments. This could potentially yield evidence of Martian habitability, said Rodriguez, lead author on "The 1997 Mars Pathfinder Spacecraft Landing Site: Spillover Deposits from an Early Mars Inland Sea," which appears in Nature Scientific Reports. Senior Scientists Mark Sykes, Maria E. Banks and Jeff Kargel are co-authors on the paper.

"Our paper shows a basin, with roughly the surface area of California, that separates most of the gigantic Martian channels from the Pathfinder landing site. Debris or lava flows would have filled the basin before reaching the Pathfinder landing site. The very existence of the basin requires cataclysmic floods as the channels' primary formational mechanism," said Rodriguez. "Unlike on Earth, this sea was likely groundwater fed. If the ancient source aquifers hosted life, the proposed marine sedimentary materials at the Pathfinder landing site might contain a record of that life, a location easily accessible by future missions."

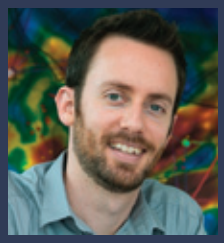
MARS LANDSCAPE | Credit: NASA/JPL/Cornell

PSI CONTINUES TO EXPAND IN 2019

As it has been for more than 45 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 2019 PSI continued to grow, adding 29 new research and administrative staff members.

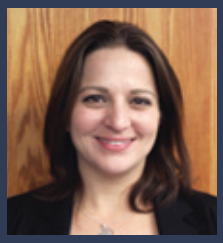


Nicholas D. Ambrose
Staff Accountant



Christopher Chance Amos
Research Associate

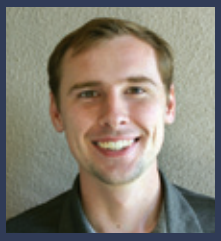
Samuel Wade Bell
Associate Research Scientist



Sarah R. Black
Associate Research Scientist

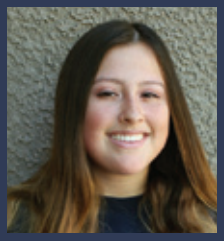
Nicholas R. Castle
Associate Research Scientist

Matthew F. Chojnacki
Research Scientist



Samuel Courville
Research Associate

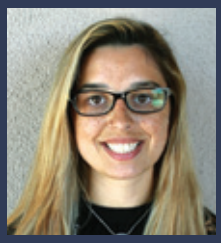
Miguel de Val-Borro
Associate Research Scientist



Estrella Herrera
Administrative Intern

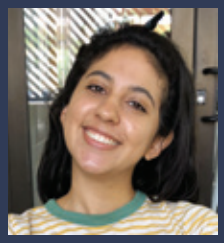
Austin Daniel Hinderliter
Junior Graphic Designer

Katelyn Jahnke
Junior Research Assistant

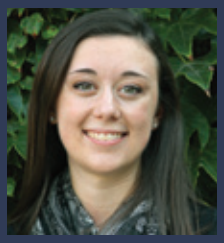


Kristina M. Lopez
Research Assistant

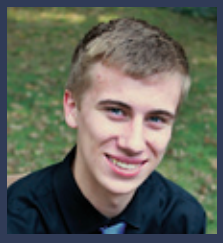
Yang Yang Lu
Junior Applications Developer



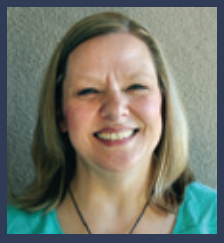
Angelica Martinez
Research Assistant



Caroline E. McCormick
Junior Research Assistant

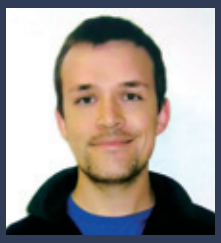


Collin Meyer
Junior Software Programmer

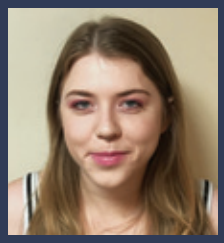


Susan M. Murph
Communication Specialist

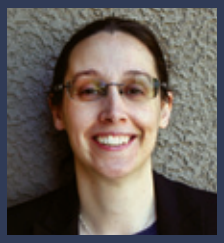
Joshua Nova-Yingst
Research Intern



Samuel Potter
Research Assistant

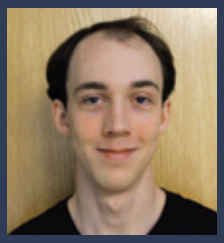


Lindsey Rollosson
Junior Research Assistant

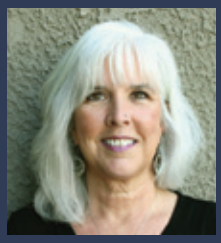


Emilie Royer
Research Scientist

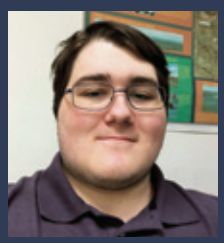
Amanda A. Sickafoose
Senior Scientist



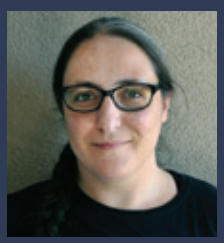
Aidan Stonum
Junior Infrastructure Specialist



Lori Lynn Stonum
Staff Accountant



Alexander Thompson
Computer Operator/ Programmer



Anastasia Marie Wilson
Communication Specialist

NOT PICTURED:

Tanner Alan Burge-Beckley
Lead Software Programmer

Matthew Ryan Forbes
Junior Research Assistant

Timothy Torres
Junior Software Programmer

PSI Education and Public Outreach

TOP: TUCSON FESTIVAL OF BOOKS

Education and Communication Support Specialist Thea Cañizo, left, discusses impact crater rocks with an attendee at the Tucson Festival of Books held at the University of Arizona Mall.

BOTTOM: FAMILY SCIFEST

A young attendee uses PSI's Infrared camera to view the heat signature of Research Assistant Maya Bakerman's hands at the Family SciFest event held at Children's Museum Tucson.

PSI supports many science education and public engagement projects that have a national and international reach. Currently, our scientists, education specialists, staff, and docents are based in 31 states, the District of Columbia, and several international locations. In 2019, PSI continued the program that supported Education and Public Outreach (EPO) through funding from the "Friends of PSI" program (see www.psi/support/friends for more info).

Programming in 2019 led by scientists and education outreach specialists ranged from large public talks, participation in international events, classroom and camp visits, and public outreach events across the U.S.

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

PSI Supported Celebrations for the Apollo 11 50th Year Anniversary

Senior Scientist and Senior Education and Communications Specialist Sanlyn Buxner, Senior Scientist Maria Banks, and high school volunteer Macey Brown participated in NASA's Apollo 11 50th Anniversary Outreach events on the National Mall in Washington, D.C. Buxner and Brown discussed lunar landing activity and talked about how NASA's Toolbox for Research and Exploration (TREX) program run by PSI is preparing for future lunar exploration.

Senior Scientist Amanda Hendrix gave a keynote presentation at the Apollopalooza Celebration at the Wings Over the Rockies Air & Space Museum in Denver, Colo.

Locally, PSI collaborated with the Arizona-Sonora Desert Museum to provide hands-on Moon-related activities. Hundreds of visitors engaged with staff and volunteers to talk about historical and current exploration of the Moon.

And in Seattle, Wash., Research Scientist Ryan Watkins was the featured presenter at the Lunar Block Party at the Museum of Flight. She also engaged visitors with 3D models and images of the lunar surface while talking about current and future exploration.

Local Tucson Outreach Events Are Popular

PSI's display at the Tucson Festival of Books attracted hundreds of visitors during the two-day event held on the University of Arizona Mall. PSI's exhibit, held in the event's Science City area, included hands-on activities featuring samples of meteorites and discussing Solar System exploration. Larry Lebofsky scheduled volunteers for the event, and participants included Maya Bakerman, Kevin Webster, Thea Cañizo, Stephen Ferris, Nalin Samarasinha, Sanlyn Buxner, Joe Spitale, and Bea Mueller.

PSI offered kids of all ages a chance to learn about meteorites, make UV bead bracelets, and use an infrared (IR) camera at the Eighth Annual Family SciFest event held at the Children's Museum Tucson. The event attracted over 2,200 visitors and featured hands-on activities presented by 39 exhibitors. Research Assistant Maya Bakerman and volunteer Mark Morris were kept busy throughout the event.

PSI scientists served as judges in science fairs such as the Southern Arizona Research, Science, and Engineering Foundation (SARSEF). Our display at the SARSEF Future Innovators' Night included a variety of hands-on activities for future scientists and their families.

Pamela Gay gave the keynote talk for the 2019 International Observe the Moon Night event held in Tucson at the University of Arizona Flandrau Science Center. Buxner and Brown provided hands-on lunar activities for the 10th annual worldwide event.

Our scientists and educators were active at Spacefest X held at the JW Marriott at Starr Pass resort in Tucson. Our display featured hands-on activities including a variety of meteorites and space rocks for attendees to study. Participants included Larry Lebofsky, Joe Spitale, Don Davis, and Thea Cañizo. Bill Hartmann showed some of his paintings at the event.

National Outreach Provided by PSI

Tom Prettyman curated a temporary exhibit on the NASA Dawn Mission for the New Mexico Museum of Natural History and Science (NMMNHS) in Albuquerque. The exhibit featured photographs, shape models, ion propulsion system information, maps and 3-D images, providing a spectacular, up-close look at Vesta and Ceres. The exhibit was viewed by nearly 500,000 visitors from all over the world.

PSI Fundraising and Development

The Planetary Science Institute is a nonprofit science research organization that secures its primary source of funding through competing for grants with NASA, the National Science Foundation, and other similar entities. Because this "soft money" is unpredictable, PSI also pursues alternate sources of revenue throughout the year.

In particular, we reach out to businesses and individuals to sustain the Institute's far-reaching education and public outreach efforts (EPO) that are led by PSI scientists across the country. These efforts include conducting science presentations at schools, science fairs, and other venues. The Institute provides scientists with the use of customized rock kits (durable cases that contain samples of meteorites and other rocks) to provide a powerful "show and tell" experience.

Throughout the year, PSI conducts a few different fundraising events and initiatives:

Annual Dinner

The PSI Annual Fundraising Dinner provides an opportunity for the Board of Trustees, local Tucson businesses, "Friends of PSI," and other donors to gather to show their support for the Institute. The evening features a cocktail hour, raffle, dinner, and a keynote presentation by a person who is active within the planetary science community.

This year's speaker was Pamela Gay, an astronomer, educator, writer, and well-known leader and pioneer in "Citizen Science" initiatives including CosmoQuest. Her popular weekly podcast, Astronomy Cast, takes listeners on a fact-based journey through the cosmos.

Table sponsors for the event included PSI Board members, PSI staff members, and local businesses that generously support the Institute's work.

A highlight of the evening was the raffle prize drawing that featured a large array of unique and fun items including a whitewater rafting trip, a resort weekend, a rare bottle of scotch, books by PSI authors, and much more.

Challenge Match Campaign

This year-end fundraising campaign is now in its fifth year and it has consistently delivered satisfying results for the Institute. In fact, the 2019 effort exceeded the campaign's goal by 78 percent.

To launch the 90-day campaign, a group of PSI supporters including Board members, scientists, staff, and "Friends of PSI" pledged the seed money to initiate the campaign. This year's campaign started with $12,000 and the goal was to raise funds to match that initial sum. The very successful campaign raised a total of $33,387 in unrestricted funds.

ANNUAL DINNER

Top: Dinner attendees peruse the array of raffle items on offer. Bottom: Featured speaker Pamela Gay, left, chats with PSI Board of Trustees member Erin Neal.

"Friends of PSI" Program

The Institute has a core group of supporters who form the "Friends of PSI" program. This group of individuals helps to further PSI's global research work through making an annual, tax-deductible membership donation. A "Friend of PSI" receives the PSI Quarterly Newsletter, a selection of PSI logo merchandise, a discount on tickets to the Annual Dinner, breaking news press release announcements, and alerts about interviews with PSI's scientists.

All revenue from this program is designated to support the Institute's nationwide education and public outreach (EPO) activities. PSI scientists volunteer their time within their own communities to conduct STEM-related activities for children and adults and serve as judges at science fairs.

Betty Pierazzo Fund

Created to honor the late Elizabeth Pierazzo, a PSI senior scientist, this program enables early-career scientists to attend a scientific conference of their choice. Two students are selected each year (one US-based, one International-based) and each receives a check of $2,000 to defray travel cost related to attending a scientific conference.

Belton Fund

Created by Dr. Michael and Mrs. Anna Don Belton, this fund supports a biennial symposium on Comets. The inaugural event is planned for 2021.

Grants and Business Sponsorships

Additional funding efforts include submitting grant applications and talking to Tucson-area businesses about supporting PSI's research and/or EPO efforts.

Other

PSI continues to partner with Amazon through the AmazonSmile program and a "PSI Gift Shop" is available on the PSI website.

THANK YOU TO OUR 2019 BENEFACTORS

With deep appreciation the Planetary Science Institute acknowledges the following individual and organizational benefactors who made contributions between Jan. 1, 2019 and Dec. 31, 2019.

$20,000 and up

Dr. Michelle Thomsen

$15,000-$19,999

Dr. Mark V. Sykes and Ms. Marilyn Guengerich

$2,000-$14,999

Mr. and Mrs. Maurizio and Tina Balistreri
Mr. Bruce Barnett and Ms. Tammi Palmer
Dr. Michael Belton and Ms. Anna Don
Dr. and Mrs. William and Gayle Hartmann
Dr. and Mrs. Tim and Carol Hunter

$1,000-$1,999

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Crest Insurance Group
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Mr. and Mrs. Alfred and Maria Anzaldua
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Dr. Thomas H. Prettyman
Dr. Nathaniel Putzig
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Dr. and Mrs. Stuart and Suzy Weidenschilling
Dr. Paul Weissman
Mr. Ross Nova and Dr. R. Aileen Yingst
Mr. and Mrs. David and Kelly Yoder

$1-$99

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Mr. and Dr. William and Kathleen Bethel
Mr. and Mrs. Bill and Ann Buckmaster
Mr. and Mrs. Donald and Darlene Burgess
Mr. Leon Byrd Jr and Ms. Patricia Roberts
Mr. John Cerney
Mr. Christopher Chyba
Ms. Ann Cleaves
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Mr. Howard Davis
Dr. Deborah Domingue Lorin
Mr. and Mrs. Bruce and Lynne Dusenberry
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Mr. Howard Frank
Dr. Rebecca Ghent and Ms. Penelope Radley
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Dr. Nadar Haghighipour and Ms. Ada Demleitner
Mr. Brian Halbrook
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Dr. and Mrs. Larry and Nancy Lebofsky
Ms. Kristin Leftwich
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Dr. and Mrs. Jonathan and Cynthia Lunine
Dr. and Mrs. Kurt and Elisabeth Marti
Dr. Ed McCullough
Dr. and Mrs. Robert and Carolyn Milkey
Mr. and Mrs. Lawrence and Ingrid Monrad
Mr. and Mrs. Jerry and Jeannine Neese
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Mr. Prentiss Sawyer
Mr. and Mrs. Geert and Renate Schmid-Schoenbein
Ms. Kathryn Schmoll
Mr. and Mrs. Dennis and Lynette Smith
Dr. Anna Spitz
Mr. Tarik Sultan
Dr. Sarah Sutton
Lt. Col. and Mrs. William and Marilyn Sykes
Mr. and Mrs. Nelson and Caryl Tilden
Mr. Maximilian von Unwerth
Dr. Kevin Webster
Mrs. Lynn Witry

PSI FINANCIAL REPORT

Bruce Barnett Chief Financial Officer

PSI continues to experience annual revenue growth with revenues totaling $15.2 million for the fiscal year ended September 30, 2019. During the fiscal year, PSI was actively involved in 114 prime awards issued directly from federal agencies and 148 subawards/ contracts issued through other institutions. 96 percent of all funding originated from NASA.

REVENUES

Grants and Contracts	$14,991,049
Contributions	198,030
Other	19,289
Total Revenues	$15,208,368

ACTIVE PROJECTS BY PRIME AWARDING AGENCY

NASA	244
NSF	5
USGS	1
Non-Federal	12
Total Projects	262

Salaries and related fringe benefits represent 71 percent of PSI's total expenses of $15 million. Operating expenses include $2.1 million paid on subawards to other institutions whose scientists are included on PSI prime awards. Program Services expenses were 89 percent of total expenses.

EXPENSES

Salaries and Benefits	$10,662,458
Operating	4,128,498
Depreciation	196,311
Interest	49,535
Total Expenses	$15,036,802

EXPENSES BY FUNCTION

Program Services	$13,408,222
Management & General	1,592,378
Fundraising	36,202
Total Expenses	$15,036,802

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, 2019 is reflected below.

Current Assets	$ 2,544,925
Property & Equipment, Net	1,079,614
Total Assets	$ 3,624,539

Current Liabilities	$ 1,911,371
Long-term Liabilities	862,385
Net Assets with Donor Restrictions	106,850
Net Assets without Donor Restrictions	743,933
Total Liabilities & Net Assets	$ 3,624,539

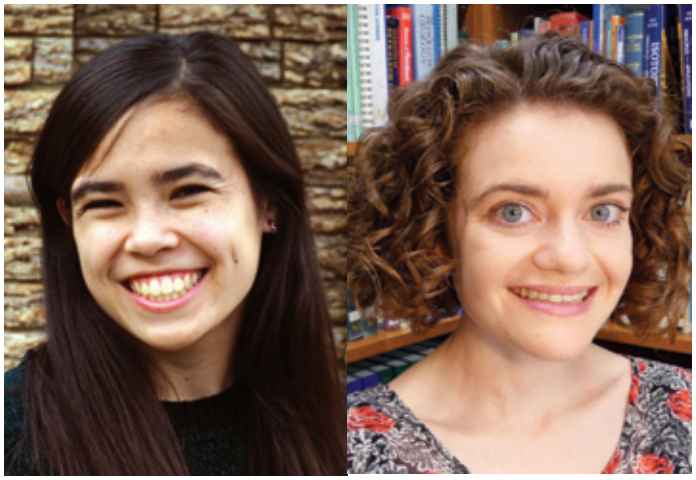
Rice and Kissick Named 2020 Pierazzo Award Winners

Malena Rice and Lucy Kissick were named winners of the 2020 Pierazzo International Student Travel Award. The Pierazzo 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.

Rice, of Yale University, will receive the award for a U.S.-based graduate student traveling to a planetary meeting outside the U.S. Her research is titled "Probing the Solar System with the Transiting Exoplanet Survey Satellite (TESS)," and she planned to attend the Expanding the Science of TESS workshop in Sydney, Australia, Feb. 10-14, 2020.

Kissick, of Oxford University, will receive the award for a non-U.S.-based graduate traveling to a planetary meeting within the U.S. Her research title is "The Sedimentary Archive of Atmospheric CO_2 on Mars" and she planned to attend the 51st Lunar and Planetary Science Conference in The Woodlands, Texas, March 16-20, 2020.

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



PIERAZZO AWARD WINNERS
Left: Malena Rice Right: Lucy Kissick

NEW PSI RESEARCH GRANTS

Natalia Artemieva. Assessing the formation and implications of self-secondary craters on Copernican impact ejecta. NASA Lunar Data Analysis program.

Susan Benecchi. The Solar System origins legacy survey. NASA Hubble Space Telescope program, Space Telescope Science Institute subcontract.

Sanlyn Buxner. Evaluation of the western regional Noyce alliance. San Francisco State University contract.

Roger Clark. Frontiers in dust mineralogical composition and its effects upon climate. Barcelona Supercomputing Center contract.

Roger Clark. Lunar Exploration Gas Spectrometer (LEGS). NASA Small Business Innovative Research program, Pioneer Astronautics subcontract.

Ryan Clegg-Watkins. Investigating the formation and evolution of the Moon's anorthositic crust. NASA Lunar Data Analysis program, University of Central Florida subaward.

David Crown. Placing terrestrial constraints on past Mars lava flow eruption conditions. NASA Solar System Workings program, University of Pittsburgh subaward.

Miguel de Val Borro. A Python package for small-body planetary astronomy. NASA Planetary Data Archiving, Restoration and Tools program, Lowell Observatory subaward.

Darby Dyar. Radiation hard and high temperature tolerant thermal imagers in a sparse array. NASA Planetary Instrument Concepts for the Advance of Solar System Observations program, Jet Propulsion Laboratory subcontract.

Darby Dyar. Spectroscopy Consortium Addressing Redox Acquired by Beads (SCARAB). NASA Apollo Next Generation Sample Analysis program.

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