THE PLANETARY SOCIETY

THE PLANETARY REPORT

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SMARTER ROBOTS

ARTIFICIAL INTELLIGENCE AIDS PLANETARY EXPLORATION

PLANETVAC TEST SUCCESS ✳ SAMPLE RETURN MISSIONS ✳ KICK ASTEROID CAMPAIGN

Seasons Change…

People often begin these letters by saying "It is with mixed feelings that I…retire/step down/move on…" Now I share those feelings. It's hard to say good-bye to a publication one has worked on for decades and to a work "family" that one loves.

But this is my last issue as editor of *The Planetary Report*.

Many of you know what it was like to be a member of this organization before the digital age changed everything. When the Society was founded, the public did not have easy access to space information and imagery. *The Planetary Report* was conceived as a way to connect our members with the people making space exploration happen. Here we shared the excitement of their discoveries. Now, almost four decades later, we're still doing that. And although the amount of information (space and otherwise) available today is mind-boggling, *The Planetary Report* remains unique among space publications.

Now it's someone else's turn to produce this magazine. On July 1, Emily Lakdawalla will be taking over as editor. You are in good hands. It will be exciting to see in what directions she takes us.

I am so grateful to have had a small part in advancing and celebrating the fruits of some of the most ambitious work that humans do. And I'm not done. Later this year I will return, part-time, to help continue archiving The Planetary Society's remarkable history.

In the meantime, I plan to enjoy having one of the most desirable things in the world to me—time. Time to spend with family and friends, to devote to personal projects, and to simply be more present to savor life on my favorite planet.

Thank you,

Donna Stevens

ON THE COVER: Three years into its time on Mars, *Curiosity*'s human operators uplinked artificial intelligence software onto its main computer, enabling the rover to choose for itself which rock targets to zap with its investigative laser beam. Thanks to this Autonomous Exploration for Gathering Increased Science (AEGIS) software, *Curiosity* can select promising targets without commands from the people who created it. This self-portrait of *Curiosity*, taken on Vera Rubin Ridge, is assembled from images taken by its Mars Hand Lens Imager (MAHLI) on January 23, 2018. The rim of Gale crater is visible at left (north) and right (south). *Image: NASA/JPL-Caltech/MSSS*

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Innovating and Legislating

We Work to Make It Happen

FOR MANY YEARS, planetary scientists have wanted to gather samples of rocks and soil from Mars, then return them to Earth where they can study the samples in the lab. As a reader of *The Planetary Report*, you probably have a pretty good idea of how extraordinarily difficult this might be.

So, could there be an easier way to gather samples of great value? We think so. In May, a group of us went out to the town of Mojave, California to watch as PlanetVac, a new planetary surface sampling technique, was successfully tested on a Xodiac rocket. This was a major step in moving a Planetary Society-supported project one step closer to flying in space someday. The Xodiac rocket lifted off, hovered and moved a short distance, and then landed PlanetVac in a bed of Mars soil simulant. Our little gizmo performed far better than expected (better than "nominal," as we say in the space biz). PlanetVac gathered hundreds of grams of sample.

These tests proved that Honeybee Robotics' PlanetVac could be adapted to a planetary lander, in this case replacing a landing foot of a Masten Space Systems Xodiac rocket. They also demonstrated that PlanetVac could survive and thrive attached to the hot, shaking environment of a rocket. The success of these tests will help make PlanetVac more likely to be selected to fly on future space missions. For me, the PlanetVac system is what we, The Planetary Society, do best in our technology programs. Our members—that's you—help scientists and engineers by kick-starting new and innovative technology. It's remarkable.

PlanetVac photos: Bruce Betts

Speaking of innovative technology, our *Lightsail 2* solar sail spacecraft is buttoned up and ready to ship to Florida for launch on SpaceX's Falcon Heavy rocket. Bruce Betts was there for the integration. Read his report on page 20. If you have a chance to make it to Cape Canaveral (the launch is slated for no earlier than October 30, 2018), consider joining us in Florida. We'll be there, sending *Lightsail 2* to a higher orbit, where it will maneuver in a way that *Lightsail 1* could not. We'll increase our orbital energy, and we will record many images that will help us to understand the sail's performance. But mainly (for me, at least), we will show the world that this technology is viable, remarkably inexpensive compared with fueled spacecraft, and just plain beautiful. Thanks to all of you for supporting LightSail and solar sail technology. We hope to see you at the launch.

Since our earliest days, one drum the Society has banged consistently is to alert Earth's citizens to the need for technology that can prevent our planet from being smashed into by an incoming space rock. Every day, over 100 tons of space rocks and dust strike our planet's atmosphere. Most of these meteors burn up harmlessly high above Earth. We simply enjoy the show as they blaze across the night sky. But every few thousand years or so, an asteroid the size of a football field hits Earth. As you can imagine, these impacts cause significant damage. And, on top of that, every few million years or so, a larger object comes along that could threaten our entire civilization. To raise awareness, we've launched a new planetary defense campaign called Kick Asteroid! Check out page 19 for how you can become an active defender of Earth.

As you may have noticed, we have been putting a good deal of energy into our advocacy efforts in Washington, D.C. and it has been paying off. Our Planetary Science Caucus in the U.S. Congress has, as of this writing, 32 members. That's a large enough bloc of lawmakers to ensure that funding for planetary science missions gets put in place year after year.

Our engagement with lawmakers on Capitol Hill in Washington has also led to a relationship with Jim Bridenstine, who was recently confirmed as the new administrator of NASA. Although we probably disagree about some things, the administrator and I agree on the importance of space exploration. In early June, the Space Policy team and I met with him in his office on the top floor of NASA headquarters. It's really something when the head of NASA seeks your advice. We agreed to meet at least twice a year.

Antonio Peronace for The Planetary Society

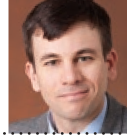
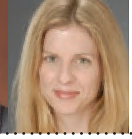
In the big picture, this means that we can do more exploring sooner. For me, it means the chance that we'll find life on another world in my lifetime is more likely than ever. And it means that humankind has a better and better chance of finding a potentially disaster-causing asteroid and designing the systems we need to give it a nudge. We've been doing the technical research and engaging the right people to shape our future in space. And we can do all of this because of you and your support. I can't say it enough—thank you!

Let's not just "change the world"… let's save it!

Bill Nye

OPPOSITE PAGE *The Masten Xodiac rocket carrying PlanetVac (visible here as the rocket's left foot) successfully blasts off.*

ABOVE *Bill Nye addresses the crowd at the congressional planetary science caucus event in Washington, D.C. on May 9, 2018.*

RAYMOND FRANCIS *is the lead system engineer for the AEGIS autonomous science system for* Curiosity*'s ChemCam.*
TARA ESTLIN *is the supervisor of the Machine Learning and Instrument Autonomy group at JPL. She leads the AEGIS project onboard the* Curiosity *and* Opportunity *rovers.*

Automating Science on Mars

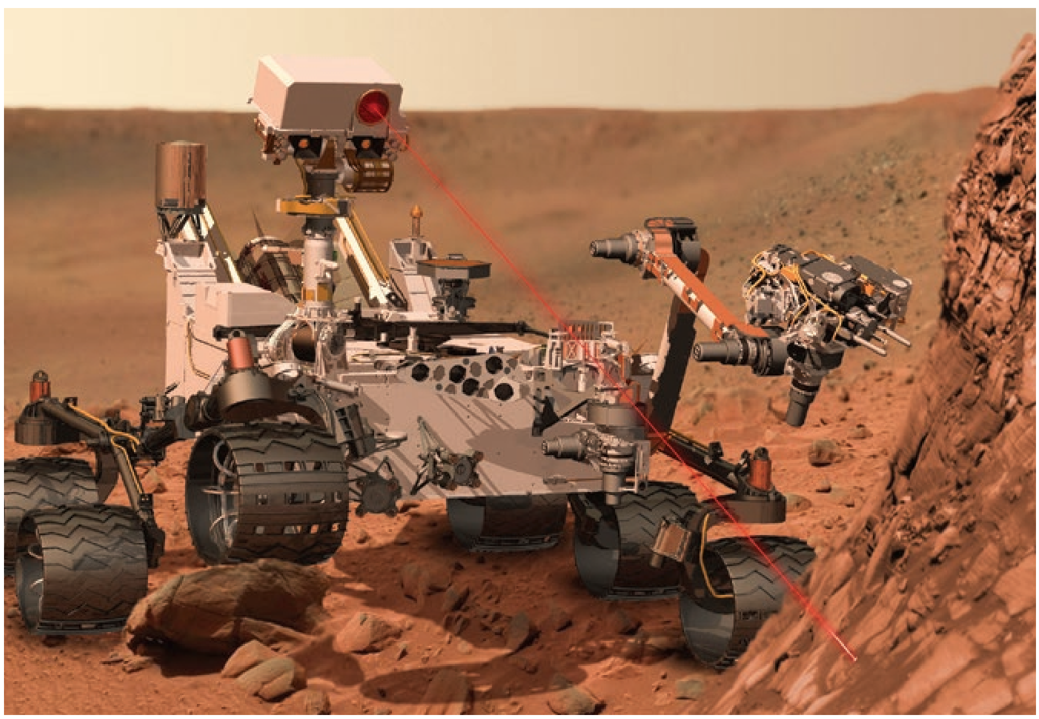
Artificial Intelligence for *Curiosity* and *Opportunity*

NASA HAS SENT a robot to Mars that autonomously picks out targets to zap with its laser, blasting a little bit of rock to plasma. It's for science!

Since 2016, NASA's *Curiosity* Mars rover has had the ability to choose its own science targets, using an onboard intelligent-targeting system called AEGIS (for Automated Exploration for Gathering Increased Science). The AEGIS software can analyze images from onboard cameras, identify geological features of interest, prioritize and select among them, and then point the rover's ChemCam instrument at selected targets to make scientific measurements.

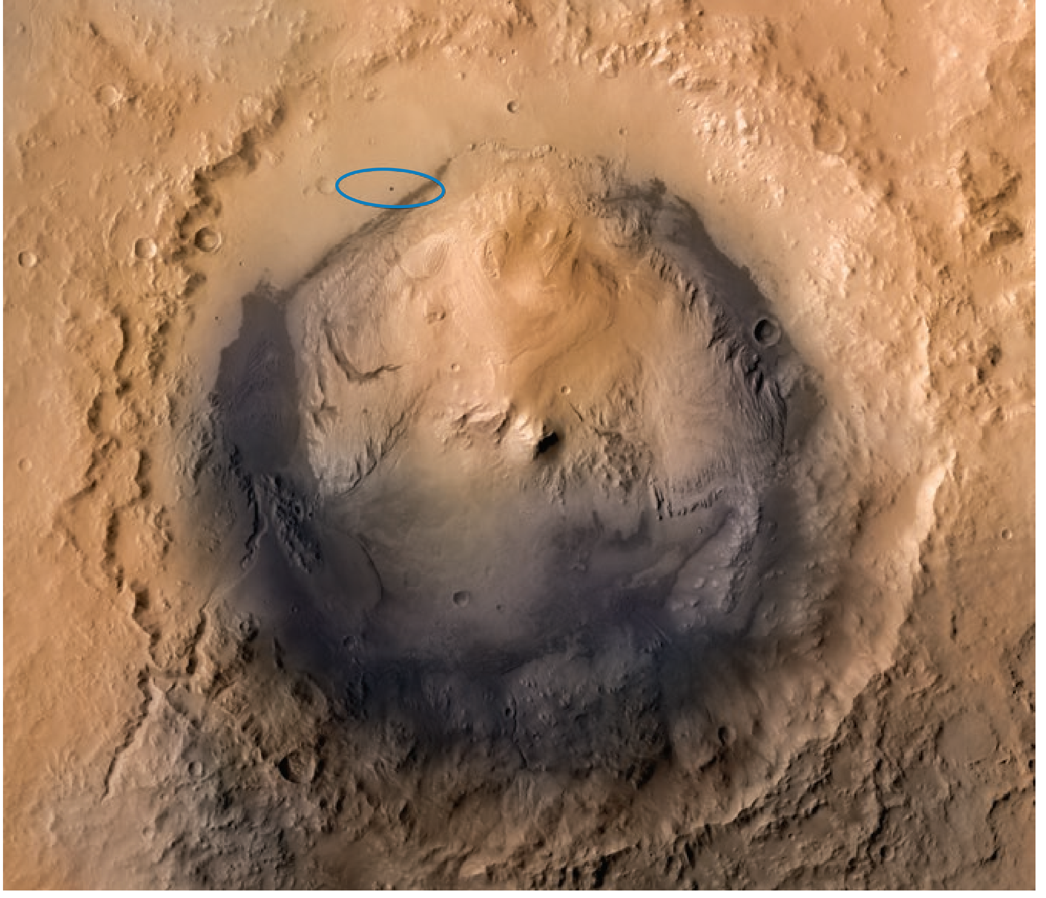
Autonomous targeting, without Earth in the loop, is a new way to operate a scientific mission. It has become a routine part of the *Mars Science Laboratory (MSL)* science team's strategy for exploring the ancient sedimentary rocks of Gale crater.

AEGIS is an example of what we call "science autonomy," where the spacecraft (the rover in this case) can make certain decisions on its own about scientific measurements and data – choosing which measurements to make or, having made them, which to transmit to Earth. This is distinct from autonomy in navigation or in managing onboard systems, both of which *Curiosity* can also do. In a solar



RIGHT *In its nearly six years on Mars,* Curiosity *has pointed the laser in its Chemistry and Camera (ChemCam) at over 1,700 rocks to vaporize samples and then analyze their compositions. The rover can decide for itself which targets to strike.*

Illustration: NASA/JPL-Caltech



LEFT *Much of the history of Mars' formation is written on the walls and central peak of Gale crater. Gale, as* Curiosity *has confirmed, once contained a series of lakes as well as the right physical and chemical conditions for hosting life.* Curiosity*'s Automated Exploration for Gathering Increased Science (AEGIS) software vastly improves its ability to sample the right spots. This view of Gale is composed of data from* Mars Express, Mars Reconnaissance Orbiter*, and* Viking Orbiter. Curiosity*'s landing ellipse, which is 20 by 7 kilometers (12 by 4 miles) in size, is shown at upper left.*

Image: NASA/JPL-Caltech/ESA/DLR/FU Berlin/MSSS

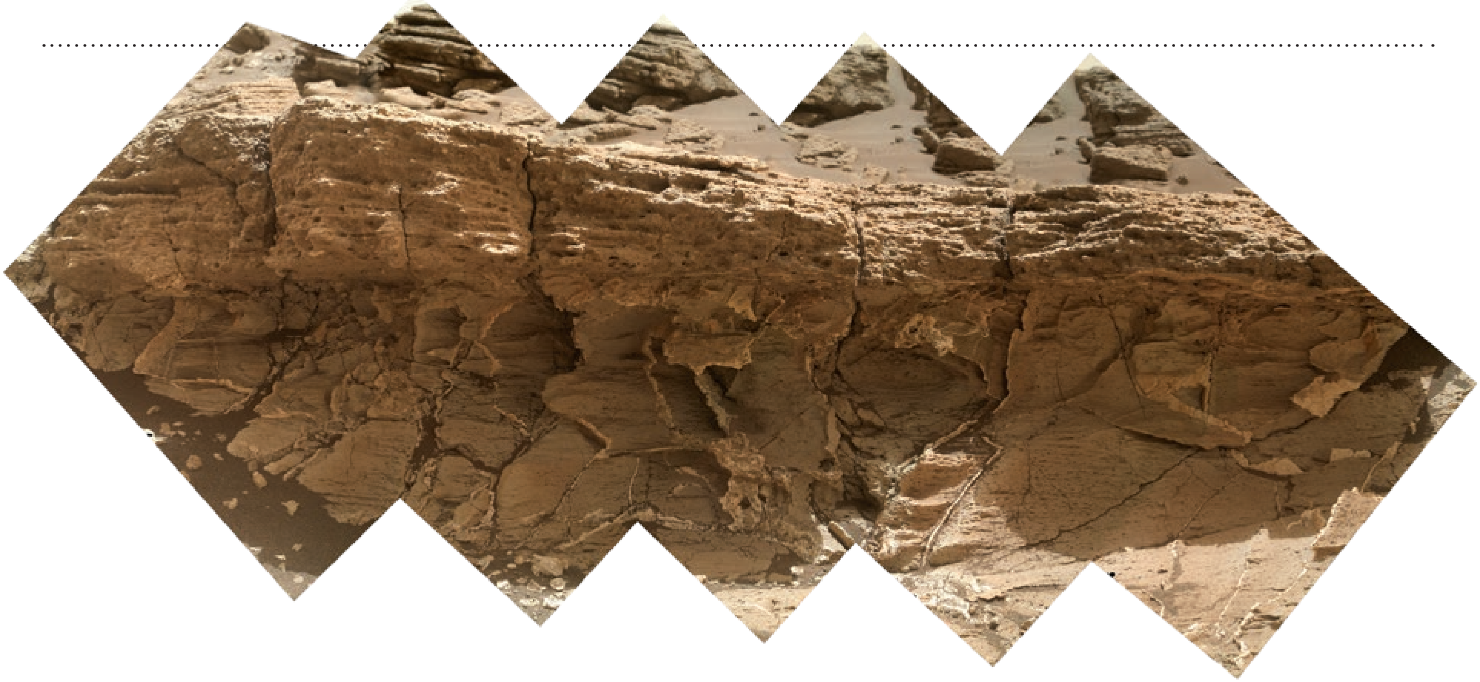
system that's tens to hundreds of light-minutes across, science autonomy allows us to make measurements that can't be made if humans must be consulted first and to make use of idle periods when our robotic explorers would otherwise be waiting for instructions.

WHY

A typical activity plan for a rover includes a period of targeted science observations followed by a drive to a new location and post-drive science activities. The first period involves the science team on Earth making decisions about where to point instruments in order to study particular surface features. To make those choices, the team has to see the features in images downlinked from the rover. Images from the rover's location after the end of a drive aren't available on Earth until shortly before the next day's operations, so post-drive science activities are limited to observations that don't need fine targeting. These include: wide-field panoramas, images of the Sun or the sky for atmospheric studies, analyses with the onboard geochemical lab instruments, etcetera. But with intelligent, autonomous targeting by AEGIS, we are able to use post-drive time for ChemCam measurements, getting a head start on the next day's work. This capability increases the amount of ChemCam data we can gather before driving away again.

Another challenge of targeted science is fine pointing. Some of the most interesting features are the smallest ones—the calcium sulfate veins found in rocks along the rover's traverse, for example, have revealed important insights about the chemistry of the watery environment in Gale's past. These veins are often less than 5 millimeters wide, which means that a pointing error of only a fraction of a degree can mean missing them

RAYMOND FRANCIS *conducts research in new techniques for autonomous science and the mission design and operations consequences of increased autonomy capabilities. He tests proposed techniques in terrestrial analogue environments from Canada's high arctic to California's hot deserts.* **TARA ESTLIN** *is supervisor of the JPL Machine Learning and Instrument Autonomy group. She leads the AEGIS project, which is providing intelligent targeting technology for multiple Mars rover missions. She is also part of the Mars 2020 rover mission team that is developing and testing multiple new autonomy algorithms for use on that mission.*



ABOVE *Insights about the chemistry of Mars' watery past are tucked away in some of its smaller surface features, such as the white veins of calcium sulfate visible at the bottom of this rocky outcrop. The feature, called Missoula, was imaged by* Curiosity*'s Mars Hand Lens Imager (MAHLI). The white veins formed when groundwater flowed into fractures, depositing calcium sulfate minerals. This view is about 40 centimeters (16 inches) across.*

RIGHT *ChemCam is mounted on* Curiosity*'s remote sensing mast. The large, round aperture is the mirror that focuses the Laser-Induced Breakdown Spectrometer (LIBS) and the Remote Micro-Imager (RMI).*

with ChemCam from a few meters away. It's hard to pinpoint such small targets. Our stereo model of the rover's surroundings (made from NavCam images) has resolution limits, and we can only control the motion of the mast so precisely. With AEGIS, we can order autonomous pointing refinement, where the software corrects small errors in the pointing, ensuring we hit the desired targets on the first try (and saving valuable time on Mars).

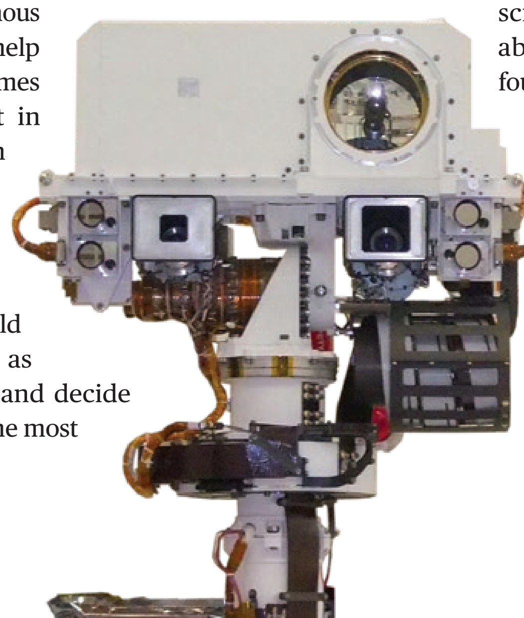
HISTORY

AEGIS began in the early 2000s as part of a Jet Propulsion Laboratory (JPL) research project. This effort developed a suite of integrated rover technologies, including autonomous navigation, onboard commanding and re-planning, and autonomous science.

The goal of the autonomous science element was to help scientists collect data at times when the rover wasn't in frequent communication with Earth. Several planetary geologists worked closely with the project to help us design software that could identify features (such as rocks) in visual images and decide which targets would be the most interesting to scientists.

Project technology was tested extensively on multiple research rovers in the JPL Mars Yard. Testing of the autonomous science element, which was eventually called AEGIS, typically involved identifying various terrain features (such as volcanic rocks or an ancient river bed) during a rover drive and then working with other autonomy software to redirect rover activities toward the identified science targets.

Based on the results of this project, the Mars Exploration Rover (MER) mission authorized AEGIS to be uploaded to the *Opportunity* rover in 2009. AEGIS has since been used to identify targets for MER's narrow-field-of-view Panoramic Camera, a high-resolution, multi-spectral imager that acquires images at various wavelengths. These images help scientists learn more about the minerals found in Martian rocks and soils. AEGIS was used on MER to collect Pancam data at times when data collection—on outcrops, cobbles, crater ejecta, and boulders—would not have been possible otherwise.



Above image: NASA/JPL-Caltech/MSSS; lower photo: Emily Lakdawalla

CHEMCAM

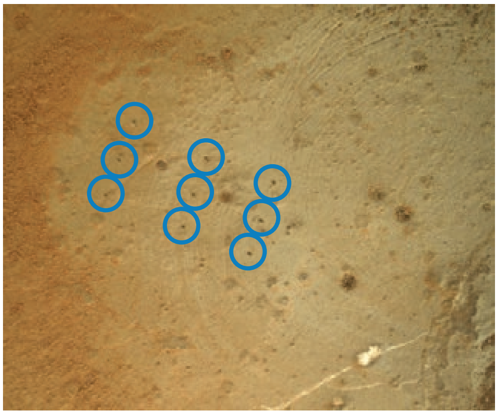
Following its success on MER, the AEGIS system went to work for the *Mars Science Laboratory*, especially for the ChemCam instrument. ChemCam is a perfect candidate for AEGIS intelligent targeting. The instrument combines a Laser-Induced Breakdown Spectrometer (LIBS) with a context camera called the Remote Micro-Imager (RMI). The RMI has a very narrow field of view, about 1 degree in diameter, which gives a high-resolution view of the LIBS targets. The LIBS focuses on rocks and soils as far away as 7 meters from the rover and captures spectra from the plasma produced by the powerful laser. The sampled spot is typically less than 1 millimeter across, so targeting is important—you want that spot to fall on something interesting.

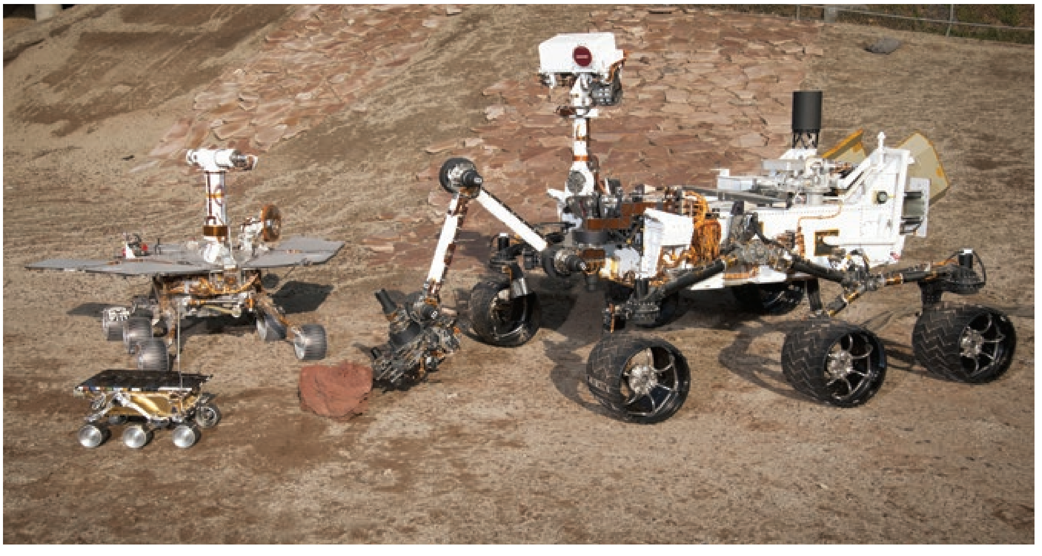
A typical ChemCam observation combines a LIBS raster (several LIBS shots on each of a series of points clustered together on a target) with before-and-after RMI images and sometimes intermediate RMIs. The science team uses ChemCam often, typically measuring several targets each time the rover stops to sample the variety of materials we observe. It's important to get ChemCam data frequently along the rover's traverse, so we have a rich geochemical survey of the terrain over distance and elevation changes.

Precise targeting and more frequent observations are benefits of automatic science data collection, made possible by AEGIS.

HOW AEGIS WORKS

The AEGIS autonomous targeting process begins with taking a source image—a photo by an onboard camera (either the NavCam or RMI). AEGIS computer vision algorithms then analyze the image to find suitable targets for follow-up observations. On MER and *MSL*, AEGIS uses an algorithm called Rockster, which looks for discrete objects by a combination of edge-detection, edge-segment grouping, and morphological operations—in short, it finds sharp edges in the images and seeks to group them into closed contours. Built originally to find

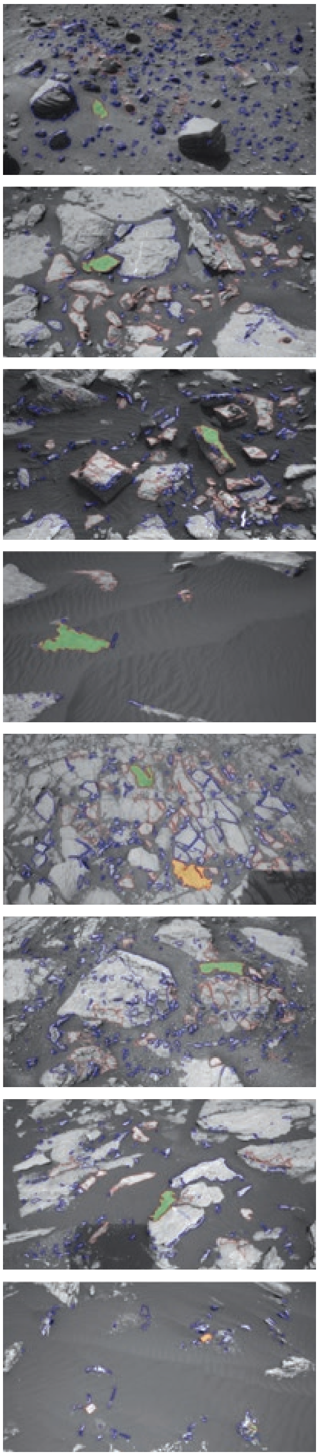




TOP *This image shows multiple tiny marks left on a Martian rock by ChemCam's laser.*

BOTTOM *AEGIS technology has been tested on several research rovers, including* Curiosity*'s terrestrial twin, in JPL's Vehicle System Testbed, also known as the "Mars Yard." This outdoor area has been outfitted with rocks and soils to resemble a few of the Red Planet's varied surface features.*

Both photos this page: NASA/JPL/Caltech



float rocks on a sandy or gravelly background, Rockster has proved remarkably versatile in finding a variety of geological target types.

Analyzing potential targets it has identified in an image, AEGIS inspects the pixels enclosed within their boundaries and generates a list of properties—average brightness, overall shape, distance from the rover (using NavCam stereo), and more. The system can then filter out targets based on defined criteria (rocks that are too small or too far away for ChemCam's 7-meter range, for example). AEGIS ranks targets according to an optimum set of parameters set by the science team (and adjustable for each run). This combination of imaging, target-finding, filtering, and ranking leads to a "scene profile," which guides AEGIS users to find different types of targets in different environments. Many such profiles can be defined for different science goals and can be adjusted as the rover drives into new terrain with new geological materials.

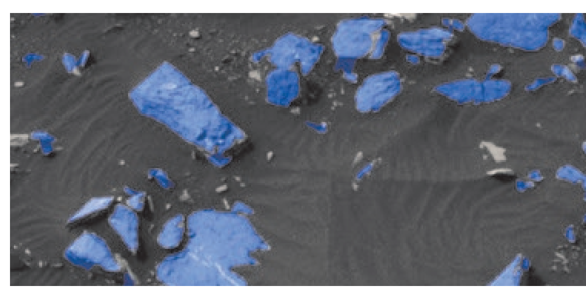
Rarely mentioned but essential to the system's use are built-in safety routines to protect both *Curiosity* and ChemCam. The LIBS laser is powerful enough that shooting at the rover could damage the vehicle, so AEGIS includes checks to ensure it never picks a target on or too near the rover. ChemCam's laser is focused through a telescope which, if pointed at the Sun, could cause damage to the instrument. AEGIS programming includes a step to exclude targets too near the Sun—a surprising but real risk, even when pointing at rocks on the ground.

GETTING UP TO SPEED ABOARD *MSL*

In preparation for the *MSL* mission, AEGIS had to be adapted to work with ChemCam, processing RMI images and targeting the LIBS laser. The system was tested at JPL on the Vehicle System Testbed (Mars Yard) using the *Curiosity* rover's well-known terrestrial twin. The tests demonstrated the software could run in parallel with other typical operations on the rover. Importantly, they also confirmed the safety checks for laser and Sun safety. After these tests, AEGIS was uploaded to *MSL* and installed in the rover's flight software in October 2015.

A suite of checkouts on Mars confirmed the system's safe and accurate behavior over a period of months. These checks were run as a series of experiments in which the software processed images under various conditions, selecting targets and gradually being given more authority to issue commands based on its analyses and decisions. The process culminated in a full test in which AEGIS analyzed images, selected targets, pointed ChemCam, and fired the laser in a series of pulses, as occurs during standard scientific measurements.

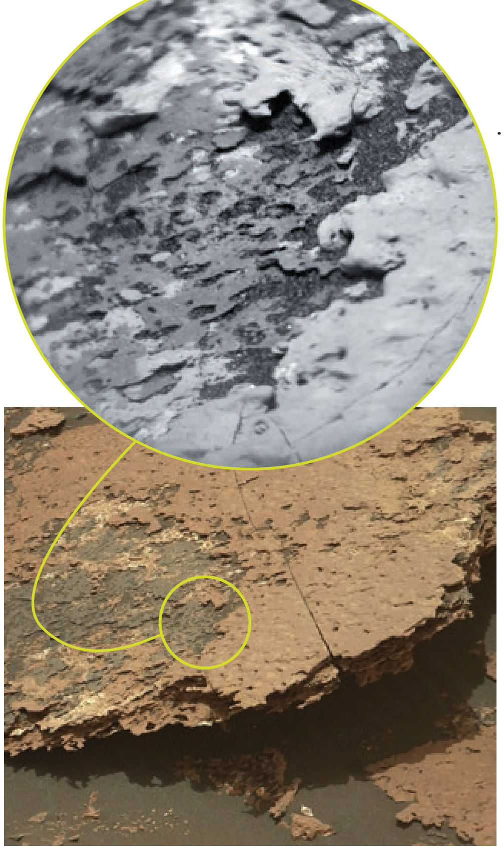
These checkouts took place over several months, partly to allow the AEGIS team to assess performance after each round, but also to fit in-between ongoing activities of the *MSL* science mission. Time on Mars is valuable, and AEGIS came aboard *MSL* just prior to the first phase of the Bagnold Dunes Campaign (January 2016). Checkouts of AEGIS were completed by February 2016. After training for mission scientists, the rover ops team, and the ChemCam ops team, AEGIS was released for use in routine science operations in May 2016.

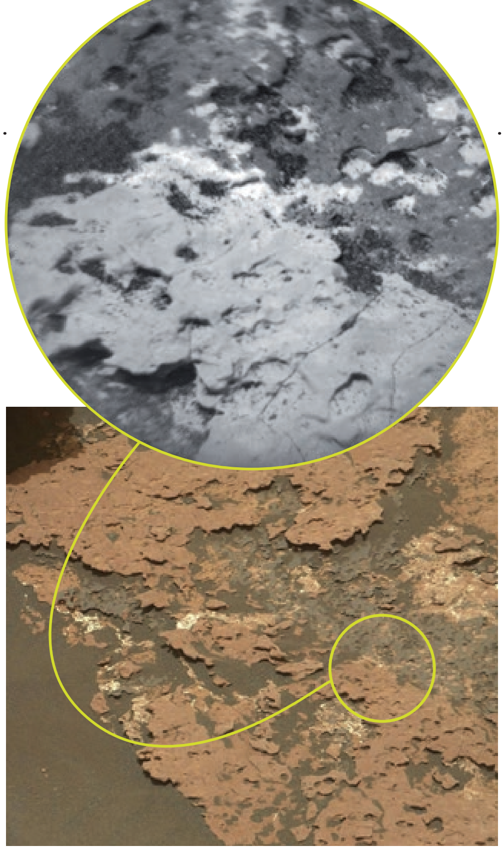


RESULTS FROM *MSL*

Since then, AEGIS has become a regular part of the team's exploration with *Curiosity*. The AEGIS pointing-refinement mode has proved helpful to the ChemCam team in situations where they believe a feature is small enough that there's some risk of missing it on the first shot. Allowing AEGIS to acquire and analyze the source image takes a little extra time but provides "pointing insurance" that

Images: courtesy of Raymond Francis, NASA/JPL





can prevent having to retarget the feature the next day or missing it altogether if the rover must move on. In every run so far, AEGIS has improved the pointing commanded from Earth and in some cases has saved ChemCam from missing the target.

The autonomous targeting mode has been heavily used. More often than not, *Curiosity* performs AEGIS-guided ChemCam activities soon after a drive. In this way, AEGIS has acquired ChemCam observations on 156 targets (as of June 2018) and significantly increased the data rate from ChemCam. Most of the post-drive data would never have been collected without onboard autonomy because of the overnight delay in sending images of a new location to Earth.

The team has learned to use the system to help guide or complete their exploration of an area. ChemCam data from features sampled by AEGIS sometimes reach Earth in time to guide target selection for the next sol (solar day). This has often resulted in the team following up on interesting chemistry recorded by AEGIS and guided subsequent interpretation of surrounding features.

When time is tight, post-drive targeting by AEGIS often helps mission scientists complete their geochemical survey of a site. For example, if there are three geological units in the rover's workspace and AEGIS has already done measurements on one of them, the team can focus their efforts on the other two. On the data analysis side, scientific studies that rely on statistics of the variability of materials or on close spacing of observations along the rover's traverse have benefited significantly from having so many more ChemCam targets.

THE FUTURE

The success of AEGIS on *MSL* has led to its inclusion in NASA's next Mars rover mission, to launch in 2020. That mission will have AEGIS available from the start of its surface operations, once again for targeting mast-mounted instruments. These will include SuperCam (the upgraded successor to ChemCam, with LIBS, RMI, and Raman spectroscopy and infrared reflectance spectrometer).

The AEGIS team also envisions other planetary destinations. There are quite a number of places in the solar system where a robotic explorer can't always wait around for earthly operators to choose targets. Smarter robots with autonomous science capabilities will likely play an important role in exploring more challenging destinations, and mission designers and operators will learn to use these systems to share responsibility for decision-making with their distant robotic systems.

OPPOSITE PAGE, FAR LEFT *This is a sampling of AEGIS targets in various locales. Green represents top-priority targets, while orange shows secondary targets. Red areas were saved as possible targets, and blue shows rejected targets.*

OPPOSITE PAGE, RIGHT *AEGIS uses a vision algorithm called Rockster to find suitable targets for follow-up observations. On sol 1508 (November 1, 2016), Rockster identified these target rocks at a place called the "Murray Unit" for sampling. The blue in this image represents potential targets.*

THIS PAGE *On sol 1666 (April 12, 2017),* Curiosity's *Mastcam and ChemCam pointed at two spots on a wind-eroded outcrop to determine whether changes in the rock's color meant changes in composition. These fine-grained sedimentary rocks formed at a time when Gale crater held a lake.*

Images: NASA/JPL/MSSS/LANL/Paul Hammond

VOLUNTEER SPOTLIGHT

KATE HOWELLS *is The Planetary Society's global community outreach manager.*

THE PLANETARY SOCIETY'S *volunteers contribute to our work through all kinds of channels, and social media is one of the most powerful. By connecting online with space fans in their communities and around the world, our volunteers share the message that everyone can have a place in space. Here's a first-hand story from Outreach Coordinator Andy De Fonseca, who traveled from Chicago to Cape Canaveral to see her first rocket launch and document it for The Planetary Society's Instagram community.* *—Kate Howells*

ABOVE *Andy De Fonseca, our outreach coordinator from Chicago, traveled to Cape Canaveral to watch her first rocket launch and share the experience via Instagram. Here, Andy points at the Atlas V rocket she would later see blast off.*

Hi, everyone, my name's Andy. I lead volunteer outreach activities for The Planetary Society in Chicago. This past winter, I signed up for a NASA Social event and had the honor of taking charge of The Planetary Society's Instagram account to cover the launch of the GOES-S weather satellite from NASA's Kennedy Space Center.

Along with a group of other social media gurus, I toured the Kennedy Space Center and spoke with people who had a hand in the GOES project, learning a lot about NASA and the intricacies of the GOES-S satellite. To me, the most exciting feature on the satellite is its ability to track lightning and detect wildfires before anyone on the ground can report them.

The launch itself was glorious. We listened to the booming speakers and counted down from 10 seconds with them, as giddy as kids at Disney World seeing their favorite princess. Our princess was about to be airborne. As the sound of liftoff rolled across the water and hit us, our cheering and squealing were probably just as loud. We watched until the rocket was just a dot in the sky. And throughout this whole adventure, The Planetary Society's Instagram followers were there with me.

The Planetary Society and NASA's Social program both offer awesome opportunities for the public to get up close and personal with space exploration. To find out more, check out **planetary.org/volunteer** and **planet.ly/nasasocial2018**. Anyone can help make science happen!

SOCIETY TRAVEL

Eclipse and Aurora Adventures Await Society Members in 2019

ALASKA AURORA BOREALIS
MARCH 7-13, 2019
Join astronomer Tyler Nordgren on our expedition to see Alaska's northern lights! Hundreds of Planetary Society members have taken this amazing journey with us. You'll see Alaska's wildlife—from grizzlies to musk oxen—in their winter habitat. Then, you'll travel by train from Talkeetna—past 20,310-foot Mt. Denali—to Fairbanks where you'll delight in the night sky's dazzling aurora borealis!

TAHITI TOTAL SOLAR ECLIPSE 2019
JUNE 25-JULY 4, 2019
WITH OPTIONAL BORA BORA EXTENSION JULY 3-7
Drink in the spectacular scenery of French Polynesia as we explore Tahiti and Moorea, then fly to the remote Gambier Islands to watch the Total Solar Eclipse from our chartered plane. Enjoy accommodations in the school or meeting house, including a festive dance program and dinner offered by our Polynesian hosts. This is a unique adventure to one of the most remote islands in the world!

CHILE TOTAL SOLAR ECLIPSE 2019
JUNE 26-JULY 6, 2019
WITH OPTIONAL EASTER ISLAND PRE-TRIP JUNE 21-27
Discover the cultural and astronomical heritage of Chile and see the Total Solar Eclipse as it passes over La Serena. Relax at a splendid hacienda as you explore Chile's northern wonders!

For more information, please contact Terri or April at Betchart Expeditions Inc., 800-252-4910. Or e-mail: *info@betchartexpeditions.com*

Volunteer photo courtesy of Andy DeFonseca; travel photo courtesy of Betchart Expiditions

KEIKO NAKAMURA-MESSENGER *is a mission research scientist in the Astromaterials Research and Exploration Science Directorate at NASA's Johnson Space Center.*

Illustration: James Vaughan

Precious Dust

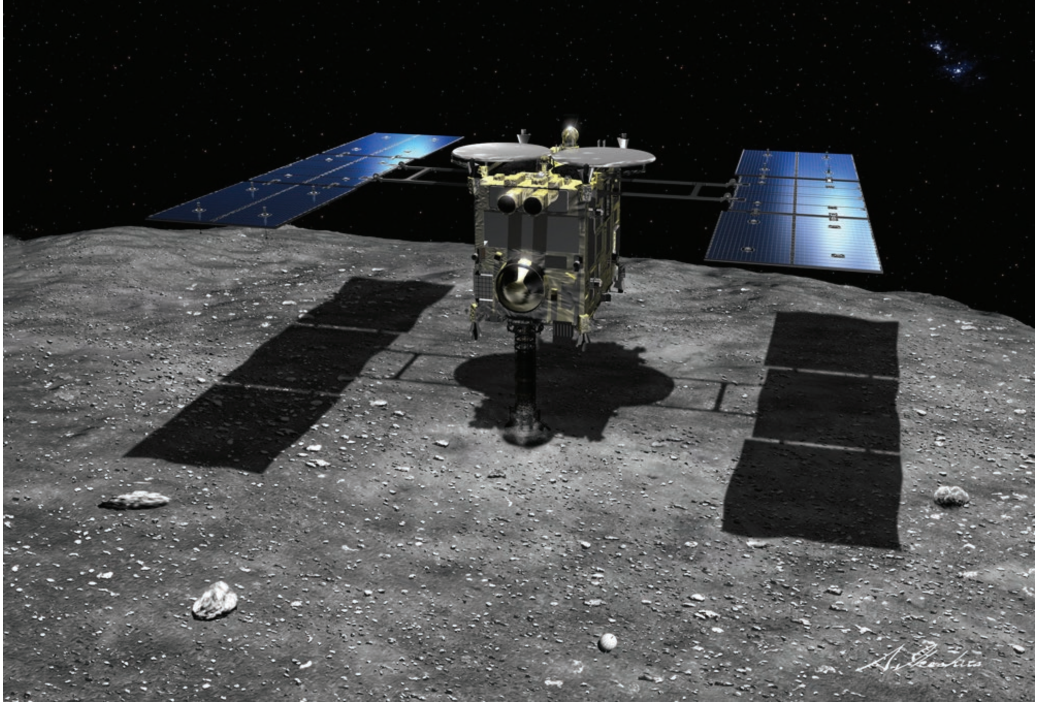
Two Missions Converge on Asteroid Sample Returns

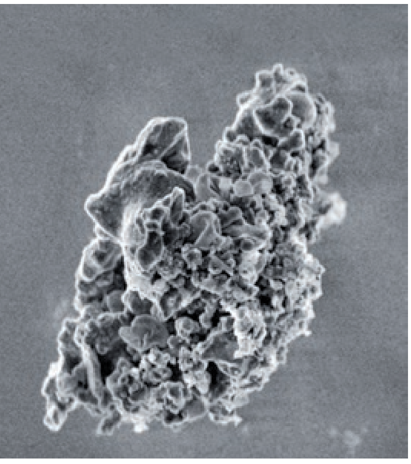
FAR-FLUNG SPACECRAFT deliver incredible views of distant worlds. But there's nothing like bringing samples back to Earth. Instruments carried by spacecraft have limitations in power, complexity, size, and number. Their investigations leave many fundamental questions unanswered—questions that we might be able to answer if only we had samples.

This summer marks the beginning of an exciting new era in sample-return missions: NASA's *OSIRIS-REx* spacecraft arrives at asteroid Bennu, and the Japanese *Hayabusa2* spacecraft arrives at asteroid Ryugu. Both are primitive asteroids—dark remnants of solar system formation that carry carbon and water—a type of asteroid that's never been visited before. After thoroughly mapping their respective asteroids for geology and mineralogy, each probe will collect surface samples and return them to Earth. I can't wait to study them in my laboratory.

Cosmic-dust pioneer Kazu Tomeoka introduced me to the dream of sample-return missions 20 years ago. In those days, the only returned extraterrestrial samples were from the Moon. He said to his students, "In the near future, we will be able to collect samples from asteroids and comets. There will be no need to wait for meteorites or cosmic dust to come and fall from the sky. And some of you might

ABOVE *On August 17, NASA's* OSIRIS-REx *will arrive at asteroid Bennu. In 2020, after a two-year orbital mission,* OSIRIS-REx *will extend its Touch-And-Go Sample Acquisition Mechanism (TAGSAM) to gather a sample of surface material to bring home to Earth.*





ABOVE LEFT *This is the highest-resolution transmission electron image of a porous interplanetary dust particle (IDP) available. The particle is 10 microns across.*

ABOVE RIGHT *In July 2018, Japan's* Hayabusa2 *will reach asteroid Ryugu, gather samples, and return them to Earth in 2020. Both Bennu and Ryugu are carbon-rich, pristine leftovers from the formation of our solar system.*

be the first to look at those samples." This inspired my life's work: laboratory analysis of returned astromaterials.

EARLY REPORTS

Returned astromaterials are not the only extraterrestrial samples we can study. Meteorites and cosmic dust have been collected by scientists at clean locations on the surface of Earth (such as Antarctica), by airplanes in the upper atmosphere, and by satellites in low Earth orbit. Interplanetary dust particles (IDPs) were first collected in the upper stratosphere by high-altitude balloon flights, and NASA now routinely collects IDPs with high-altitude aircraft.

Scientists would like to link cosmic dust and meteorites with their parent asteroids or comets. To do that, scientists have dispatched high-altitude flights timed to sample meteor showers from known comets and asteroids whose orbits pass near Earth's. Scientists have connected some meteorites to certain classes of asteroids or comets based on composition, spectral properties (color), or orbits (inferred from observing the path of their parent fireball in the atmosphere). But these inferences are uncertain and controversial.

Studies of meteorites and cosmic dust built a strong foundation for sample-return missions by revealing the early history of the solar system and pushing the development of ever more capable instrumentation. But this type of study is compromised by the uncertain origins of found specimens and effects of terrestrial weathering and contamination. As instruments have become more sensitive and we examine materials at finer scales, these effects have become bigger problems. Our progress is especially relevant to studies of organic matter, which is ubiquitous in the solar system.

NEW TECHNOLOGIES, NEW INSIGHTS

Professor Tomeoka was among the first scientists to examine IDPs using transmission electron microscopy (TEM). With TEM, he saw component crystals at the atomic scale. Tiny dust particles became immense landscapes that record the origins of their parent bodies.

I followed my mentor's path to study IDPs and meteorites using electron microscopy. While investigating an IDP collected during the April 2003 Pi Puppid meteor shower (associated with comet 26P/Grigg-Skjellerup), I discovered a new mineral with the chemical formula MnSi (mono-manganese silicide).

KEIKO NAKAMURA-MESSENGER *is an expert in analysis of extraterrestrial materials, especially at the nano-scale. She has a PhD in material science from Kobe University and, in addition to* OSIRIS-REx *and* Hayabusa2 *responsibilities described in this article, she is deputy principal investigator for NASA's CAESAR mission (Comet Astrobiology Exploration Sample Return), serving also as the mission's interface with international partners such as JAXA and ESA's* Rosetta *team.*

Image: Scott Messenger, NASA/JSC; *Hayabusa2* illustration: Akihiro Ikeshita

Photo: European Southern Observatory

LEFT *Comet tails are produced by particles of dust and gas emitted from the comet's nucleus as it nears the Sun. Interplanetary dust particles most likely originate from comet jets and from collisions among asteroids. However, where any specific particle came from is still unknown.*

We named the mineral Brownleeite after Donald Brownlee, the pioneer of cosmic dust collection. Identified in a single grain comprising just a few thousand atoms, it was the smallest mineral ever approved by the International Mineralogical Association. Studying its possible origins, we obtained data that gave us clues to how Brownleeite forms. And though we'd like to think the Brownleeite came from comet 26P/Grigg-Skjellerup, we can't be sure.

Brownlee was the principal investigator of NASA's *Stardust* mission, which returned the first direct samples of a comet. *Stardust* flew by comet 81P/Wild 2, beyond the orbit of Mars, and captured particles streaming from the comet's surface. The spacecraft returned to Earth in January 2006. The *Stardust* samples from Wild 2 provided surprises about the nature of early solar system materials, including "refractory" minerals that formed in high-temperature environments near the Sun. This unexpected discovery, made possible by the opportunity to study samples brought directly from the comet, showed that the cold, distant regions where comets formed were not isolated refuges of interstellar materials. Instead, comets formed from mixed materials, many of which came from the heart of the solar system.

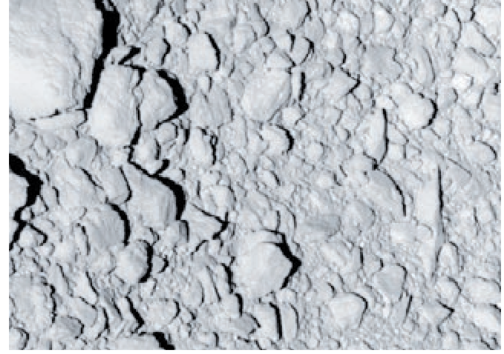
We have learned from fruitful experience with Apollo specimens that more discoveries are yet to come. Developments in technology have added capabilites to laboratory instruments and enabled new studies that were inconceivable when Apollo astronauts returned lunar samples a half-century ago. At the same time, materials once thought to be contaminants, such as organic matter in

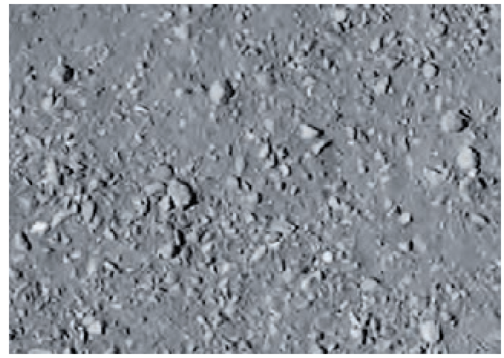
Astromaterials in Tiny Grains

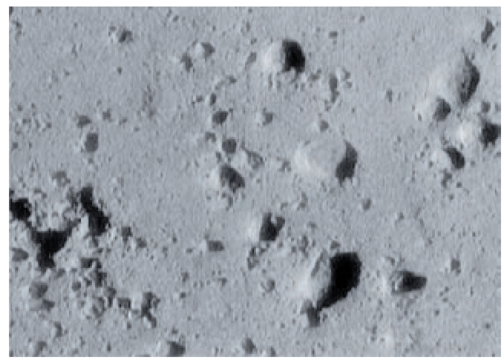
A good example of our new understanding of astromaterial chemistry is the presolar organic nanoglobule. Organic globules are round, often hollow, carbonaceous grains less than a micrometer in diameter (a human hair is typically 60 to 100 micrometers in diameter). They occur in almost every primitive astromaterial sample. These tiny grains used to be viewed as probable contaminants because meteorites are usually collected from dirty locations or many years after their fall.

I was extremely fortunate to be able to study a primitive meteorite that was quickly recovered after landing on a frozen lake in British Columbia during the dead of winter. It was about as pristine as a sample collected on Earth can get. In this Tagish Lake meteorite, I could see hundreds of organic nanoglobules, looking just like the "empty Easter eggs" we saw all over TEM images of samples thought to be less pristine.

Even so, there was skepticism that the globules were truly extraterrestrial. The proof of their origins was made possible with a new instrument, the NanoSIMS. With coordinated isotopic measurements, we showed that organic globules carry isotopic anomalies characteristic of certain photochemical processes, which would take place in cold molecular clouds in deep space or in the outermost regions of the protosolar disk. This finding is significant for both astrochemistry and astrobiology because it suggests primitive meteorites and cometary dust particles delivered organic precursors to the early Earth and to other planets and satellites as well. Organic nanoglobules have now been reported in almost every primitive astromaterial sample.







ABOVE *Spacecraft have touched down on the surfaces of three small worlds, which have surfaces variously covered with boulders, sharp-edged gravel, and dust: asteroid Itokawa (top), comet Churyumov-Gerasimenko (middle), and asteroid Eros (bottom). All three images are about 12 meters across. The pictures are somewhat soft because none of the spacecraft cameras used to take them were designed to capture images at such close range.*

BELOW *These odd shapes are tracks made by particles from comet Wild 2 after they crashed into an aerogel sample cell on the* Stardust *spacecraft. The largest particles fragmented on impact. Several particles are visible near the ends (at left) of these tracks.*

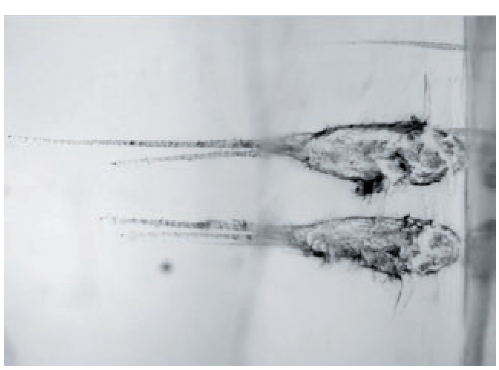
OPPOSITE PAGE *Inside the* Stardust *Sample Curation Clean Room at Johnson Space Center, Keiko Nakamura-Messenger points to a microscopic image of the very first comet particle returned by* Stardust. *With her are colleagues Andrew Westphal (left) and David Brownlee.*

astromaterials, are now understood to be significant constituents.

Sample-return missions make it possible to solve the mysteries of how the solar system's primordial organic matter formed in space and evolved within asteroids and comets. By collecting material directly from primitive bodies in a well-studied geological context and keeping them uncontaminated all the way from space into the laboratory, we can eliminate the most vexing sources of uncertainty. We plan missions carefully and track all possible sources of contamination or sample alteration, from spacecraft assembly and launch through the recovery of the sample-return capsule. At NASA, we begin planning how we will curate samples at the very beginning of the mission. This approach ensures that archived samples remain pristine for future generations, which will certainly wield even more advanced analytical technologies.

BEST OF BOTH WORLDS

Today I work on two asteroid missions: JAXA's *Hayabusa2*, built by my mother country, Japan, and NASA's *OSIRIS-REx*, built by my adopted country, the United States. Both spacecraft approach their target asteroids this summer. JAXA and NASA have agreed to exchange portions of the samples they will return, and the science teams are actively collaborating. Several Japanese scientists will join *OSIRIS-REx* mission operations in Tucson, Arizona, and there are NASA-funded scientists on *Hayabusa2*. The collaboration between these missions will benefit both.



Hayabusa2 will obtain the first of three planned samples from asteroid Ryugu in October 2018. It will descend, briefly touch the surface with a sampler, and collect regolith loosened by a small projectile. This touch-and-go sampling operation presents the mission's most significant risk. (*Hayabusa2*'s predecessor, *Hayabusa*, was damaged during its sample collection attempts and almost did not recover.)

Hayabusa2 carries a couple of landers that will study the asteroid's surface. *Hayabusa2*'s data on asteroid surface properties will be valuable for *OSIRIS-REx*, even though that mission has targeted a different asteroid. Since no one has ever visited the surface of a primitive asteroid, the structure of the surface of this type of body is unknown. Everything we learn at Ryugu has the potential to help us at Bennu.

As the sample site scientist for *OSIRIS-REx*, I am leading the effort to identify the most

Images: University of Tokyo/JAXA/ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA/NASA/JPL; *Stardust* image: NASA/JPL-Caltech/University of Washington scientifically valuable sites on asteroid Bennu using data we will obtain as the spacecraft gets closer to its target. One early effort will focus on developing a 3D-shape model that will be crucial for precise navigation around the asteroid. The *OSIRIS-REx* team is sharing expertise and software with the *Hayabusa2* team to aid them in making their own 3D model and navigation plans. These collaborations make both missions stronger and safer. As a NASA employee who is Japanese deep inside of my heart, I am particularly grateful to see these two missions, which could otherwise be rivals, working together toward mutual success.

THE WAY WE EXPLORE IN THE FUTURE

I am honored to be the curator of NASA's portion of the Ryugu sample to be returned by *Hayabusa2* and the deputy curator for the *OSIRIS-REx* sample. At Johnson Space Center, we will document, protect, and prepare samples for analysis by qualified scientists all over the world. This will take place inside the same building where all of NASA's returned extraterrestrial materials have been curated since the Apollo missions.

Hayabusa2 and *OSIRIS-REx* scientists are developing plans for sample analyses that will maximize science results from these missions. Ryugu and Bennu are both thought to be carbonaceous and water-rich asteroids. In terms of quantity, *Hayabusa2* will return less than *OSIRIS-REx*, but it will sample three different locations. *OSIRIS-REx* will obtain a more massive sample from a single site. In these two missions combining different sampling strategies we have an unprecedented opportunity to study the most pristine, least-altered asteroid materials and their geological processes.

Sample-return missions like *Hayabusa2* and *OSIRIS-REx* are laying the groundwork for future exploration of the solar system. Analyses of returned samples can provide detailed understanding of the environmental hazards for astronauts and spacecraft as well as previews of resources and models for how to extract those resources. Prospecting precedes mining on Earth, and sample return is the prospecting that will precede mining in space.

We owe an enormous debt to the pioneers of astromaterial sampling—those who collected from the deep sea, Antarctica, the stratosphere, the Moon, comet Wild 2, and more. Thousands of engineers and scientists worked to make those discoveries happen. Thousands more are working today on new missions. Sample return pays enormous dividends, and once samples are back to Earth, they can be studied by our children and their children, regardless of their nationality, with the best instruments that the future will offer.

Photo: NASA/JSC, courtesy of the author

Where We Study Returned Samples

In total, we have 380 kilograms (more than 800 pounds) of extraterrestrial rocks, including specimens from all six Apollo landings, more than 10,000 meteorites collected by United States expeditions to Antarctica, samples of cosmic dust, and samples from *Stardust*, *Genesis*, and *Hayabusa*. Each collection has unique clean room requirements.

At Johnson Space Center, the dedicated *Hayabusa2* sample clean room design is now complete, and soon construction will begin next to our *OSIRIS-REx* facility. NASA is now evaluating proposals to return samples from Mars, a comet's surface, or Enceladus.

As analysis techniques improve, the required sample sizes become smaller. We have been developing new techniques for processing tiny astromaterial samples inside a specially designed "glovebox," which will minimize the prospect of Earth life contaminating future returned samples.

For more information on these missions, go to:

asteroidmission.org

planet.ly/hayabusa2

twitter.com/OSIRISREx

RICHARD CHUTE *is The Planetary Society's chief development officer.*

Our Engaged Community

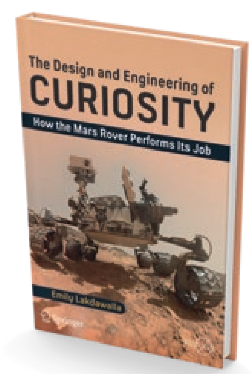
Fueled by Member Support, PlanetVac Xodiac Soars

Bill Nye and PlanetVac Xodiac donors pose in front of the Xodiac rocket following a successful sampling test flight. Front row, shown left to right: Scott Purdy, Lauren Roberts, Dustin Roberts, Brian Pope, Shirley Ginzburg, and Allen Ginzburg. Back row, shown left to right: Pendleton Ward, Bill Nye, Martin Schmitt, and Sue Ganz-Schmitt.

Photo: Richard Chute

THIS SPRING, the innovative sample-return technology called PlanetVac was successfully tested, thanks to the hundreds of Planetary Society members who helped advance our work with Honeybee Robotics on this project. Many members will recall our earlier work with Honeybee to test the PlanetVac concept in a vacuum environment in 2013. PlanetVac continues to climb NASA's Technology Review Level (TRL) ladder, and this time we helped fund the instrument's adaptation to fit on the lander legs of a Masten Xodiac rocket and then demonstrate its ability to collect simulated Mars regolith.

Collectively, nearly 800 members beat our funding goal of $60,000 for PlanetVac by more than $5,000. Several members stepped forward to challenge the community as part of this ambitious effort, including Pendleton Ward, self-proclaimed space geek and creator of the animated series *Adventure Time*, and Dusty Roberts, whose "blow out" challenge over the final three days of the fundraising campaign took us over the top. You can learn more about PlanetVac at **planetary.org/planetvac**. Thank you to everyone who participated in this exciting project!



Congratulations to Emily Lakdawalla who has just published her first book, *The Design and Engineering of* Curiosity*: How the Mars Rover Performs Its Job*.

To celebrate, Emily was the guest of honor at an evening recording of Mat Kaplan's *Planetary Radio Live!* held at Caltech's storied Athenaeum on April 19. Catch that recording at planet.ly/planetvacradio. More than a hundred Southern California members joined Mat and Emily for a discussion of *Curiosity*, followed by a book signing.

You can purchase a signed copy at our online store at planetary.org/store.

Will McPhail/The New Yorker Collection/The Cartoon Bank

Don't Let This Happen to Us!

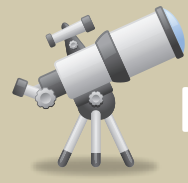
You Can Help!

ASTEROID AND COMET impacts, while not common, are very real threats. That's why, as part of The Planetary Society's *Be A Planetary Defender* campaign, we are excited to partner with space artist and designer Thomas Romer and backers around the world to create Kick Asteroid!—a colorful graphic poster that will tell the story of the very real threats posed by asteroid and comet impacts. Just imagine eye-grabbing Kick Asteroid graphics for posters, T-shirts, and other cool stuff that will turn backers into a walking, talking, alliance of Planetary Defenders.

By backing this project, you will join the growing movement to spread the word about stopping the asteroid threat. You will be doing your part to protect the people of Earth from a devastating impact. Saving Earth—and everything on it—is going to take all of us.

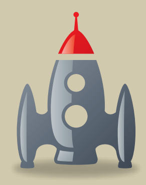
The good news is an asteroid impact is the only large-scale natural disaster that we can prevent. Become a Planetary Defender, and you can help save our planet. For details, go to **planetary.org/kickasteroid**.

WHAT'S UP? *by Bruce Betts*



IN THE SKY

There are great evening viewing opportunities for all five naked-eye planets. Mercury is the toughest to view, low in the west after sunset early in July. Venus dominates the early evening west through September. Mars gets bright, reaching opposition (opposite side of the Earth from the Sun) on July 27. Throughout August and September, there is an evening line of planets from the western horizon to the eastern horizon: Venus, Jupiter, Saturn, and Mars. The Perseid meteor shower peaks August 12/13, with increased activity several days before and after; moonlight will not be an issue this year because it will be New Moon. On July 27, there is a total lunar eclipse visible from South America, Europe, Africa, Asia, and Australia.



RANDOM SPACE FACT

According to Greek mythology, the dog constellations Canis Major (Greater Dog) and Canis Minor (Lesser Dog) are the constellation Orion's hunting dogs following him through the sky.

TRIVIA CONTEST

Our December Solstice contest winner is Nicholas Green of Waterloo, Iowa. Congratulations! The question was: ***Who was the first NASA administrator (head of NASA)?*** The answer: ***T. Keith Glennan***, who served from 1958 to 1961

Try to win a copy of *Cosmos* by Carl Sagan, and a *Planetary Radio* T-shirt by answering this question:

By volume, about how many of Mars would fit inside Earth?

E-mail your answer to *planetaryreport@planetary.org* or mail your answer to *The Planetary Report*, 60 S. Los Robles Ave., Pasadena, CA 91101. Make sure you include the answer and your name, mailing address, and e-mail address (if you have one). By entering this contest, you are authorizing *The Planetary Report* to publish your name and hometown. Submissions must be received by August 1, 2018. The winner will be chosen in a random drawing from among all the correct entries received.

For a weekly dose of "What's Up?" complete with humor, a weekly trivia contest, and a range of significant space and science-fiction guests, listen to *Planetary Radio* at *planetary.org/radio*.

BRUCE BETTS *is chief scientist for The Planetary Society.*

RIGHT *In California, engineers install* LightSail 2 *into its P-POD deployer before shipping it to New Mexico. From left: Alicia Johnstone, David Pignatelli, and Stephanie Wong.*

Photo: Bruce Betts/The Planetary Society

Integrated and Delivered

LightSail 2 Leaves California

IN MARCH, WE PASSED two major milestones in our LightSail program. In California, we integrated the *LightSail 2 (LS2)* spacecraft into its deployer (called a P-POD). Then, in New Mexico, *LS2* and the deployer were integrated into the *Prox-1* spacecraft that will carry them to space. *LightSail 2* is a small—one might say tiny—vehicle with a big goal. It's designed to be the first small-spacecraft demonstration of solar sailing, using the push of sunlight to propel it across space.

FALCON HEAVY'S FIRST LAUNCH

LightSail 2 spent all of 2017 with uncertain launch dates, which continually slipped. However, the delays provided an opportunity to perform improvements, tests, tweaks based on the tests, and more tests, which were eventually followed by closing up the spacecraft and putting it in storage (see *The Planetary Report*, December Solstice 2017 issue, for more details).

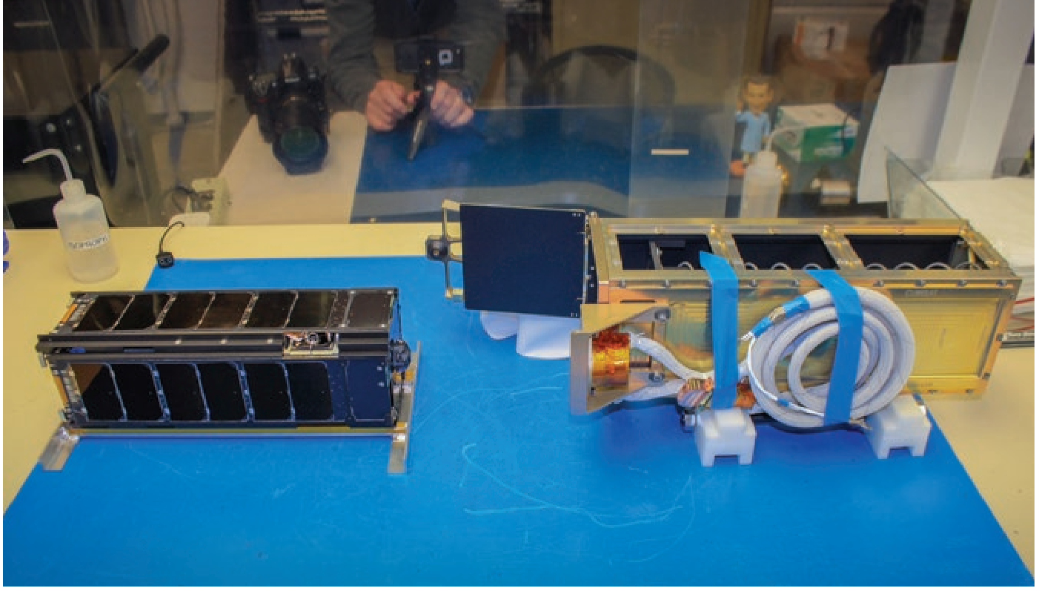
We are scheduled to be aboard the second or third flight of the new SpaceX Falcon Heavy, so the successful first launch of one of these huge rockets on February 6, 2018 was a significant event. It meant it was time to take *LS2* out of storage. Things started moving forward, and the next steps were planned for *LS2*.

DELIVERING A SPACECRAFT

LightSail 2 will fly to space inside the Georgia Tech spacecraft *Prox-1*, which was selected for flight by the University Nanosat Program of the U.S. Air Force. *Prox-1* will ride to space aboard SpaceX's Falcon Heavy as part of a larger Air Force payload, the Space Test Program-2 (STP-2). After the launch of the first Falcon Heavy, discussions began in earnest about delivery of *LS2* to the Air Force Research Laboratory (AFRL) in New Mexico for integration into *Prox-1*.

As the first step, we integrated *LightSail 2* into

Thanks! Planetary Society members have helped make this project—and many others—possible! Thank you.



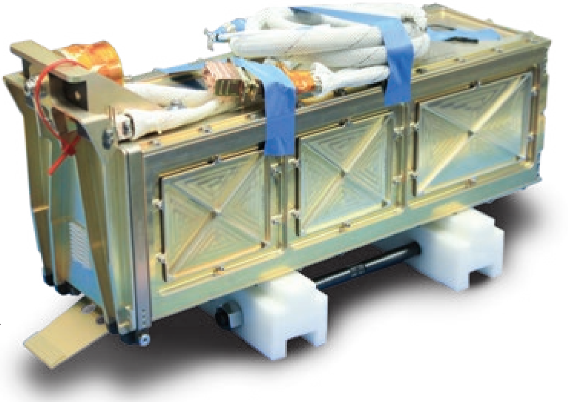
its P-POD (Poly Picosatellite Orbital Deployer), a highly technical (but reliable!) kind of jack-in-the-box used to push CubeSats into space. On March 12, I traveled to Cal Poly San Luis Obispo to witness the integration into the P-POD. Everything was slow and cautious and quite laborious. The engineers weighed, measured, and re-measured the spacecraft. They measured and tweaked adjustment bolts to ensure perfect placement of *LightSail 2* inside the P-POD and then positioned the side panels. They applied glue (twice) to each of the many screws and bolts. It was one more reminder that flying in space is complicated–even the "simple" things.

Then we were off to Albuquerque. How does one get a small spacecraft to a different state? On commercial airlines, inside carry-on luggage! It just requires a sturdy case, lots of padding, appropriate documentation, and a little heads-up for the Transportation Security Administration.

Next, it was back into a clean room, this time with a bunch of engineers and two spacecraft. The P-POD with *LS2* inside was carefully bolted, screwed, glued, and electrically connected to the core of the larger–but still small–*Prox-1* spacecraft. In the following weeks, engineers put all the other pieces of *Prox-1* together around the P-POD.

LAUNCH AND THE FUTURE

Next up for *LightSail 2* will be combined testing with the P-POD and *Prox-1* at AFRL, which will include vacuum tests, thermal tests, and vibration tests–all of which we've already performed on *LightSail 2* as a separate spacecraft. Eventually, all the STP-2 spacecraft will be integrated into a SpaceX Falcon Heavy rocket. As of this writing, launch will be no earlier than October 30, 2018.



Once launched, the rocket will deploy *Prox-1* into space. One week later, *Prox-1* will command the P-POD to deploy *LightSail 2*. After a few days of checkout, the solar panels will extend, and about a day later we will unfurl the sail and begin our first-of-its-kind voyage–small-spacecraft solar sailing. We anticipate operating in this mode for at least a month and hope to measure mission success by using the power of pressure from sunlight.

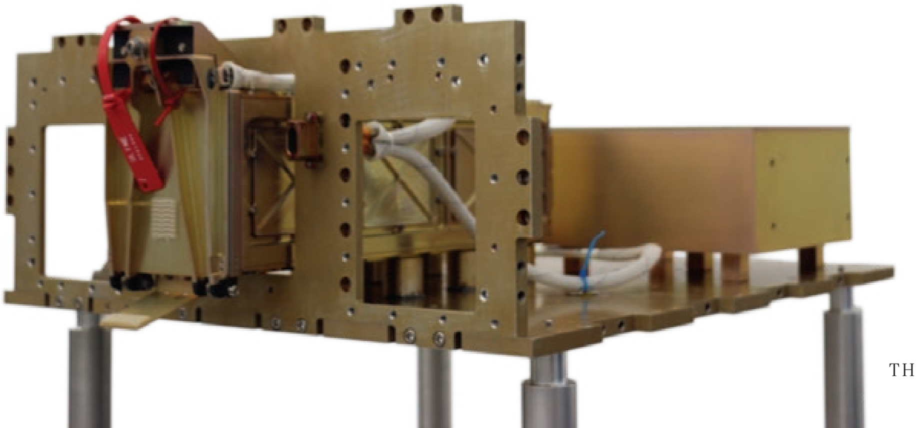
To keep up with the next few months of *LightSail 2*, and for more details about the LightSail program, see **sail.planetary.org**.

TOP LightSail 2 *sits next to the P-POD that will carry it into space.*

ABOVE *The very well-secured P-POD with* LightSail 2 *inside.*

BELOW LightSail 2, *bundled up in its P-POD, sits inside the Prox-1 spacecraft. The other Prox-1 components and side panels will be re-installed around the P-POD.*

Top photos: Bruce Betts/The Planetary Society; bottom photo: AFRL/The Planetary Society



CASEY DREIER *is director of space policy for The Planetary Society.*

Where Are All The Samples?

Sample Return is Entering a Golden Age, Though Plans for Mars Remain Vague

THREE DECADES PASSED between the final sample-return mission of the 20th century and the first sample-return mission of the 21st. *Apollo 17* was in 1972. The Soviet Union's robotic *Luna 24* was in 1974. It wasn't until 2004 that off-world samples were once again brought to Earth. In the intervening years, we have witnessed a new golden age of sample return, with an international fleet of missions flying now or being prepared to fly in the coming decade. So what changed?

Scientists have long desired pristine samples of other worlds to study in laboratories on Earth, which provide far better instrumentation than the under-powered, miniaturized, soon-outdated versions that ride along on robotic missions.

Despite strong scientific interest, sample return is rare because these types of missions are hard, and hard things are costly. They combine the demanding engineering needs of human spaceflight (safe transit and return to Earth) with those of robotic spaceflight (high autonomy, deep space operations). It is no accident that sample-return efforts languished in the years after Apollo, as science budgets for planetary exploration dwindled in the wake of the Space Shuttle program.

Fortunes began to change in the 1990s, thanks to improved technology and the chance discovery of the ALH84001 Martian meteorite, which a team of scientists claimed contained signatures suggestive of ancient life. The announcement, made in 1996, propelled sample return into the United States National Space Policy, which directed NASA to pursue "a long-term program...to obtain in-situ measurements and sample returns from the celestial bodies in the solar system."

The establishment of the low-cost Discovery mission line allowed NASA to pursue more missions and take more risks in planetary spaceflight. In alignment with national space policy, two sample-return missions launched

RIGHT *On February 28 of this year, The Planetary Society's space policy team hosted a briefing on Capitol Hill in Washington, D.C. to raise awareness of the exciting scientific opportunities that sample return missions provide.*

Photo: Antonio Peronace for The Planetary Society under the Discovery line in the late 1990s: *Genesis*, which returned samples of the solar wind in 2004, and *Stardust*, which brought back cometary tailings in 2006 (see page 17).

As for Mars, flush with confidence from the success of the *Pathfinder* and *Mars Global Surveyor* missions–and before the calamitous, back-to-back failures later that year of *Mars Climate Orbiter (MCO)* and *Mars Polar Lander (MPL)*–NASA proposed an international effort to land sample-collection rovers on Mars as early as 2003 and return their contents by 2008.

Mars sample-return ambitions were dashed after the loss of the *MCO* and *MPL* missions. In 2000, NASA reformulated its Mars Exploration Program around the "follow the water" strategy of in-situ (in place) science, pushing sample return off to the 2010s. In 2006, George W. Bush released an updated National Space Policy that dropped robotic sample return in favor of human lunar exploration. Cost overruns by the *Curiosity* rover delayed this effort even further.

But the scientific community rallied around sample-return missions in their Decadal Survey reports of 2003 and 2011, identifying high-priority missions to the Moon, asteroids, comets, and Mars. In 2011, NASA agreed to one of the recommendations, *OSIRIS-REx*, which will return a sample from the surface of the asteroid Bennu in 2023. Another recommendation–returning samples of a cometary surface and its volatile materials–is currently under study and could launch in 2024.

Mars, however, remains the ultimate challenge, with its deep gravity well and commensurately hefty price tag. The cost and risk associated with a multi-mission cache, launch, and return effort from Mars have repeatedly created conflict between White House budgeteers and the scientific community. The upcoming *Mars 2020* rover, though now adhering to recommendations by the 2011 Decadal Survey to cache samples for future return, was not initially billed as a sample-caching mission by NASA due to cost concerns. But the mission's science-definition team made it clear that "the preparation of a returnable cache…is the only acceptable mission concept" for *Mars 2020*. The budgeteers relented, and, barring any technical calamities, sample tubes will be sitting on the surface of Mars by the early 2020s, waiting for a ride back to Earth.

Last summer, NASA Associate Administrator of Science Thomas Zurbuchen announced that NASA intended to a build a sample-retrieval rover and Mars ascent vehicle for launch no earlier than 2026. Despite the announcement, the fiscal year 2019 budget request for NASA contained no funds for this mission, though it did propose $50 million to study various concepts.

International space agencies have not waited for NASA. JAXA has pursued ambitious sample-return missions, beginning with its *Hayabusa* mission in 2003. *Hayabusa2* is en route and arrives at its target asteroid (Ryugu) this year. In 2024, JAXA will launch a sample-return mission to the asteroid-like Martian moon Phobos. The Chinese space program plans to pursue a lunar sample-return mission in 2019, followed by a Mars sample-return mission in the 2020s.

Private companies could soon benefit from a new initiative that supports NASA's lunar exploration ambitions. Depending on the availability of funding and the presence of a Lunar Gateway space station, companies may find a willing customer in NASA in the next decade to purchase sample-return services from the lunar surface with delivery to orbiting astronauts or back to Earth.

The steady hand of scientific consensus and policy alignment along with increasing technological ability have lowered the bar for sample return, at least for destinations in smaller gravity wells. Mars still presents the biggest obstacle–and potentially the biggest scientific return–of any destination under consideration, and as such, sample-return plans remain frustratingly vague.

TOP *Under this protective glass dome is a fragment of ALH84001, also known as the "Mars Meteorite." This famous space rock was displayed on the panelists' table at the congressional briefing.*

BOTTOM *In August 1996, NASA and Stanford University scientists surprised the world by announcing that they'd found evidence within a Martian meteorite that pointed to ancient life on the Red Planet. The wider scientific community has now rejected this claim, but the scientific attention and public interest stirred up by this event are considered to be turning points in the history of astrobiology.*

Photo: Antonio Peronace for The Planetary Society; image: NASA/JSC

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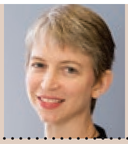
SNAPSHOTS FROM SPACE



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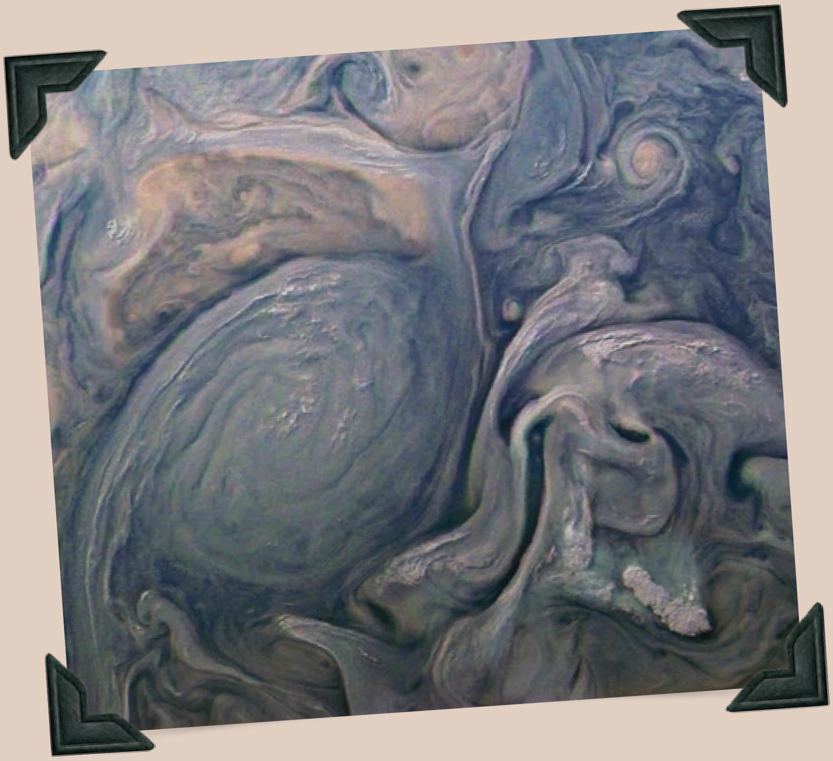

SPACE ARTIST Don Davis produced this view of Jupiter's cloud tops by processing data captured during *Juno*'s twelfth close Jupiter flyby on April 1, 2018. It was near sunset in Jupiter's Northern Turbulent Region, so the clouds cast shadows, indicating their height. In his photo processing as well as his space art, Don prefers to present color more or less as it would appear to the human eye. The resolution of this view is about 10 kilometers (6.2 miles) per pixel, and it covers an area about 8,800 kilometers (5,500 miles) across.

–Emily Stewart Lakdawalla

Image: NASA/SwRI/MSSS/Mattias Malmer/Don Davis

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