THE PLANETARY SOCIETY

THE PLANETARY REPORT

JUNE SOLSTICE 2019
VOLUME 39, NUMBER 2
planetary.org

SMALL-BODY RENDEZVOUS

JAGGED LITTLE WORLDS HOLD CLUES TO EARTH'S ORIGINS BUT YIELD NEW PUZZLES

DEFENDING EARTH ✦ SAMPLING AN ASTEROID ✦ ADVOCATING FOR SPACE

Precise Movements

Earth-Bound Tracking Devices Help Manage Spacecraft

DEEP-SPACE EXPLORATION by robotic spacecraft requires the support of thousands of workers back on Earth in facilities around the world. Canberra, Australia hosts one of NASA's 3 Deep Space Network (DSN) stations, operated by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Each DSN station hosts one 70-meter and multiple 34-meter dishes that receive data from spacecraft across the solar system. Here, mechanical engineer Rachel Twomey (apprentice), servo systems engineer Paul Richter, and mechanical engineer Clayton Locke discuss maintenance on the hydrostatic azimuth bearing on the 70-meter antenna. The team is performing maintenance and installation on pump and oil-flow fittings. The hydrostatic bearing literally floats the moving structure of the antenna, which weighs about 4 million kilograms (8 million pounds), on a film of oil only 0.1 millimeter (4 thousandths of an inch) thick, permitting the gigantic antenna to smoothly track spacecraft as Earth rotates.

"Space on Earth" seeks to highlight all kinds of ground-based facilities worldwide that are involved in planetary exploration. If you'd like to make a suggestion for a facility to feature in "Space on Earth," please email planetaryreport@planetary.org.

CSIRO

NASA/SwRI/MSSS/Gerald Eichstädt/Seán Doran

JUNO CAPTURED a swirling region of bright clouds in the wake of a cyclonic storm as it dove toward its 18th close encounter with Jupiter on 12 February 2019. At left is the turbulent, blue-tinted pole; at right, the polar clouds give way to the pinker belts and zones of Jupiter's midlatitudes. The Juno team posts their images in raw, relatively unprocessed form on the web as soon as they land on Earth—and wait for members of the public to process them. This image is the result of an automated processing pipeline developed by Gerald Eichstädt of Germany, followed by further enhancement by Seán Doran of Ireland.

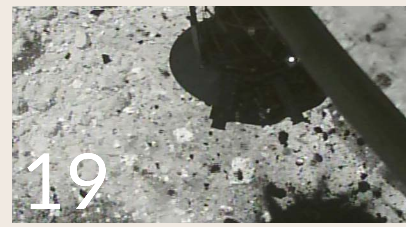
—*Emily Stewart Lakdawalla*

SEE MORE AMATEUR-PROCESSED SPACE IMAGES PLANETARY.ORG/AMATEUR

SEE MORE EVERY DAY! PLANETARY.ORG/BLOGS

Contents

JUNE SOLSTICE 2019



BILL NYE *is chief executive officer of The Planetary Society.*

Space Defense for Us All

Your Membership Dollars at Work to Save the Planet

LIFE IS UNCERTAIN, but you can be sure of this: Earth will be hit by a huge rock some day—or night. The chance is 100 percent. The thing we don't know is when. It could happen tomorrow, or it could be 2,356 years from this afternoon, but it will happen. If you're a member, you are doing something about it. Thank you.

Looking for a typical asteroid is like looking for a typical charcoal briquette…in the dark. I mean the absolute pitch-black, sooty-jet, tar-pit dark. However, dark as they are, asteroids glow in the infrared because they're warmer than space. They're at about 150 Kelvins (150 degrees Celsius above absolute zero or minus 190 degrees Fahrenheit). That's why we at The Planetary Society provide our Gene Shoemaker Near-Earth Object grants to amateur astronomers who keep a lookout, and we advocate strongly to ensure governments continue to invest in more observations and more space missions to near-Earth asteroids and comets. Thanks again for your support.

Let's say we found an asteroid headed for us, crossing Earth's orbit on a collision course. What would we do about it? We have to think about a hands-free course correction—a gentle tug or nudge from a spacecraft just big enough to ensure the object crosses our orbit when we're not there.

Several far-out but reasonable schemes have been proposed. The gravity tractor is an idea for a spacecraft so massive that its gravity could act like a tow rope, pulling the potential impactor aside. The kinetic impactor concept would slam one or more spacecraft into a dangerous asteroid to alter its course. You might think a nuclear weapon would do the trick. It might, but it might cause other problems. Blasting an object in deep space far enough in advance to deflect it might turn it into interplanetary buckshot, which would hit Earth just as hard as the original unshattered object would have, only more spread out. Ouch.

I hope you're familiar with the Laser Bees idea. We supported some early lab research at the University of Strathclyde in Scotland. The idea is that we'd build spacecraft outfitted with lasers driven by solar panels. We'd concentrate laser beams onto a promising area of an asteroid. The ablating (burning off) material would have momentum, which would nudge the asteroid onto an ever-so-slightly different course. As an engineer, this is my favorite plan.

In any scheme, the key is early detection. A timely nudge could save us all. I cannot help but recall the last line in the movie *The Thing From Another World*. The journalist warns us: "Keep looking. Keep watching the sky."

Bill Nye

CONTACT US: The Planetary Society, 60 South Los Robles Avenue, Pasadena, CA 91101-2016; General calls: 626-793-5100; Email: *tps@planetary.org*; Internet: *planetary.org*; *Editor* **EMILY LAKDAWALLA**; *Art Director* **LOREN A. ROBERTS for HEARKEN CREATIVE**; *Copy Editors* **NICOLE YUGOVICH**, **KELLY BEATTY**, and **JASON DAVIS**; *Technical Editor* **JAMES D. BURKE**; *Science Editor* **BRUCE BETTS**

ON THE COVER: Comet Churyumov-Gerasimenko's surface has been ravaged by close passages around the Sun. Pits mark the sources of dusty comet jets, and scalloped cliffs have receded and collapsed to generate dusty ponds of comet material. Bluer areas in this false-color image hint at the presence of frozen water and other volatile compounds. *Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; Jacint Roger* ✻ *The Planetary Report* (ISSN 0736-3680) is published quarterly at the editorial offices of The Planetary Society, 60 South Los Robles Avenue, Pasadena, CA 91101-2016, 626-793-5100. It is available to members of The Planetary Society. Annual dues are $50 (U.S. dollars) for members in the United States as well as in Canada and other countries. Printed in USA. Third-class postage at Pasadena, California and at an additional mailing office. Canada Post Agreement Number 87424. ✻ Viewpoints expressed in articles and editorials are those of the authors and do not necessarily represent positions of The Planetary Society, its officers, or its advisers.

You're a Planetary Defender

Bringing Together the World's Experts

PLANETARY DEFENDERS like you are helping to protect Earth from dangerous asteroids. Every 2 years, scientists, engineers, and decision makers gather together at the International Academy of Astronautics Planetary Defense Conference to discuss the latest in finding, tracking, characterizing, and deflecting asteroids. Your support of The Planetary Society helped make this conference happen. This year's conference took place 29 April to 3 May 2019 in the Washington, D.C. area. The Planetary Society was a primary sponsor of the conference, and Planetary Society chief scientist Bruce Betts served on the organizing committee and presented 2 papers. In association with the conference, The Planetary Society hosted a public event at the University of Maryland: "Bill Nye vs. the Asteroids." It featured not only Bill Nye but also several asteroid-threat experts and NASA chief scientist Jim Green. Mat Kaplan hosted an episode of *Planetary Radio Live* with a panel of asteroid experts. You can hear the show at **planet.ly/pdc19** and see videos from the public event and conference at **planetary.org/defense**.

Helping Observers Search the Skies

PLANETARY SOCIETY members play a direct role in planetary defense through the Shoemaker Near-Earth Object Grant program. The grant program supports highly skilled amateur astronomers from around the world who track and characterize near-Earth asteroids. Thanks to your support, over its 22-year history the program has awarded $382,000 in 56 awards to astronomers in 18 countries on 6 continents. The

grants have been used to purchase more sensitive cameras, equipment to allow remote-controlled observation, and telescope improvements. At the Planetary Defense conference, The Planetary Society announced a new call for proposals. The proposal deadline is 30 July 2019. For more information, including updates on the impressive work enabled by grants to past winners, visit **planetary.org/neogrants**.

New Planetary Mission Webpages

WE'RE EXPLORING more! Planetary exploration has kept a brisk pace over the past several years. To keep members up to date, we have created new webpages tracking missions, including near-Earth asteroid explorers OSIRIS-REx and Hayabusa2, Israel's Beresheet lunar lander, InSight on Mars, the International Space Station, future plans for humans in deep space, and many more. The pages provide background information and frequently updated news briefs. See them all at **planetary.org/missions**.

LEFT *Mat Kaplan hosted Planetary Radio Live at the 2019 Planetary Defense Conference public event.*

TOP RIGHT *Shoemaker Grants support upgrades to observatories such as this one in Morocco.*

BOTTOM RIGHT *To date, the grants comprise 56 awards to astronomers in 18 countries on 6 continents.*

PDC: Bruce Betts/The Planetary Society; *Planetary Radio*: Antonio Perance/The Planetary Society; Shoemaker Grant photo: Morocco Oukaïmeden Sky Survey

More on each story can be found online! Use the link provided.

You’re an Explorer

ABOVE *Planetary Society events empower the public to participate in space exploration.*

TOP RIGHT *Engineers install LightSail 2 in its deployment device. From left: Alicia Johnstone, David Pignatelli, and Stephanie Wong.*

BOTTOM RIGHT *In February 2018, SpaceX launched its first Falcon Heavy. LightSail will launch on Falcon Heavy’s third flight.*

Planetary Society on the Road

WE WANT SOCIETY members (and not-yet Society members) to have more opportunities to get together and celebrate our passion for space. Want to know what events are coming up? Check out **planetary.org/events**. Here are a few highlights from recent months.

SXSW PANEL: SPACE EXPLORATION FOR ALL At this year’s South by Southwest Festival, Planetary Society CEO Bill Nye joined Richard Garriott, one of the private astronauts from Soyuz TMA-13’s mission to the International Space Station, and Molly Cain, former director of venture at U.S. Homeland Security, for a conversation about the present and future business opportunities in space. Listen to the panel at **planet.ly/2019sxsw**.

EXTREME STEA2M The Planetary Society joined with other partners to offer STEA2M Fair: Extreme STEA2M, Extreme Fun. More than 20,000 students, teachers, and families attended a fun-filled day full of hands-on activities that included an inspiring talk by CEO Bill Nye, a live recording of *Planetary Radio* with Mat Kaplan, and myriad educational opportunities. Visit **planet.ly/stea2m19** to listen.

YURI’S NIGHT is a global celebration of humanity’s past, present, and future in space. Society members all over the world attend local Yuri’s Night events in commemoration of Yuri Gagarin’s pioneering 12 April 1961 flight and the first space shuttle launch 20 years later. If you missed out this year or didn’t have one near you, know that anyone can create a Yuri’s Night event. **yurisnight.net**

LightSail 2 Spacecraft Launching Soon

CITIZEN PARTICIPATION in space is about to launch to new heights. Your LightSail 2 spacecraft will be on the next flight of SpaceX’s Falcon Heavy rocket as early as 22 June 2019. To prepare for this milestone, the LightSail 2 team completed final testing and made some small improvements. In February, the team carried out an Operational Readiness Test (ORT) using BenchSat, the tabletop demonstrator that mimics the solar sail flight spacecraft. An ORT simulates major spacecraft events, allowing the team to practice and refine procedures. The team also tested some minor software updates and then uploaded them to the flight computer. In early May, we shipped LightSail 2 to the Air Force Research Laboratory in Albuquerque, where it was reintegrated with the Georgia Tech spacecraft Prox-1. At the time of this writing, we are expecting to ship to Florida in late May to be integrated with the rocket. For the latest details, keep your eye on **sail.planetary.org**. Go LightSail!

LightSail lab photo: Bruce Betts/The Planetary Society; Launchpad: SpaceX

You're an Advocate

You're Building Support for Planetary Science

IN FEBRUARY, The Planetary Society supported the reestablishment of the Planetary Science Congressional Caucus in the new 116th Congress with new co-chairs Rep. Derek Kilmer (D-WA) and Rep. Steven Palazzo (R-MS). The caucus, which was first created in the 115th Congress, expired with last November's election. Your chief of Washington operations, Brendan Curry, has been working to increase membership in the caucus, which now boasts 20 members. The partial government shutdown earlier in this year and the recent announcement of an amended budget for NASA in May has delayed the introduction of the President's budget request for fiscal year 2020. The Planetary Society is keeping a close eye on these events and will work to keep our members informed. Follow **planetary.org/caucus** for all the developments.

100 Members. 1 Day of Action.

IN MARCH, 100 members of The Planetary Society carried out a remarkable day of space advocacy at the U.S. Congress. They came from 25 states and the District of Columbia. Some were grade-school students. Some were retired. A few were professional scientists and engineers. They were men and women from all walks of life, but they all shared one thing: they so believed in the promise of space science and exploration that they traveled to Washington on their own dime to advocate directly to Congress. Participants attended a half-day advocacy training session before breaking into groups to visit 127 Congressional offices. The energy, passion, and enthusiasm of these dedicated members of The Planetary Society serve as an ongoing source of inspiration for Planetary Society members and staff. Learn more about the Day of Action at **planet.ly/action2019**.

Planetary Society members like you make this work possible. *Thank you!*

Day of Action photos: Antonio Perance/The Planetary Society

Bricks Hit the Ground

THERE MAY BE more stars in the Hollywood Walk of Fame, but the real stars in our universe are the members who have purchased a piece of rock. Another set of 61 planetary pavers has arrived, and they are now installed in the walkway into your Planetary Society headquarters. The proceeds of the brick program support the purchase of capital equipment items. Check out the inspiring and heart-warming messages written by your fellow members by heading to **planetary.org/bricks** and tapping "Find Your Brick."

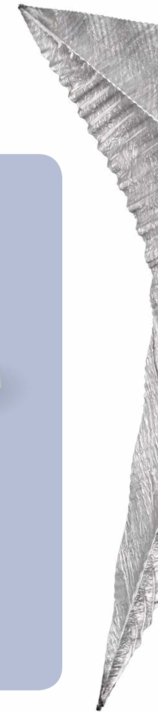
TOP *100 members of The Planetary Society show their passion for space at the 2019 Day of Action.*

BOTTOM LEFT *Members received a science briefing on New Horizons during the Day of Action.*

BOTTOM RIGHT *NASA Administrator Jim Bridenstine addresses Planetary Society members as part of the Day of Action.*

Help Defend the Earth From Asteroids

OUR PALE BLUE DOT *is sitting in a cosmic shooting gallery. Asteroid and comet impacts, while not common, are very real threats. You can make an impact (get it?) in the battle against threatening asteroids. Here's how:*



GET EDUCATED

Check out our new **Asteroid Defense 101**, a short course about the threat of asteroid impact and what we can do to prevent it. **courses.planetary.org**

TEACH OTHERS

Download our **Planetary Defense Toolkit** and raise awareness of the asteroid threat in your local community. **planetary.org/volunteer**

SUPPORT DIRECTLY

For 22 years, the Society has supported asteroid hunters through our Shoemaker Near-Earth Object Grants. Donate by 30 June, and your gift will be matched, dollar for dollar, up to $15,000. **planet.ly/shoemakerdonate**

ASTEROID DAY 30 JUNE

BE LOUD

#AsteroidDay is 30 June. This United Nations-recognized global awareness day marks the 111st anniversary of the Tunguska impact event. Tell your representatives in Congress to prioritize the issue of protecting Earth from asteroids so that when the next threat arrives, we're ready. **planetary.org/neopetition**

BE VISIBLE

The city-sized asteroid that doomed the dinosaurs 65 million years ago shall not be forgotten. Remember Chicxulub! Buy your shirt and support our efforts. **planet.ly/cxshirt**

107
total known near-Earth comets

896
total known NEOs larger than 1,000m

8,609
total known NEOs larger than 140m

20,141
total known near-Earth asteroids

20,248
total known near-Earth objects

ABOVE *Near-Earth asteroid Bennu, the target of the OSIRIS-REx mission, was named by then-9-year-old Michael Puzio in a Planetary Society contest.*

Current known NEO totals reported at cneos.jpl.nasa.gov; Bennu image: NASA/Goddard/University of Arizona

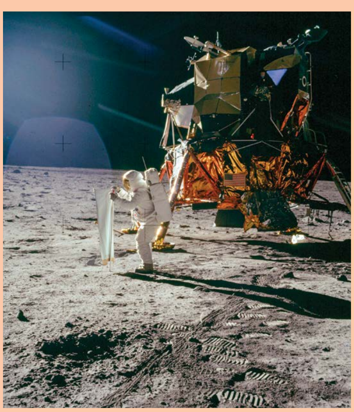
MORE WAYS TO GET INVOLVED IN SPACE EXPLORATION THIS SEASON

LIGHTSAIL 2

The world's first controlled solar sail flight in Earth orbit is ready for launch—thanks to you. Keep your eyes on **sail.planetary.org** for updates about our launch aboard a SpaceX Falcon Heavy rocket.

TOTAL SOLAR ECLIPSE SOUTH PACIFIC, CHILE, AND ARGENTINA

On 2 July, invite your friends to witness one of humanity's most transformative celestial experiences: a total solar eclipse. **planet.ly/190702eclipse**



CELEBRATE THE GREATEST FEAT OF HUMAN EXPLORATION IN HISTORY WITH US

Humans' first footprints marked the Moon 50 years ago on 20 July. Listen to the fascinating stories behind the mission in our multi-part podcast special, *The Political History of Apollo*. **planet.ly/apollo50**

What does the Apollo anniversary mean to you? Share your story at *myapollostory@planetary.org* or #MyApolloStory on social media.

SPACE ADVOCACY 101

School's out! But that doesn't mean classes are done. Now's the time to level up your United States space advocacy expertise. Take our free online course at **courses.planetary.org**.

The Planetary Society; NASA; Getty Images

Society Travel Adventures for You and Your Friends

ANGKOR WAT & BINTAN ISLAND "RING OF FIRE"
18-27 DECEMBER 2019

Explore the mysteries of Angkor Wat. Discover the amazing 500 Lohan statues on Bintan Island beneath the "Ring of Fire" of the 26 December annular eclipse. This is a once-in-a-lifetime opportunity!

ALASKA AURORA BOREALIS 2020
27 FEBRUARY–4 MARCH 2020

Join us as we explore the great beauty of Alaska in winter and see the famed aurora borealis, or northern lights, the greatest light show on Earth.

ARIZONA SKIES & NEW DISCOVERIES 2020
19-26 APRIL 2020

Explore this desert paradise, meet scientists, and see observatories in the astronomy capital of the world: Tucson. See Biosphere 2, Kitt Peak, and the stunning red rocks in Sedona. Marvel at the night sky.

ARGENTINA TOTAL SOLAR ECLIPSE
8-19 DECEMBER 2020

Join us north of San Martín de Los Andes to see the total solar eclipse on 14 December 2020. Visit Buenos Aires and Iguazu Falls for an extraordinary eclipse adventure!

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

IN THE SKY

On 2 July, there will be a total solar eclipse visible from parts of the southern Pacific, Chile, and Argentina, with a partial solar eclipse visible from much of South America. On 16 July, a partial lunar eclipse will be visible throughout much of Europe, Africa, and western and central Asia. The Perseid meteor shower peaks 12-13 August, with increased activity several days before and after, but the Moon will be almost full at the peak, limiting the number of meteors visible. Bright Jupiter and yellowish Saturn are visible in the evening sky going from east to west as the weeks pass.

RANDOM SPACE FACT

The 6 Apollo missions that landed humans on the Moon brought to Earth a total of 382 kilograms (842 pounds) of rocks, core samples, pebbles, sand, and dust from the lunar surface. There were 2,200 separate samples.

TRIVIA CONTEST

Our December Solstice contest winner is Joel Beebe of Ann Arbor, Michigan. Congratulations! The question was: ***Who were the final members of the backup crew for the Apollo 8 mission?*** The answer: ***Neil A. Armstrong, Edwin E. Aldrin, Jr., and Fred W. Haise, Jr.***

Try to win a copy of *Astronomy for Kids: How to Explore Outer Space with Binoculars, a Telescope, or Just Your Eyes!* by Bruce Betts and a *Planetary Radio* T-shirt by answering this question:

What was the first spacecraft mission to return samples from a comet?

Email 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 email 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 1 September 2019. 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*.

ABOVE *One of the last photos returned by SpaceIL's Beresheet lander, which crash-landed on the Moon on 11 April 2019.*

Where We Are

An At-A-Glance Spacecraft Locator

THE LAST QUARTER has seen few changes in the roster of planetary exploration spacecraft. SpaceIL's lunar lander Beresheet is now on the lunar surface. Its descent on 11 April seemed to go nearly perfectly. Unfortunately, a cascade of events shortly before its planned landing caused it to hit the ground too fast, and it did not survive.

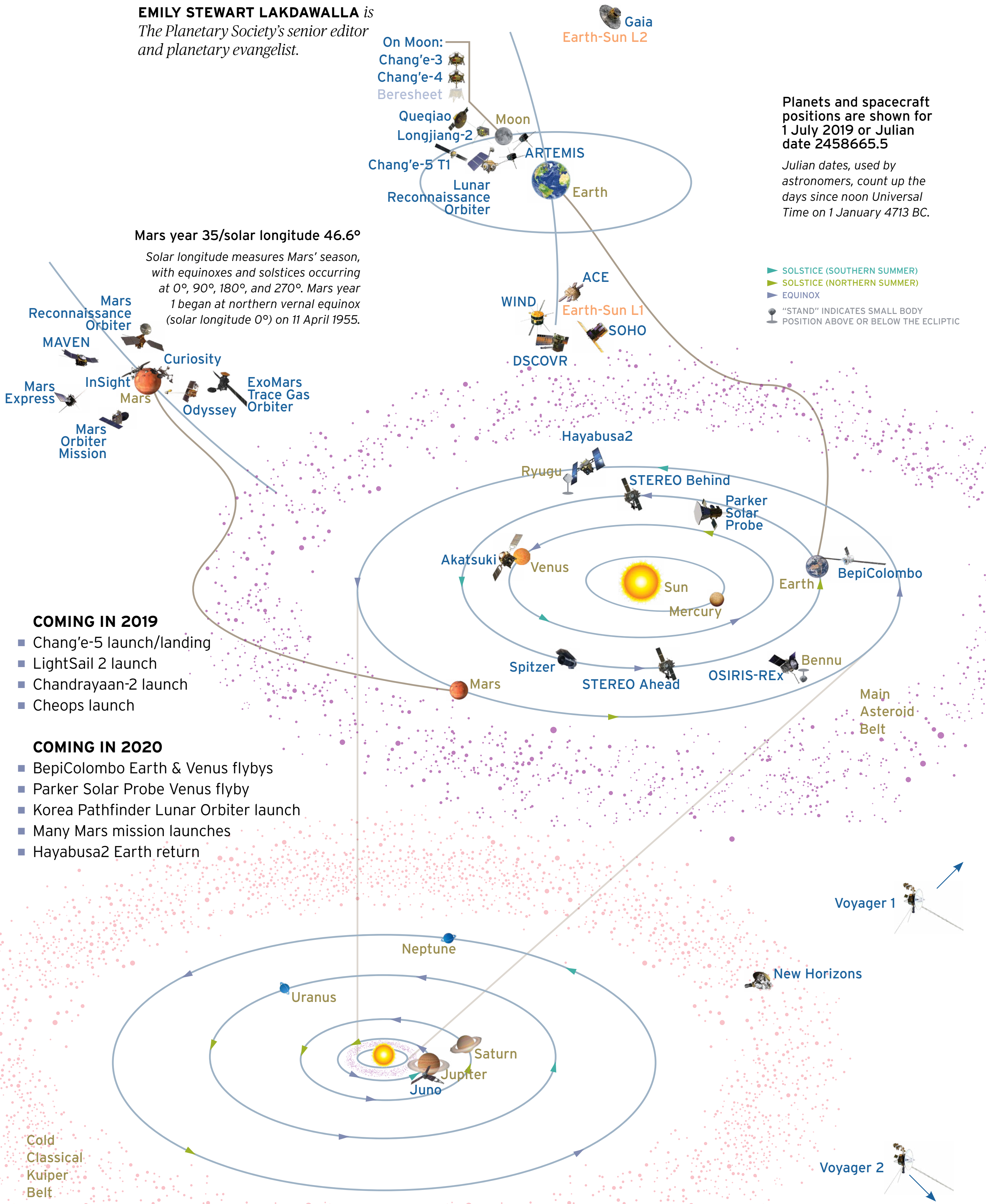
I've corrected an earlier omission (spotted–as they always are–by a sharp-eyed reader): the map at right now includes ESA's Gaia star-mapping spacecraft, which orbits in step with Earth at the gravitationally stable L2 point, farther from Earth than the Sun.

Chang'e-4 and Yutu-2 are now past their prime mission and are in their extended mission phases. Their companion SmallSat, Longjiang-2, will crash into the Moon on 31 July to bring its mission to an intentional end. Parker Solar Probe is near aphelion as of 1 July and will reach its third death-defying solar perihelion on 1 September. BepiColombo completed its near-Earth commissioning phase on 5 April and is now settling into its long-cruise phase. Earlier this year, the ESA-JAXA Mercury mission was racing ahead of Earth on an inside track, but its elliptical orbit has now taken it farther from the Sun than Earth, allowing Earth to catch up. It will return to Earth's neighborhood in April 2020 for a flyby.

At Mars, InSight has struggled to bury its heat probe beneath the surface, but its seismometer is recording good data and has finally detected one very small Marsquake. Scientists are hopeful for more. Curiosity recently completed its first drilling activity in Glen Torridon, a clay-rich valley at the base of Mount Sharp. Out at Jupiter, Juno will be swinging through 2 perijove passes on 21 July and 11 September.

Beresheet: SpaceIL; Loren A. Roberts for The Planetary Society after a concept by Olaf Frohn

EMILY STEWART LAKDAWALLA *is The Planetary Society's senior editor and planetary evangelist.*

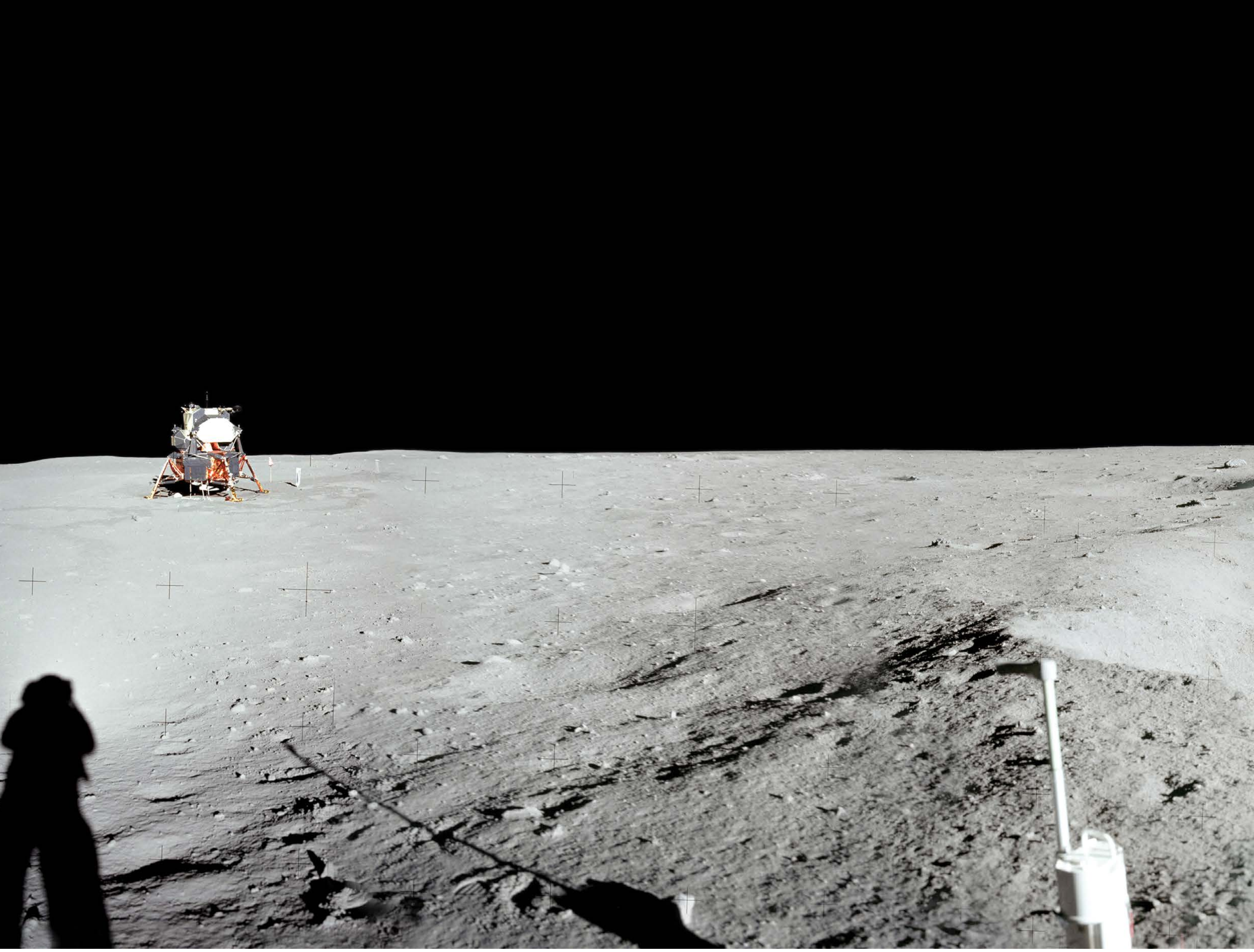


COMING IN 2019

- Chang'e-5 launch/landing
- LightSail 2 launch
- Chandrayaan-2 launch
- Cheops launch

COMING IN 2020

- BepiColombo Earth & Venus flybys
- Parker Solar Probe Venus flyby
- Korea Pathfinder Lunar Orbiter launch
- Many Mars mission launches
- Hayabusa2 Earth return



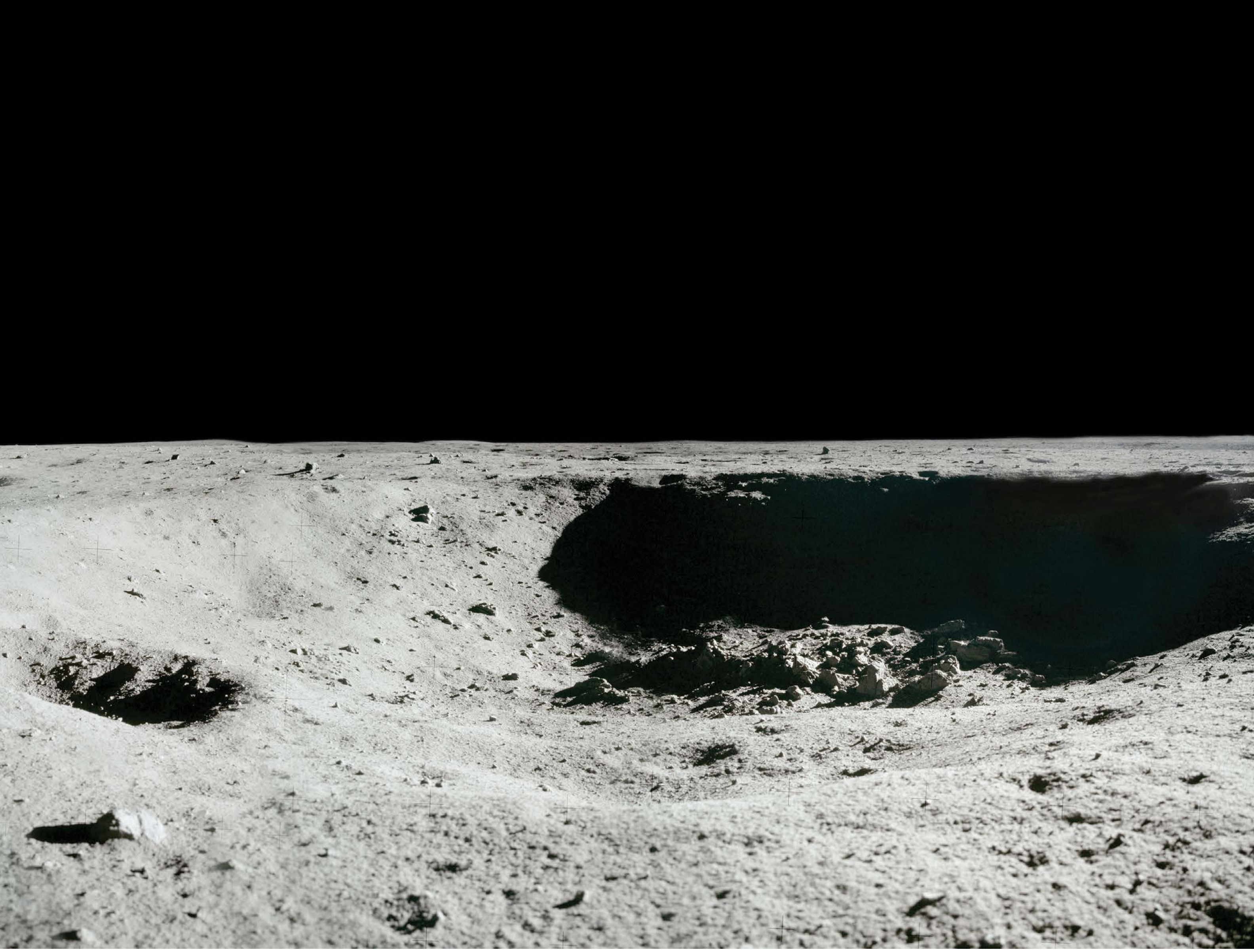
Apollo 11 Little West Crater Panorama

by Mike Constantine

RIGHT *Lunar Reconnaissance Orbiter was sent to the Moon in 2009 to map future human landing sites. It acquired this view of the Apollo 11 landing site on 5 November 2011. Armstrong's tracks out to the rim of Little West Crater are still clearly visible.*

APOLLO 11'S LANDING on 20 July 1969 was the day humans first set foot on another world. For the risky, challenging endeavor, NASA sought a smooth landing site, one lacking craters or mountains. Following years of survey by lunar orbiters, NASA selected Mare Tranquillitatis for Apollo 11, as it was a flat plain of basalt with few topographic features. Ironically, during descent, Mission Commander Neil Armstrong had to take semiautomatic control of the lunar module to avoid a large boulder field and the 30-meter-wide Little West Crater, landing with only 25 seconds' worth of fuel remaining.

Capturing this panorama was not part of the originally scripted mission plan. Armstrong took time out of the scheduled activities to venture 60 meters east of the lunar module to Little West, the hazard he had to avoid during the landing. It was the largest feature Armstrong could see from the landing site. The white object in the foreground is the handle of the Apollo Lunar Surface Close-up Camera,

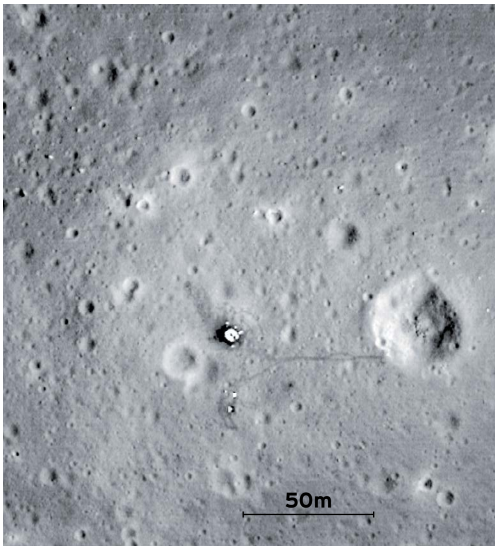


a device that allowed the crew to take close-up photographs of the lunar surface.

In 2005, upon seeing this panoramic assembly, Armstrong told me that it didn't look nearly as big as it had when he was there and that visiting the crater had been a "worthwhile deviation." For more of my conversation with Armstrong, visit **planet.ly/ap11story**.

Mike Constantine is the author of Apollo: The Panoramas *and director of* **moonpans.com**.

NASA/Mike Constantine; Inset: NASA/GSFC/ASU



We're celebrating each Apollo mission's 50th launch anniversary with a brand-new online resource page. Visit planetary.org/apollo for photos, maps, timelines, videos, and more.

MARTIN RUBIN, *a researcher at the University of Bern, is on Rosetta's mass spectrometer team.* **CECILIA TUBIANA**, *at the Max Planck Institute for Solar System Research, is on Rosetta's camera team.*

RIGHT *ESA's Rosetta mission accompanied comet 67P/Churyumov-Gerasimenko in its orbit around the Sun from August 2014 until its landing on the comet in September 2016. The comet was most active just after perihelion in August and September 2015, its jets carrying streams of primordial dust into space.*

ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA/Jacint Roger Pérez/Emily Lakdawalla

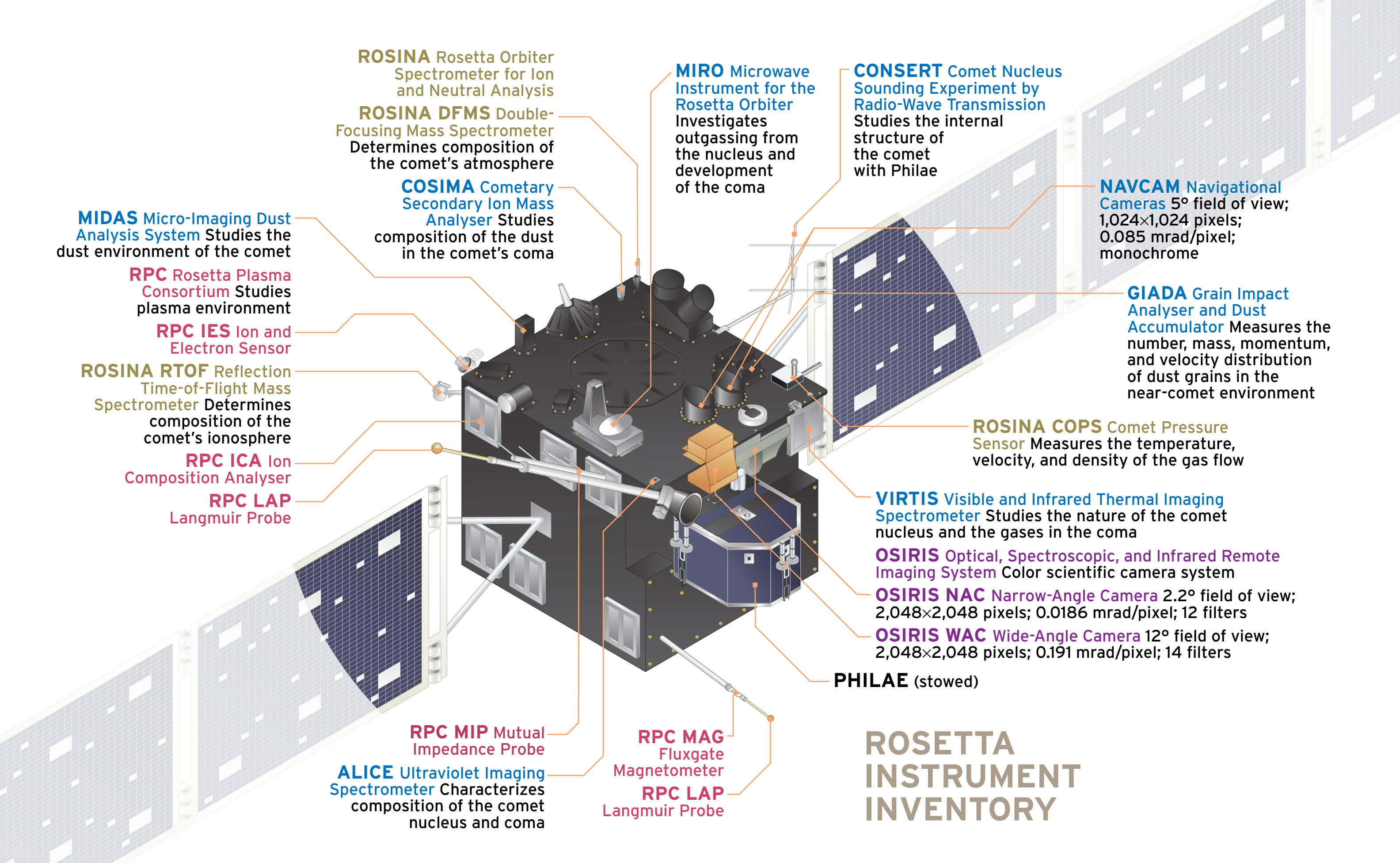
Rosetta's Ancient Comet

ESA Mission Unlocks the Secrets of Icy Relics

ROSETTA IS A European Space Agency mission with contributions from its member states and NASA. Operating such a complex mission with its 11 instruments and Philae lander is a success story in itself, but Rosetta's greatest success is the science it delivered. Although the mission is over, the investigation of the data acquired by its instruments is bound to keep us busy for many years to come. Rosetta succeeded only because of the tremendous work and dedication of the more than 2,000 engineers, technicians, and scientists involved.

Prior comet missions have only briefly visited their targets, seeing just one moment in their evolution. Comets are dynamic worlds with dramatically varying activity. With Rosetta, we sought to visit a quiet comet and then accompany it on its path into the inner solar system, observing its evolution while approaching the Sun, passing through perihelion, and moving back into the outer solar system.

One driving question for Rosetta concerns the origin and history of comet 67P: how primordial is this cometary nucleus? How did it evolve since its formation 4.5 billion years ago? How is it evolving now? Here, we present a few selected highlights of the mission, but



Emily Lakdawala, Charles H. Braden, and Loren A. Roberts for The Planetary Society

this is just scratching the surface and is by no means complete.

RAPIDLY CHANGING NUCLEUS

After more than 10 years of flight, Rosetta arrived at comet 67P on 6 August 2014. From earlier Hubble Space Telescope observations, we expected 67P to be more of a diamond-shaped object. The peculiar bilobate shape of the comet was a big surprise. The resemblance to a rubber ducky was striking. The team quickly adopted the duck nomenclature not just for the humor of it but as a useful orientation: when somebody talked about the neck, everybody knew where to look.

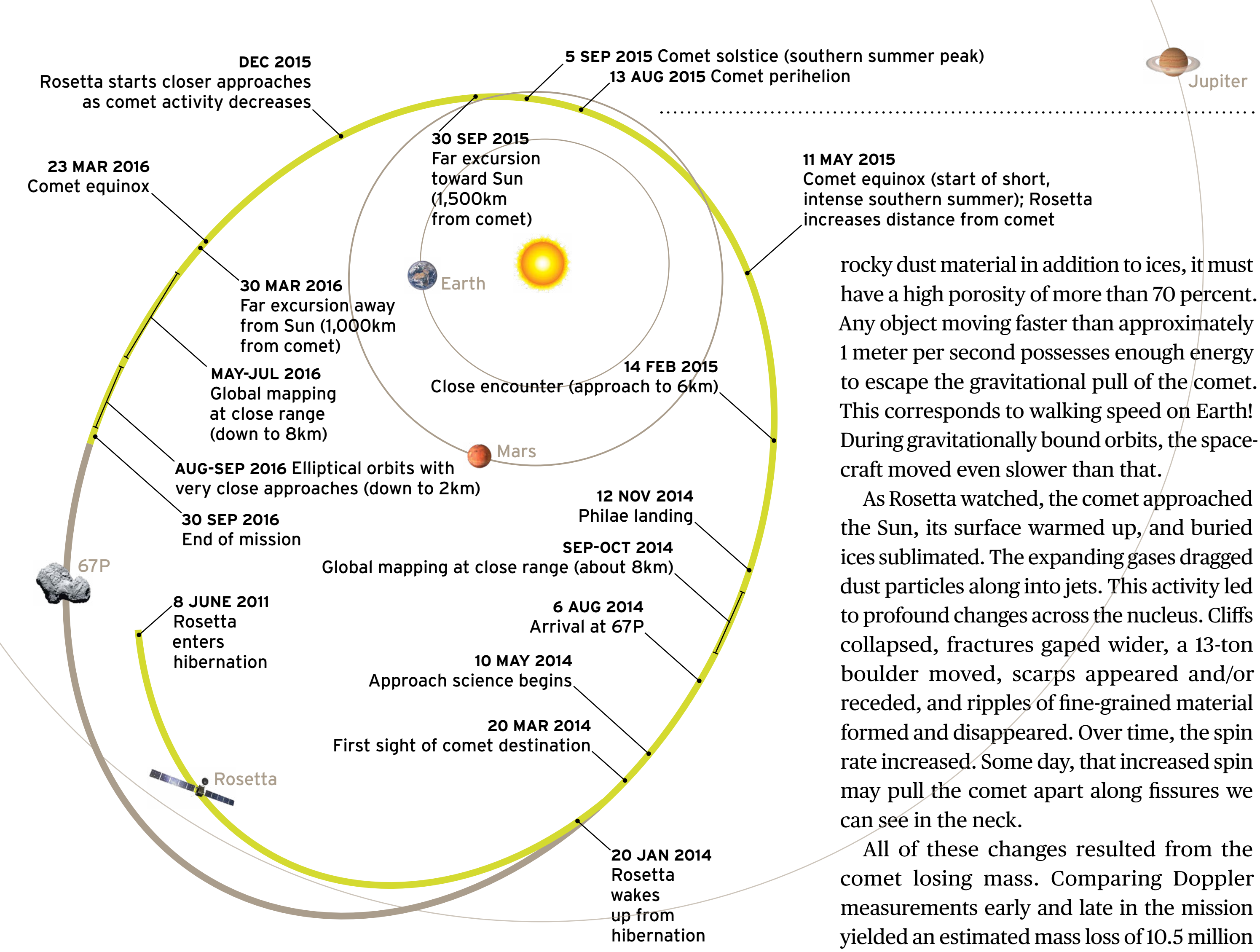
Rosetta's OSIRIS camera images of 67P revealed a nucleus with a rich variety of landforms such as steep cliffs, terraces, and circular pits, many of which exposed internal layering. The layers do not match across the two lobes, suggesting that the nucleus began as two independent objects that merged in a gentle collision. We also saw a contrast between smooth, dust-covered areas and rugged terrains.

At the time and place of arrival, well beyond 3 AU, the comet's activity was low, releasing material at a rate of a few kilograms per second. Rosetta inspected the comet very closely, selecting a landing site and then deploying Philae late in 2014 while the low activity provided a safer environment for close approaches. Over the course of the mission, the outgassing gradually increased to several hundred kilograms per second during its peak activity some weeks after perihelion.

Rosetta and Philae's instruments worked together to reveal the details of the structure of the comet's surface and interior. The CONSERT experiment passed radio waves through the nucleus between the orbiter and the lander. The waves did not bounce off many internal boundaries, so the interior is probably mostly homogeneous. The surface itself is very dark, very hard, very dry (lacking much water ice), and rich in organic compounds.

High-resolution images of the southern hemisphere acquired after December 2015 revealed a clear north-south dichotomy across the nucleus' surface. The southern hemisphere appeared rugged and more consolidated, with little dust and a flatter terrain (fewer cliffs and pits) than the northern hemisphere. The consensus is that the southern

ABOVE *Rosetta is a cornerstone mission of ESA. The spacecraft carried 11 science instruments, some of them having multiple components, contributed by scientific institutes in ESA member states and the U.S. The spacecraft was huge—a box 2.8 by 2.1 by 2 meters in size with a wingspan of 32 meters. The Philae lander had 10 more instruments.*



ABOVE *Being solar powered, Rosetta had to hibernate when it reached 4.5 AU in June 2011. After waking, it rendezvoused with 67P on 6 August 2014 and accompanied the comet through its changing seasons and perihelion passage until the mission was brought to an end on 30 September 2016. Distances are given with respect to the comet surface.*

Emily Lakdawalla and Loren A. Roberts for The Planetary Society

hemisphere is more representative of the comet's interior, while the north is cloaked under a blanket of fallback dust that originated from the southern hemisphere.

The images permit us to measure the nucleus' dimensions. The small lobe measures about 2.6 by 2.3 by 1.8 kilometers (1.6 by 1.4 by 1.1 miles), while the large lobe is about 4.1 by 3.3 by 1.8 kilometers (2.5 by 2.1 by 1.1 miles). Radio Science Investigation (RSI) measurements of Rosetta's Doppler-shifted radio signal gave us the comet's mass (about 10^{13} kilograms). Together, these numbers yield an estimated density of half that of water ice. Since the comet certainly contains denser, rocky dust material in addition to ices, it must have a high porosity of more than 70 percent. Any object moving faster than approximately 1 meter per second possesses enough energy to escape the gravitational pull of the comet. This corresponds to walking speed on Earth! During gravitationally bound orbits, the spacecraft moved even slower than that.

As Rosetta watched, the comet approached the Sun, its surface warmed up, and buried ices sublimated. The expanding gases dragged dust particles along into jets. This activity led to profound changes across the nucleus. Cliffs collapsed, fractures gaped wider, a 13-ton boulder moved, scarps appeared and/or receded, and ripples of fine-grained material formed and disappeared. Over time, the spin rate increased. Some day, that increased spin may pull the comet apart along fissures we can see in the neck.

All of these changes resulted from the comet losing mass. Comparing Doppler measurements early and late in the mission yielded an estimated mass loss of 10.5 million tons, about 0.1 percent of the comet's total. This is equivalent to a 70-centimeter-thick (2-foot-thick) layer of material removed from the comet nucleus during each orbit. Yes, this means that comets have a finite lifetime.

COMETS: NOT EARTH'S MAIN WATER SOURCE

In planetary science, elements that have a low sublimation temperature are often referred to as "volatiles." A comet outgasses more volatiles when it's closer to the Sun and less when it's farther away. Like planets, comets can also have seasons. Comet 67P has pronounced seasons due to the tilt of its rotation axis with respect to the orbital plane. The northern

MARTIN RUBIN *is a senior lecturer at the University of Bern in the Department of Space Research and Planetary Sciences. His research interests cover a wide range of objects in our solar system, in particular the investigation of comets by means of spacecraft exploration.* **CECILIA TUBIANA** *is a research scientist at the Max Planck Institute for Solar System Research in Göttingen (Germany). Her main research interest is comets. She is part of the team that designed, planned, and commanded the Rosetta OSIRIS comet images.*

hemisphere summer is much longer and weaker compared to the short and intense summer around perihelion in the south, and the ROSINA, MIRO, OSIRIS, and VIRTIS instruments monitored these seasonal variations.

The comet's releases of gas and dust must originate at or near the nucleus' surface. Yet despite all of the changes we witnessed, we had difficulty locating active areas or exposed ices on the surface of the nucleus. On rare occasions, the VIRTIS instrument detected patches of water and carbon dioxide frost on the dawn side of the nucleus.

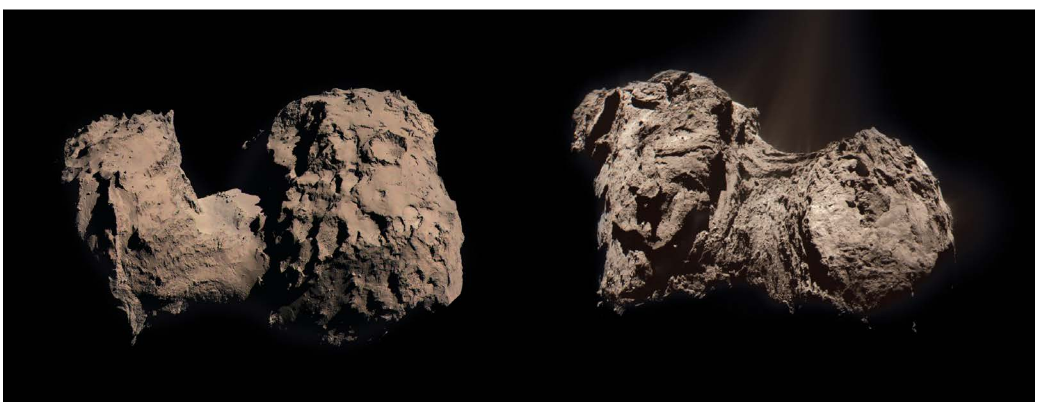
One of the surprising results was the detection of abundant amounts of molecular oxygen (O_2) by ROSINA and Alice. We saw that the abundance of oxygen correlated well with water but less well with molecular nitrogen. The relationship between oxygen and water in the comet likely dates back to their origin in the interstellar medium before the solar system formed. We also studied the isotopes of hydrogen in the comet's water and came to a similar conclusion: the comet's water originated in the interstellar medium.

We were surprised by the relatively large amount of heavy hydrogen (deuterium) in the comet's water. That discovery ruled out a popular hypothesis for the origin of Earth's water. We now know that comets of 67P's type were not a major source of the water that became Earth's oceans. However, noble gas measurements suggested that maybe 22 percent of Earth's atmosphere has a cometary origin. If this is true, then organic chemicals detected by the ROSINA, COSAC, and Ptolemy mass spectrometers on both the lander and the orbiter would have also found their way to the early Earth. Organic materials that Earth potentially received from comets include a host of molecules relevant to early life, such as the simplest amino acid: glycine.

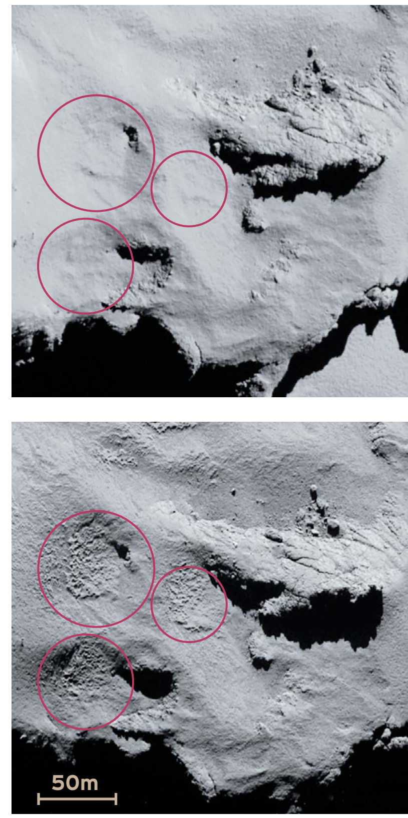
MAGNETIC FIELD SURPRISES

As Rosetta escorted the comet from 3.6 to 1.2 AU and out again, the RPC instrument suite witnessed the ever-changing comet interactions with the solar wind. When hit by solar radiation and energetic particles, the gases emanating from the nucleus lose electrons, becoming charged particles themselves. Because of their charge, they interact with the solar wind, thus forming a magnetosphere around the comet that grows as the outgassing increases. For its part, the Philae lander magnetometer detected no permanent magnetization of the nucleus, so the comet did not originate inside a strong magnetic field that left its imprint in the incorporated material.

As the comet got closer to the Sun, the comet's magnetosphere grew and eventually blocked the solar wind from reaching the nucleus' surface. The comet formed a "diamagnetic cavity," a region close to the nucleus without any detectable magnetic field. Comet scientists had seen a diamagnetic cavity before during Giotto's 14 March 1986 encounter with comet 1P/Halley. Contrary to our expectations,

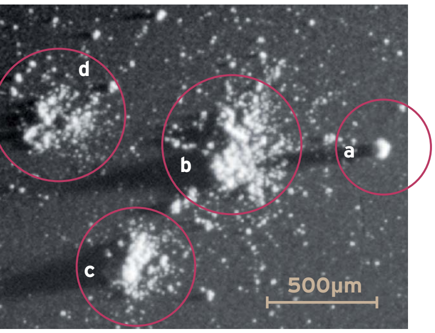


LEFT *The northern (left) and southern (right) hemispheres of 67P. The southern hemisphere came into view in mid-2015 during its summer, which coincides with perihelion and the peak of comet activity.*



ABOVE *As Rosetta watched, the comet's surface changed. Between September 2014 (top) and March 2015 (bottom), honeycomb features appeared in depressions on the Ma'at region on the comet's "head." By the end of 2015, the surface texture had reverted to an appearance similar to that in 2014.*

Left: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA/Emily Lakdawalla; Right: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA/Emily Lakdawalla after Xuanyu Hu et al. (2016)



ABOVE *Dust particles imaged by COSIMA were diverse. In this image, (a) marks a compact particle, while (b), (c), and (d) are particle clusters that were more or less glued together before impacting the instrument.*

ABOVE RIGHT *In some places, the comet appears to be a coherent block crossed with long fissures; in other places, this material appears to break up into boulders. Yet other areas seem smooth, with what appear to be collapse pits.*

ESA/Rosetta/MPS for COSIMA Team MPS/CSNSM/UNIBW/TUORLA/IWF/IAS/ESA/BUW/MPE/LPC2E/LCM/FMI/UTU/LISA/UOFC/vH&S/Langevin et al. (2016); ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

though, the shape of 67P's cavity changed all the time. Rosetta's slow velocity around the comet and the dynamic nature of the cavity's shape meant that the boundary of the diamagnetic cavity swept across the nearly stationary spacecraft more than 600 times over the course of a few months around perihelion.

COMET DUST'S ANCIENT ORIGINS

The environment of 67P proved to be quite dusty. At times, there would be so much dust near the nucleus that wayward specks would confuse Rosetta's star trackers, and navigators had to back the spacecraft significantly away from the nucleus to avoid danger. However, Rosetta stayed as close as possible because it was at 67P to study this material. Dedicated instruments investigated the amount, composition, and shapes of dust particles around the comet. Rosetta studied dust on all scales, from meter-sized boulders seen in camera images to sub-millimeter-sized fluffy aggregates seen by the COSIMA microscope to tens of nanometers measured by the MIDAS atomic force microscope. The GIADA instrument counted particles, detecting both loosely and densely packed particles. Loosely packed agglomerations likely date from the formation processes operating in the early solar system. The densely packed particles resembled those brought back to Earth by NASA's Stardust mission to comet 81P/Wild 2.

COSIMA measured the elemental abundances of the dust in 67P and found them to match the elemental abundance of the entire solar system, suggesting that the comet is a very primitive body dating back to solar system formation. Nearly half of the mass of 67P's dust comprises organics. These are not small molecules; they are huge, carbon-rich macromolecules similar to those found in carbonaceous chondrite meteorites. However, unlike meteorites, 67P's dust contained silicate (rocky) minerals without any water in their crystal structures. The lack of water in 67P's mineral particles is evidence that the comet has never been part of a larger object containing liquid water.

THE COMET'S STORY

Taken together, Rosetta's study of 67P has helped us see past the modern appearance of the comet and understand its origin. We have learned that the comet is made of primitive material, preserved almost unchanged since the comet accreted in the distant reaches of the protoplanetary disk that would eventually become our solar system. The comet contains materials that originated from a wide range of distances from the Sun and even material from the interstellar medium that predated the formation of the solar system.

The comet's appearance today is very different from its primordial one and changes with every perihelion pass. Some comets, so-called sungrazers, do not survive their first close passage at the Sun, while others, such as 1P/Halley, may have already visited the inner solar system thousands of times. On its current orbit, 67P will return, but how many times—and in how many pieces—nobody knows. NASA is now considering a mission to bring back a sample from 67P. One day, we may return to see how much it has changed.

The Rosetta team has exerted considerable effort to make all Rosetta data publicly available. Would you like to rummage through thousands of images to find your personal favorite? Go to **rosetta-osiris.eu** and **imagearchives.esac.esa.int**.

MAKOTO YOSHIKAWA *is JAXA's mission manager for Hayabusa2.* **ELIZABETH TASKER** *is an associate professor at ISAS, JAXA.*

JAXA/Tokyo University/Kochi University/Rikkyo University/Nagoya University/Chiba Institute of Technology/Meiji University/Aizu University/AIST

LEFT *The moment that Hayabusa2 contacted asteroid Ryugu, it fired a bullet through its sampler horn (center) to knock material loose from the surface and then immediately fired its thrusters to ascend. This photo, taken from an altitude of 8 meters, demonstrated the success of the bullet; dark-colored fragments tumble in Hayabusa2's shadow in the space beneath the craft.*

Treasure Hunting With Hayabusa2

JAXA's Fleet of Mini-Robots Lands on a World Full of Surprises

IN THE EARLY hours of 22 February, light was just beginning to brighten the campus of JAXA's Institute of Space and Astronautical Sciences (ISAS) in Kanagawa, Japan. It should have been a quiet time, but the Hayabusa2 control room was packed with people. We were about to land on an asteroid.

More than 340 million kilometers (210 million miles) away from us, our spacecraft hovered only meters above asteroid 162173 Ryugu, making sure of its targeting. Then, like its namesake peregrine falcon, Hayabusa2 descended and snatched a sample. When we received the images from the touchdown, we were surprised to see a dark stain over the sample site. Ryugu was already the darkest world ever visited; our brief touchdown had left it darker.

MISSION TO A NEO

Near-Earth objects (NEOs) like Ryugu are thought to have once been part of larger bodies that orbited in the asteroid belt between Mars and Jupiter. Collisions between asteroids and the push from solar radiation can move these bodies onto slightly different trajectories. These small changes can have orbital dynamics effects, such as a close approach to Mars that greatly changes the asteroid's orbit so that it approaches the orbit of Earth as a NEO.

The Hayabusa2 mission is analyzing Ryugu's composition through remote observation. These data, together with the examination of returned samples, should give us clues to this asteroid's parentage. We can use this history to map the movement of water and organics

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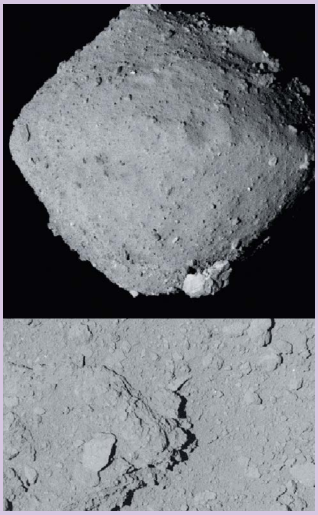
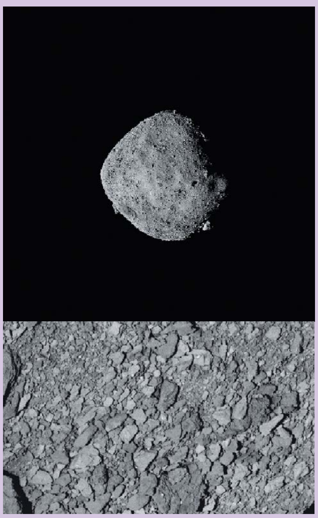
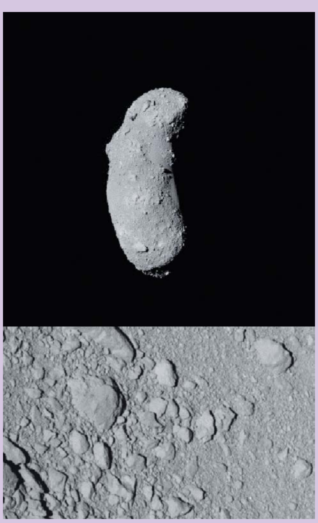
Read this article in Japanese at
planet.ly/haya2jaxa



162173 Ryugu 1.0x0.9km



101955 Bennu 0.5km



25143 Itokawa 0.5x0.3x0.2km

Emily Lakdawalla, using data from JAXA/ISAS (Ryugu, Itokawa) and NASA/JPL/U. Arizona (Bennu)

through the solar system and to the terrestrial worlds. While returning a sample is a challenging and risky endeavor, the analyses that can be performed in a laboratory back here on the ground greatly outstrip anything that can be achieved in space.

The predecessor of Hayabusa2—the spacecraft Hayabusa—returned to Earth with a sample from an S-type asteroid, 25143 Itokawa, in 2010 (see *The Planetary Report* 30, no. 4). Ryugu is a C-type, or carbonaceous asteroid, a categorization for primitive asteroids that are expected to contain carbon-rich material. One theory for how Earth became habitable suggests that our young planet was pelted with meteorites from asteroids like Ryugu. These delivered water and simple organics that formed our seas and triggered the start of biology.

Testing this hypothesis drives the science behind Hayabusa2. If samples from asteroid Ryugu are found to contain hydrated (water-bearing) minerals or organic compounds that match those on Earth, then C-type asteroids may be a key component to forming a livable world.

TREASURE BOX

The Hayabusa2 asteroid explorer mission launched on 3 December 2014. Some 1,302 days later, the spacecraft arrived at its destination. On 27 June 2018, the spacecraft thrusters fired to maintain a constant position 20 kilometers (12 miles) from the asteroid on a line between Earth and Ryugu. This is our "home position," where we perform the majority of our remote observations. Our instruments revealed a new world that surprised the whole team.

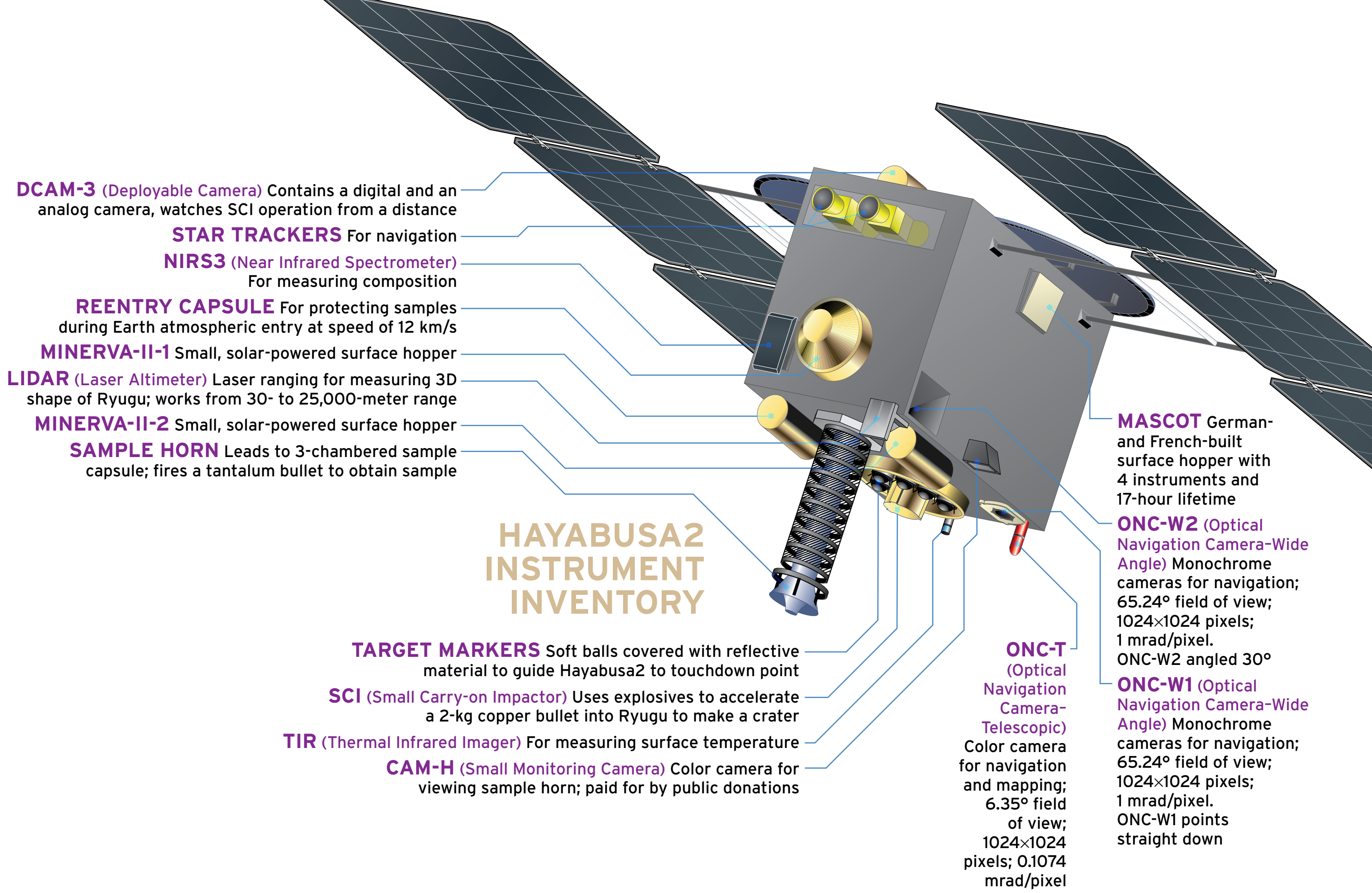
Ryugu is roughly 1 kilometer (0.6 miles) across and is shaped like a spinning top (or abacus bead), with a thick equatorial ridge. One of the most visually striking features is a 290-meter-diameter crater that straddles the equator, which we named Urashima. Urashima is the name of a character in Japanese legend who traveled to a dragon's underwater palace, Ryugu castle, and brought back a treasure box.

The top shape was a surprise. Rapidly rotating bodies experience a centrifugal force that is the same outward push you feel on a merry-go-round. This can push material toward the equator to create the bulging shape of a spinning top. However, Ryugu rotates only once every 7.6 hours, which is too slow for reshaping by centrifugal force to occur. If rotation is the cause of the top shape, then the asteroid must have been spinning faster in the past.

Seen through the 7 different filters on the telescopic optical navigation camera, Ryugu appears homogenous in color, with a slight blue tinge to the equatorial ridge. The color homogeneity is consistent with the hypothesis that Ryugu formed from fragments of a larger asteroid that became well mixed as they coalesced. After it formed, the surface of Ryugu was weathered by radiation and light from the Sun, cosmic rays, and collisions with micrometeorites. This space weathering tends to make a surface darker and redder. When loose material slides down the slope of the steep equatorial ridge, the slides expose fresher material, offering a likely explanation for the ridge's bluer hue.

The expected collisional history for NEOs meant that we anticipated that Ryugu would have a "rubble-pile" structure: rather than

MAKOTO YOSHIKAWA *is mission manager for Hayabusa2 at the Japan Aerospace Exploration Agency (JAXA) Institute of Space and Astronautical Sciences (ISAS). He specializes in celestial mechanics, particularly orbital analysis of small solar system bodies. He is also interested in the issue of planetary defense, which concerns potential Earth impacts from celestial bodies.* **ELIZABETH TASKER** *is an associate professor at the Japan Aerospace Exploration Agency (JAXA) Institute of Space and Astronautical Sciences (ISAS). Her research uses computer models to explore the formation of planets and galaxies. Her popular science book,* The Planet Factory, *was published in 2017.*



a coherent body, it's made of rocks held loosely together by the asteroid's gravity. We had expected to see a surface pitted with craters and boulders, interspersed with flatter regions and covered with a layer of finer-grained regolith. However, we were shocked to find that Ryugu appears to have almost no fine-grained regolith. A global look at Ryugu shows a homogeneous spread of boulders larger than 8 meters, while closer inspection reveals a high density of boulders about 1 meter in size. The largest boulder, 130 meters across and named Otohime Saxum, sits near the south pole.

Itokawa (the destination of Hayabusa) also had a surface covered in boulders. However, this asteroid had a flat plain with a width of about 50 meters covered with approximately centimeter-sized grains of regolith. We had expected a similar open space on Ryugu, and its absence made landing a serious challenge.

ROVING AN ASTEROID

Hayabusa2 has 4 different types of surface operations. The spacecraft carried 3 rovers, a European-built lander, and a Small Carry-on Impactor (SCI) for generating an artificial crater to expose subsurface material. The spacecraft itself also needed to touch the surface to gather material.

After almost 2 months of remote observations, the Japanese and international team members of the Hayabusa2 Joint Science Team gathered at ISAS to choose landing sites. Data from optical navigation cameras and a laser altimeter had been used to create a 3-dimensional model of the asteroid to guide the selection. Considerations such as surface temperature, local slope, and boulder density were major factors for the landing site selections, which also had to be safely separated in distance so as not to interfere with one another.

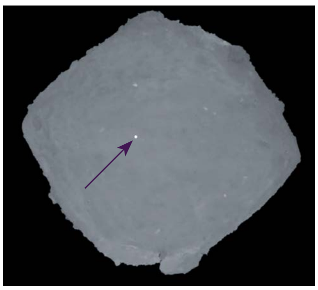
The day of intense discussion resulted in choosing sites on the asteroid's northern side for the rovers, the southern side for the lander, and close to the equator for touchdown. The sites were also separated in longitude around the asteroid.

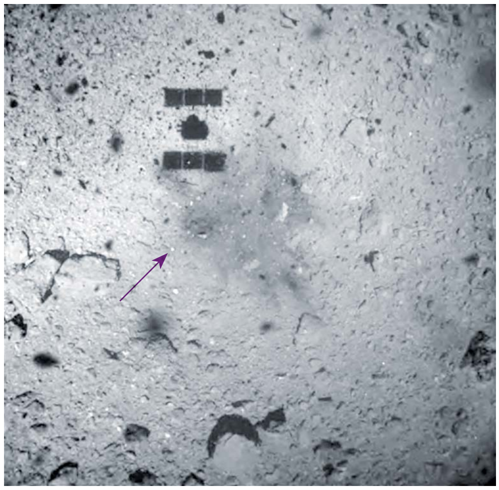
About a month later on 21 September, Hayabusa2 descended to a low altitude of about 55 meters over Ryugu's surface and separated 2 of the rovers, MINERVA-II-1A and -1B, later named HIBOU and OWL. They were designed to test motion in a low-gravity environment. On Ryugu, there is not enough friction for wheels to roll.

ABOVE *The Hayabusa2 mission is examining Ryugu using remote-sensing instruments, rovers, and a lander, with an impact experiment to expose a sample of subsurface material to carry back to Earth.*

OPPOSITE PAGE *Hayabusa2's target asteroid, Ryugu, is very small but still larger than OSIRIS-REx's Bennu and Hayabusa's Itokawa. All have boulder-rich surfaces, but Ryugu and Bennu have less dust and fine gravel than Itokawa. Each closeup is 60 meters wide.*

Emily Lakdawalla, Charles H. Braden, and Loren A. Roberts for The Planetary Society





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LEFT *With the Sun directly behind Hayabusa2 on 8 January 2019, the tiny target marker makes its presence known by its brilliant reflecting glint (purple arrow). Ryugu looks strangely flat because in this geometry, called opposition, Hayabusa2 can see no cast shadows.*

CENTER *Hayabusa2 snapped this picture while ascending from its sample grab. Hayabusa2's shadow can be seen along with a dark splotch where the spacecraft's thrusters lifted dust and fragments off Ryugu's surface. The purple arrow points to the bright target marker.*

RIGHT *Hayabusa2's ONC-W1 camera captured this view of the Small Carry-on Impactor (SCI) just seconds after separation. It successfully produced a crater on Ryugu on 5 April.*

The rovers therefore have an internal weight that rotates and rebounds to create a force that hops the rover across the surface. The rovers are solar powered and autonomous, hopping when their batteries are sufficiently charged. Cameras and thermal sensors send data back to Hayabusa2, providing a close-up look at the rugged landscape.

HIBOU and OWL transmitted data for 113 and 10 Ryugu days respectively and then went quiet. They may have moved into a shadowed region on the asteroid surface and may have been unable to recharge their batteries. It may be possible to regain contact with one or both as the Sun shifts on Ryugu's surface later in the year.

On 3 October, Hayabusa2 descended once again to deploy the Mobile Asteroid Surface Scout (MASCOT) lander. The German (DLR) and French (CNES) space agencies provided this powerful, shoebox-sized laboratory. The lander was equipped with 4 instruments to image the surface, measure surface temperature and any magnetic field, and analyze the surface composition. Powered by a lithium battery, MASCOT was designed to last about 16 hours, or 2 asteroid days. It exceeded this expectation by operating for 17 hours, and the results are currently being analyzed by the European team.

The original plan was for Hayabusa2 to collect a sample at the end of October 2018. However, with the surface being more treacherous than expected, we decided to postpone that in order to further analyze a safe way to operate the touchdown. At the end of 2018, everyone on the team celebrated with a limited-edition "touchdown beer," created by the Yatsugatake Brewery in Kiyosato. As Japan welcomed in the new year, we began preparations for descending.

SAMPLE GRAB

To confirm the technique for touchdown and to investigate the landscape in more detail, we performed 3 rehearsal descents in September and October 2018. During the third rehearsal, Hayabusa2 descended to an altitude of 12 meters and dropped a target marker, a highly reflective, baseball-sized object. A flashlight on the spacecraft can illuminate the marker while optical navigation cameras take photos. The reflective surface makes the marker easy to spot. The spacecraft can track the marker's position and use that to navigate precisely during touchdown.

The high-resolution rehearsal images revealed exactly how challenging Ryugu's terrain would be for sampling. Although the boulder density was lower in the chosen landing site than elsewhere on the asteroid, the flat area we finally selected for landing was only about 6 meters across. This was far smaller than the 100-meter flat region required by our original touchdown plan.

Touchdown was scheduled for about 8:00 a.m. Japan time on 22 February (23:00 UTC on 21 February), with the descent toward the surface beginning the morning before.

As the sampler horn touched the surface, Hayabusa2 fired a 5-gram tantalum bullet along its sampler horn and into the asteroid. This was designed to break up larger boulders and stir the surface material to allow a portion to rise up inside the sampler horn and into the sample container. Shortly after the spacecraft began to ascend, Hayabusa2 decelerated so that any material caught in the inverted teeth of the horn tip would be lifted into the container. At 11:20 a.m. (02:20 UTC), the first of the 3 chambers ("room A") within the container closed. We were satisfied that we had collected our first sample.

ASTEROID STRIKE

In March, Hayabusa2 prepared to use its Small Carry-on Impactor (SCI) to generate an artificial crater at a site about 100 degrees east of the first touchdown point.

The SCI is a cylindrical container containing 9.5 kilograms (21 pounds) of explosive. When detonated, the explosion rapidly accelerates a 2-kilogram (4.4-pound) copper plate on the base of the SCI to a speed of about 2,000 meters per second. The plate strikes the asteroid to freshly expose subsurface material. This new crater will allow us to see material unaltered by space weathering, confirming if the blue tinge on the equatorial ridge is indeed from a less-weathered surface.

The SCI experiment worked as planned on 5 April. Before the SCI detonated, Hayabusa2 began an evacuation trajectory that took the spacecraft behind the asteroid and out to an altitude of about 3,500 meters at the moment of the explosion. We did not want to get hit by any escaping debris from the impact!

As this article goes to press, we are deciding whether to collect a second sample from a region close to the crater or from a second site on the asteroid. This second sample will likely be our last since by July, Ryugu will be nearing the perihelion of its orbit, and its surface will become too warm for touchdown operations.

Hayabusa2 will then continue to examine Ryugu remotely until the end of the year and return to Earth with the samples at the end of 2020. It is going to be a busy few years!

Documenting Debris

Since we wanted to see what happened when the SCI exploded, Hayabusa2 released a deployable camera called DCAM3 before evacuating. This camera monitored the action and relayed images back to the spacecraft. Through the eyes of DCAM3, we saw debris lifted off the surface of Ryugu as the SCI hit.

We allowed time for the debris to clear from the vicinity of Ryugu, and then Hayabusa2 descended again to observe the impact spot and analyze the crater with the onboard suite of instruments. We found that the SCI had created a crater about 10 meters in diameter inside an affected area about double that size.

TOP *DCAM3 worked successfully to document the spreading cone-shaped ejecta curtain from the SCI impact.*

BOTTOM *On 25 April, Hayabusa2 found the impact site. The science team will use stereo images to analyze the shape and size of the crater and spectrometers to compare the weathered surface to the freshly exposed material.*

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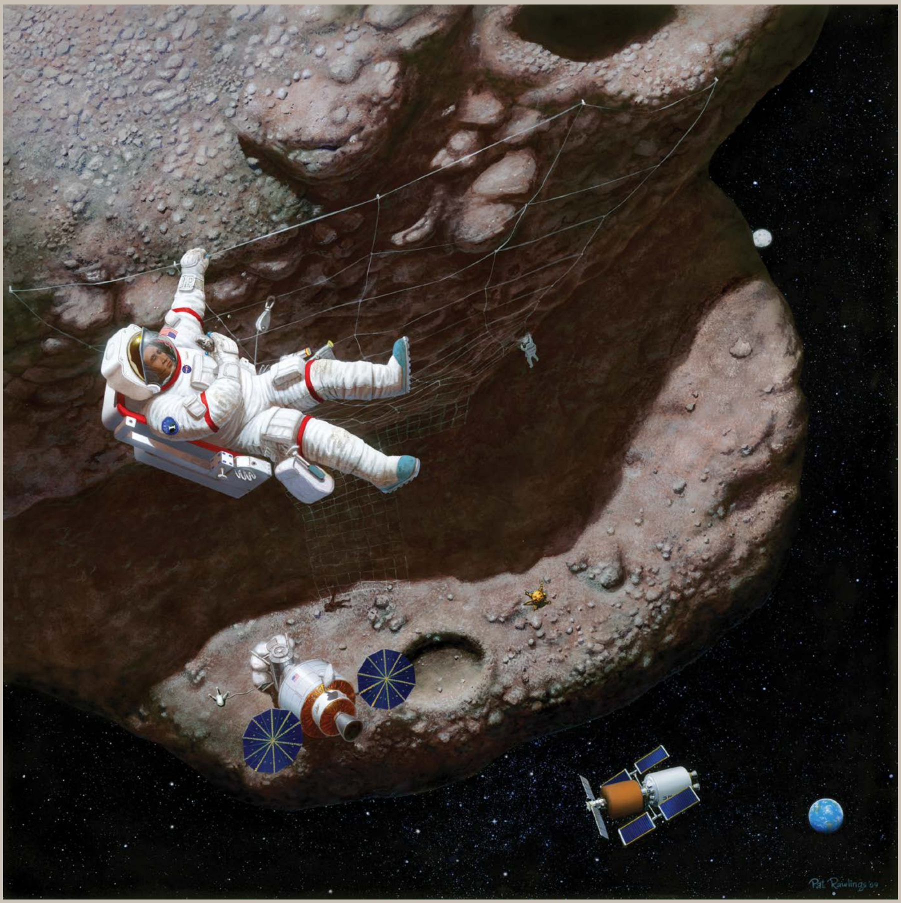

Pat Rawlings, *Summit*

Pat Rawlings envisions a future in which humans explore potentially resource-rich, near-Earth asteroids. He explains: "A planetary geologist uses an anchored net to traverse the highly irregular, loosely packed regolith of an ancient binary asteroid. Using centuries-old tech of a rock hammer and cloth sample bag, the explorer selects unique samples for later inspection on the transfer vehicle that is station-keeping nearby. The module that will carry the explorers back to the mothership has docked with the asteroid using tethered penetrators and Mars Pathfinder heritage airbag impact attenuators."