THE PLANETARY SOCIETY

# THE PLANETARY REPORT

SEPTEMBER EQUINOX 2018

VOLUME 38, NUMBER 3

*planetary.org*

## RETURN TO MERCURY

**EUROPE AND JAPAN AIM BEPICOLOMBO TOWARD NEW DISCOVERIES**

CHINA & INDIA LUNAR MISSIONS ✻ PLANETVAC TESTS ✻ AUSTRALIAN SPACE INITIATIVE

Dear loyal members of The Planetary Society,

It is my great pleasure to accept editorial responsibility for *The Planetary Report*. I'm honored to pick up the red pen formerly held by Charlene Anderson, Jennifer Vaughn, and Donna Stevens.

I look forward to the challenge of meeting the high standard set by Donna. For nearly 30 years, she dedicated herself to showing off the beauty of space exploration in *The Planetary Report*'s pages and on its covers. She has always been thoughtful, precise, and deeply invested in getting every detail right. I want to thank Donna for her mentoring during the last 6 months. My goal is to achieve a similar balance of editorial and aesthetic quality in the magazine.

I have served The Planetary Society since 2001, first as your science and technology coordinator and later as your senior editor and planetary evangelist. In 2004, Charlene, then editor of both *The Planetary Report* and *planetary.org*, put me to work writing about Cassini-Huygens for the website. It was my first of many science-writing beats.

The transition wasn't seamless; my recent academic training as a planetary geologist had made my writing stilted, convoluted, and dull. I credit Charlene with training me to write for the public. She peppered her advice with anecdotes about the arguments she'd had with Carl Sagan about grammar and style. (As one example, she told me that Carl disliked the word "stuff," demanding more precise language instead. I've always found that funny, since I can hear him quite clearly in my head saying "We are made of star stuff.") After 2 years under Charlene's tutelage, I was freed to exercise editorial control over the website, a duty I've fulfilled ever since.

All of which is to say: I'm steeped in Planetary Society history and plan to carry on the established, successful format of bringing the voices of Earth's planetary explorers directly to you. At the same time, I've been charged with the task of reexamining *The Planetary Report* and bringing the magazine and the website closer together, unifying our messages and storytelling across media. Longtime readers will notice some changes to our style in this issue, and you'll see other changes in the months and years ahead. I and the rest of us at The Planetary Society welcome your feedback and suggestions for both the magazine and the website. Please don't hesitate to contact us at *tps@planetary.org*.

Sincerely,

Emily Lakdawalla

Emily Lakdawalla

THE PLANETARY SOCIETY

**ON THE COVER: So far, Mercury has been visited by only two spacecraft. This enhanced-color mosaic of Mercury was assembled by Ted Stryk from many individual frames taken by Mariner 10 as it departed Mercury after its first flyby on March 29, 1974. The subtle colors weren't visible in contemporary versions of the mosaic; returning to it with modern digital image processing, Stryk found orange, purple, and brown shades in the color data. *Credit: NASA/JPL/Ted Stryk***

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*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.

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

# On Orbits and Org Charts

## Putting Membership Dollars to Work Across the Globe

**TO ANSWER THE** traditional question "What did you do on your summer vacation?," here at The Planetary Society, we got ready to launch LightSail 2. It's a little bit difficult to describe how much this next mission means to the Society and to me. Three years ago, we managed to fly LightSail 1. It was a big success, but there are even better things ahead. Our second solar sail mission could launch as early as November from Cape Canaveral. We do not yet have a specific launch date, but once we do, we'll share it with you on our website and via email. I hope many of you will consider a trip to Cape Canaveral for the launch. It'll be historic and spectacular.

Our small solar sail spacecraft will be atop a Falcon Heavy rocket, the vehicle's second-ever flight. Our LightSail 2 spacecraft is far more capable than its predecessor. We will get to a higher orbit than we could with LightSail 1. Because we will maneuver with each orbit, add kinetic energy, and gain orbital altitude, LightSail 2 will be flying and visible for many months. This is a dream of our founders; it goes back to the 1970s, even before they created The Planetary Society. But it's you—and tens of thousands of other Planetary Society members and supporters—who funded this dream and made it a reality.

Every time I think of it, I am delighted that well over half of you reading along here joined the Society (and thank you for that) many years after our solar sail projects got underway. What an exciting time to join the world's largest space team! Maybe you joined to support LightSail or one of our other citizen-funded technology projects, like PlanetVac; maybe you appreciate learning about planetary exploration through The Planetary Society's blogs, podcasts, and *The Planetary Report*; or perhaps you were inspired to advocate for more missions, more science, and more discoveries. The Planetary Society exists to connect you to space. That's our business, and we're proud to see this community of passionate explorers expand.

No matter where you live on Earth's surface, you are probably aware of the extraordinary political events that have transpired in the United States. It's important to keep in mind, though, that the regular processes of the U.S. government keep ticking and grinding away. A very large fraction of the U.S. Congress may change from conservative to progressive or progressive to conservative in the midterm election in November of this year. This could have far-reaching effects on the world's largest space agency, NASA, and other space agencies around the world. Your advocacy team is positioned to establish and maintain relationships with the many new politicians and staffers who will be coming to Washington, D.C.

While these significant programs grow and move apace, we have been working to develop and solidify our goals and objectives over the next 5 years. We want to expand our role in Washington, Paris, Tokyo, Ottawa, Johannesburg, and Canberra. Someday, I'd like us to have volunteers and good relations with space enthusiasts in Baikonur and Beijing. In short, we want more people to be more engaged and more connected to space exploration. Our growth and growth in influence is important to us as an organization. It's important to me as your CEO, and it's especially important to me as a citizen of this world. I want humankind to be completely capable of detecting and then deflecting an asteroid or comet headed for our orbit. I very much want us as a species to conduct a robust, reasonably priced search



Judy Chu photo: Antonio Peronance for The Planetary Society; The Planetary Society

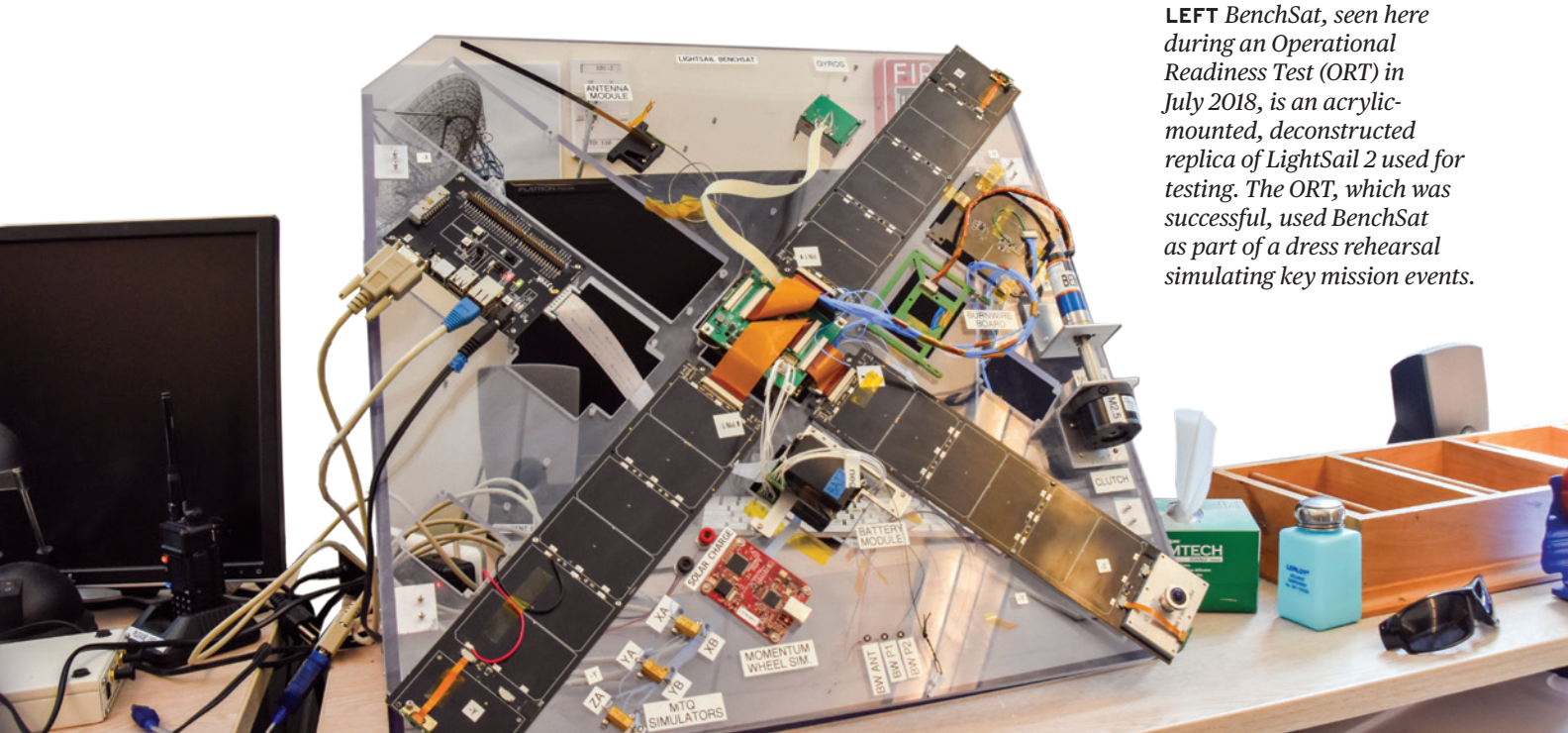

for life—or even survey of life—in our solar system and beyond. We can do this because of you.

As the guy at the top of our organization, I often reflect on the "org" chart. As a young engineer, I fit in somewhere on an org chart in various aerospace companies. Right now, my box would likely be shown at the top of the page (with the Board of Directors staring down from above). For us here at your Planetary Society, you are at the top. You as a member drive this organization. We work to connect you with space exploration, and together we're working to ensure that everyone everywhere will one day have a hand in directing our future in space. I hope you'll write to me and to us here at The Planetary Society. Where should we be heading? What's your favorite place in space? What matters most to you? Let's go!

Bill Nye

**ABOVE LEFT** *Representative Judy Chu (D-CA-27) learns about the Mylar used in The Planetary Society's LightSail project from Bill Nye during the Planetary Science Caucus launch event on 9 May 2018.*

**ABOVE RIGHT** *LightSail 2 team members gather at the LightSail exhibit in the foyer of The Planetary Society headquarters. Members are welcome to drop by to visit.*




**LEFT** *BenchSat, seen here during an Operational Readiness Test (ORT) in July 2018, is an acrylic-mounted, deconstructed replica of LightSail 2 used for testing. The ORT, which was successful, used BenchSat as part of a dress rehearsal simulating key mission events.*

**ELSA MONTAGNON** *is the spacecraft operations manager for the BepiColombo mission.*

# Voyage to Mercury

## The BepiColombo Mission Prepares for Launch

**ABOVE** *BepiColombo approaches Mercury for one of its 6 flybys, the ion thrusters on its broad-winged Mercury Transfer Module (MTM) firing. Two months before BepiColombo enters Mercury orbit, it will discard the MTM.*

**EUROPE AND JAPAN** are ready to journey to Mercury together. The BepiColombo mission is a collaborative project between the European Space Agency (ESA) and Japan Space Exploration Agency (JAXA), launching in October or November 2018 on an Ariane 5 rocket.

Because it occupies an extreme position close to our Sun, Mercury plays an important role in helping scientists to develop theories of solar system formation. BepiColombo will continue the global study of Mercury started by Mariner 10 and continued by MESSENGER. But before BepiColombo can study Mercury, it faces a long journey. I am part of the operations team that will see the spacecraft safely there.

The BepiColombo mission will deliver two independent spacecraft to Mercury. ESA's Mercury Planetary Orbiter (MPO) carries 11 instruments dedicated to the study of Mercury's surface, interior structure, composition, exosphere, and magnetic field. Its radio science experiment will also perform a test of Einstein's theory of relativity. JAXA's Mercury Magnetospheric Orbiter (MMO, recently named "Mio" through a public contest) carries instruments mostly dedicated to the study of the magnetic field, waves, and particles in the space environment around Mercury.

Illustration: ESA/ATG medialab; Mercury: NASA/JPL


To enable its journey to Mercury, BepiColombo has two other hardware components. The Mercury Transfer Module (MTM) is responsible for propulsion through the 7-year interplanetary voyage of the composite spacecraft. Equipped with its own set of solar arrays, power conditioning and distribution system, and chemical and electric propulsion, MTM is controlled by MPO's computer. Another component, a protective structure referred to as MOSIF, will shield MMO from excessive solar heating until Mercury orbit insertion.

## LAUNCH AND EARLY OPERATIONS

The first few days of the mission are intensely busy. About 40 minutes after launch, once the spacecraft separates from its rocket, it will make contact with us through ESA's New Norcia communications station. BepiColombo will configure itself for interplanetary cruise by priming its chemical thrusters, establishing its orientation in space, and deploying the large MTM and smaller MPO solar arrays. The automatic sequence completes in about 1 hour.

Over the next 2.5 days, the Mission Control Team at the European Space Operations Centre (ESOC) will bring the spacecraft into its normal operating mode. The 100-person Mission Control Team includes experts on spacecraft operations, flight dynamics, ground software, ground station, and communications. The team works 24 hours per day for 3 days, in 2 shifts of 12 hours each. The team will activate and check out star trackers and reaction wheels, deploy medium- and high-gain antennas, and switch to using the medium-gain antenna, enabling faster telecommunications. A test maneuver using MTM chemical propulsion thrusters concludes the Launch and Early Orbit Phase.

## NEAR-EARTH COMMISSIONING

As long as the spacecraft is close to Earth, round-trip communications are quick, and the Mission Control Team will work to perform a more in-depth checkout of the spacecraft subsystems and instruments. Planned to last about 2 months, this phase requires the continuous support of an 11-person Flight Control Team. Representatives of the project, industry, scientific payload teams, and JAXA will be present at ESOC to support specific operations.

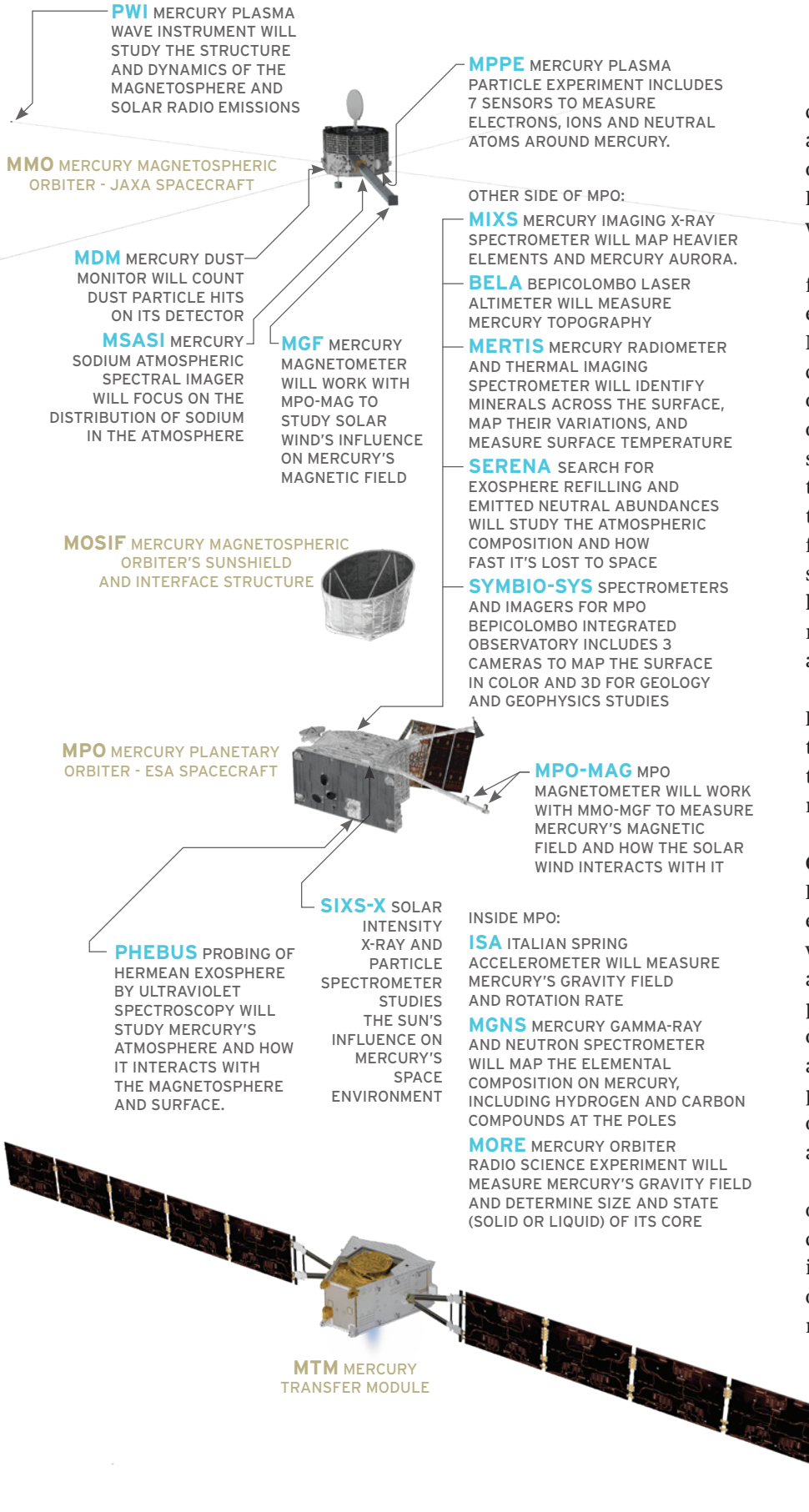
The first 5 weeks will focus on the platform subsystems: data handling, attitude and orbit control, propulsion subsystems, telecommunications, and power. As part of this phase,

**TOP** *ESA has established a worldwide network of 35-meter radio antennas for round-the-clock communication with its planetary missions. The dish at New Norcia in western Australia will be the first to receive a signal from BepiColombo after launch.*

**BOTTOM** *BepiColombo Ground Segment Team, ready for the final launch preparations.*

**ELSA MONTAGNON** *is an expert in interplanetary spacecraft operations. She has engineering degrees from the Ecole Centrale Paris and Technical University of Munich. She joined ESA in 1999. Before becoming the BepiColombo spacecraft operations manager in 2007, she previously worked as flight operations system engineer on ESA's Rosetta mission. She supported the Philae landing as deputy flight director.*

ESA; ESA/P. Shlyaev




communications will be moved to the high-gain antenna, which will serve as the primary means of communication throughout the mission. Each of the 4 electric propulsion thrusters will be test-fired for a few hours.

During this phase, we will check out the function of MMO's subsystems and activate each science instrument on both MPO and MMO for a functional checkout. However, no campaign of scientific observations nor checks of simultaneous instrument operations will occur during this phase. Most of the remote sensing instruments on MPO face directly toward MTM during cruise, so they are unable to perform science observations. Still, the functional checkouts produce data that the spacecraft will return to Earth. Payload teams located at ESOC will process the data in near real-time and generate command requests if an instrument exhibits unexpected behavior.

At the end of the Near-Earth Commissioning Phase, ESA will convene a formal review. After the review, a large part of the industrial team that designed and built the spacecraft will be released by ESA.

## CHALLENGES OF ELECTRIC PROPULSION

BepiColombo will be ESA's first interplanetary electric propulsion mission. In preparation, we needed to develop new software and operations concepts. Our first use of MTM's electric propulsion system (see sidebar at right) will occur as soon as near-Earth commissioning activities are complete. Two large electric propulsion periods will occur, each consisting of about 2 months. We refer to such periods as "arcs."

As NASA's ion-powered Dawn mission observed, standard methods of Doppler spacecraft tracking will not be precise enough for interplanetary navigation while we are using our low-thrust ion engines. The mission design requires precise orbit determination weekly for continuous optimization of the thrust level and thrust direction. Therefore, we plan to interrupt the thrust once a week to

ESA/ATG medialab/Loren A. Roberts for The Planetary Society

allow 8 hours of tracking with the high-gain antenna from one of ESA's 35-meter deep space ground stations.

We will gradually phase in electric propulsion operations, regularly increasing the duration of uninterrupted thrust, until we reach the goal of only weekly interruptions. At the moment, only the first electric propulsion arc is being planned in detail. Each arc will be subject to a dedicated planning cycle, typically starting a year prior to the planned start of the arc as per reference trajectory.

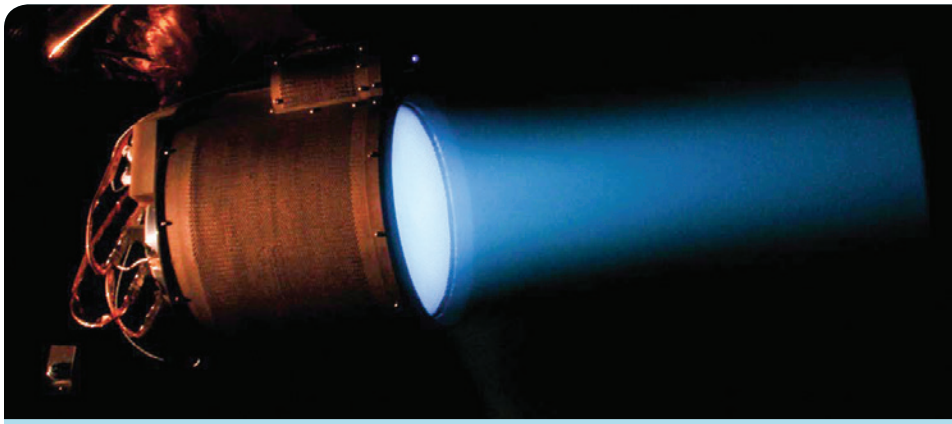
### INTERPLANETARY TRANSFER

The cruise to Mercury lasts 7 years and consists of a mixture of planetary flybys, electric propulsion arcs, and coast arcs. The baseline trajectory foresees 9 planetary swingbys at Earth, Venus, and Mercury. The first part, as the spacecraft cruises from launch to an Earth flyby, constitutes the "cold" phase of the mission, a period where the spacecraft will reach its maximum distance from the Sun, 1.2 AU (180 million kilometers or 110 million miles).

The 10 April 2020 flyby of Earth sets the spacecraft on a course for Venus. After the Earth swingby, the spacecraft will move closer to the Sun. Once it becomes closer to the Sun than Venus at 0.7 AU (100 million kilometers or 65 million miles), it enters the "hot" phase. This mainly affects MTM solar array operations. The maximum-allowed temperature of this critical element of the BepiColombo spacecraft is 190 degrees Celsius (374 degrees Fahrenheit). For electric propulsion during the Earth-to-Earth arc, the array can be kept face-on to the Sun and still stay below this temperature. From a Sun distance of 0.7 AU inward, the array needs to be tilted away from the Sun to keep it from overheating.

Tilting the solar arrays will reduce the amount of electricity they can generate, and we must predict their performance in order to select what electric propulsion thrust level to command. While observing how solar array performance degrades with time, our predictions will be updated accordingly. During coast arcs, when we will not be firing the electric thrusters, the arrays will be angled away from the Sun in order to minimize their degradation.

The two flybys past Venus on 16 October 2020 and 11 August 2021 will change the spacecraft's orbital plane to match Mercury's and also drop the orbit perihelion much closer to the Sun, nearly to the distance of Mercury's orbit. Long arcs of electric propulsion and 6 swingbys of Mercury will reduce the spacecraft's relative velocity and reduce its orbit aphelion to get closer and closer to Mercury's orbit. The orbit matching will be so close that BepiColombo would be weakly captured by Mercury's gravity on orbit insertion day, even if it does not fire its rockets.

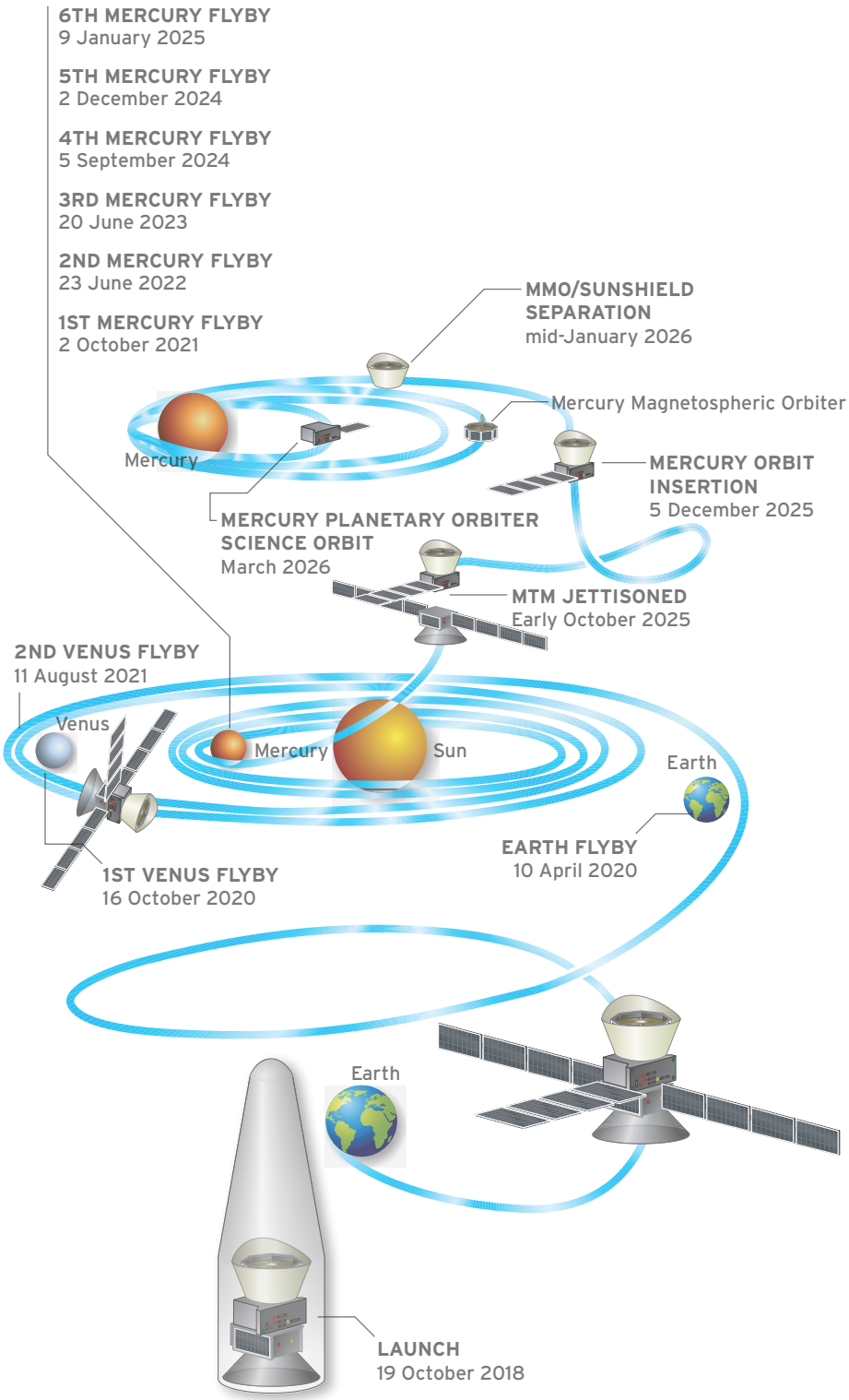


ESA

## Solar Electric Propulsion

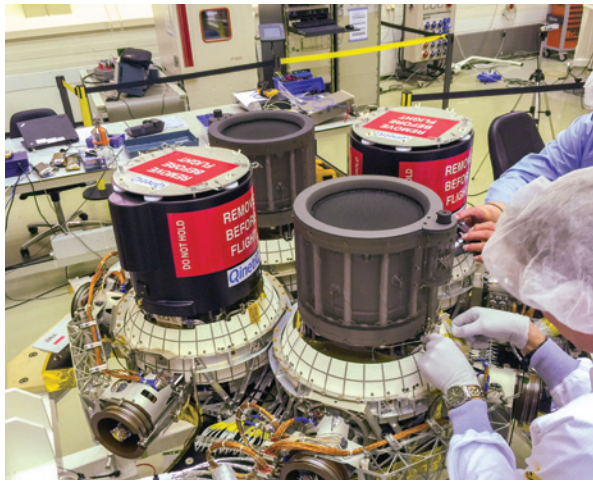
BepiColombo is the first ESA interplanetary mission to rely on solar electric propulsion, but many previous NASA and JAXA missions, including Deep Space 1, Dawn, Hayabusa, and Hayabusa2 have employed it to great success. The spacecraft's solar panels generate electricity, which is used to ionize xenon atoms. The ion engine generates powerful magnetic fields that propel the positively charged xenon atoms out of the thruster at extremely high speeds, much faster than a chemical rocket expels its propellant. (The engine also emits a neutralizing stream of electrons so that the net charge of the spacecraft remains neutral.) The high speed of the xenon atoms makes ion engines more efficient than chemical engines, but an ion engine expels far less mass per unit time than chemical thrusters do. Thus, ion engines must be fired continuously over long periods of time—months to years—to accomplish their task of bending a spacecraft's orbit.

**ABOVE** *An ion thruster emits a glowing stream of xenon during a test firing. BepiColombo's Mercury Transfer Module will use 4 of these thrusters, powered by solar panels spanning 30 meters, to take the spacecraft from Earth to Mercury.*




### INSTRUMENT OPERATIONS DURING CRUISE

When the mission was first outlined, ESA did not plan to perform any scientific observations during the interplanetary cruise phase. The only baselined instrument operations were a radio science campaign during one of the solar conjunctions (when the Sun lies between the spacecraft and Earth) and a checkout every 6 months.



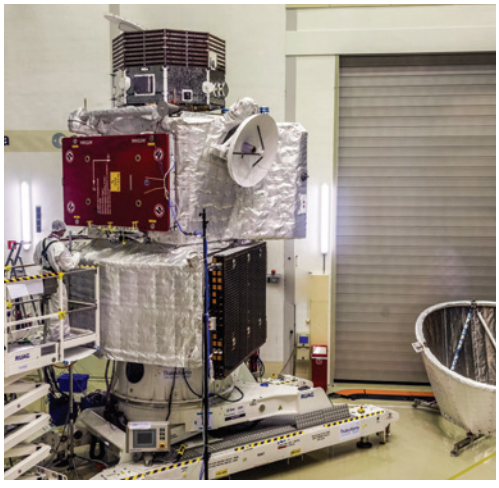
The views from most remote-sensing instruments are blocked during cruise by MTM, but we now plan to operate all other instruments on a best-effort basis during coast arcs and outside critical mission operations. In particular, the BepiColombo scientific community has expressed a strong interest in making observations during the 2 Venus swingbys. We have tight constraints on the orientation of our spacecraft that impose limits on what the instruments can do, but an initial assessment indicates that there are options to accommodate the scientists' requests. We will work with the scientists to plan operations during the Venus flyby, beginning in mid-2019.

### MERCURY ARRIVAL AND SCIENCE

Two months before Mercury orbit insertion, BepiColombo will jettison MTM, its work complete; BepiColombo will use a chemical

ESA/M. Gaido/Loren A. Roberts for The Planetary Society

thruster system for the rest of the mission. Orbit insertion will start with a rocket firing on 5 December 2025. We will command 14 more maneuvers over a period of 100 days to bring first MMO and then MPO into their targeted scientific orbits. The two spacecraft will separate once they have reached the planned MMO orbit, and then MPO will continue to descend. Shortly after MMO separation, MOSIF will be jettisoned.



**OPPOSITE PAGE** *Engineers attach 4 ion thrusters to BepiColombo's Mercury Transfer Module in April 2016.*

**THIS PAGE, LEFT** *The flight model of the BepiColombo Mercury Magnetospheric Orbiter (MMO), which arrived at ESA's European Space Research and Technology Centre, The Netherlands, in April 2015. The MMO has been lifted off of the base of its transport container and is ready to be mounted on its integration stand.*

**THIS PAGE, RIGHT** *BepiColombo integrated and almost ready for launch.*

This phase is operationally very intense. The first 6 weeks, from the first maneuver to reaching the MMO orbit, are mission critical. The spacecraft must reach MMO's orbit before Mercury reaches aphelion, a period when the BepiColombo orbits will spend periods of every orbit eclipsed by Mercury's shadow. Five maneuvers are required to reach the MMO orbit, spaced by only a few days. Because this period is so critical, we in flight operations will run this part of the sequence in a mode very similar to that of launch and early operations, with a fully capable backup ground station available for tracking and command uplink in case of adverse events at ESOC. All of ESA's 35-meter deep space ground stations will be used, and NASA's Deep Space Network will be asked to support us as well.

After a 30-day commissioning phase, scientific operations will finally start in April 2026. The nominal science mission duration is 1 Earth year, with a built-in extension capability of another year. Operations will remain critical and very intense due to the short orbital period of the spacecraft (2.3 hours), the need to continuously operate the 11 MPO instruments in order to maximize scientific coverage of the planet, and the scorching thermal environment where external surfaces of the spacecraft are expected to experience temperatures up to 350 degrees Celsius (660 degrees Fahrenheit). As during cruise, the MPO solar array needs to be kept angled away from the Sun at all times. A substantial portion of our work in flight operations is to command the spacecraft's attitude profile (how the spacecraft and solar arrays point) during the normal operations mode and in any backup or safe modes. The spacecraft needs attitude updates no less frequently than every 20 days; the nominal plan foresees weekly updates.

Approved in 2000, the ESA/JAXA BepiColombo mission to Mercury is finally getting ready for launch. The spacecraft has been undergoing its final integration and test activities at Kourou in French Guiana since the beginning of May. At ESOC, the simulation campaign for the launch phase has started. The countdown is running…

MMO Unpacked: ESA/Anneke Le Floc'h; integrated: ESA/C. Carreau

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


**ABOVE** *Volunteers in Western Australia came together to represent The Planetary Society at Astrofest, an annual public celebration of all things space.*

# Supporting A New Space Agency

## Planetary Society Volunteers Maintain Momentum in Australia

**AS THE AUSTRALIAN SPACE** *sector heats up, The Planetary Society's volunteers are building a thriving outreach network to match. Our volunteer coordinator for Australia, Nyssa Lonsdale, reports on how The Planetary Society is reaching out to communities across the country to build nationwide support for space.*

The long-awaited establishment of the Australian Space Agency has awoken a renewed sense of exuberance within national and international science communities. The Australian Space Agency plans to support our commercial space industry, maintain international partnerships, and enhance our reputation for leadership in the space sciences and radio astronomy. It also stands importantly as inspiration for the next generation of researchers, scientists, and engineers.

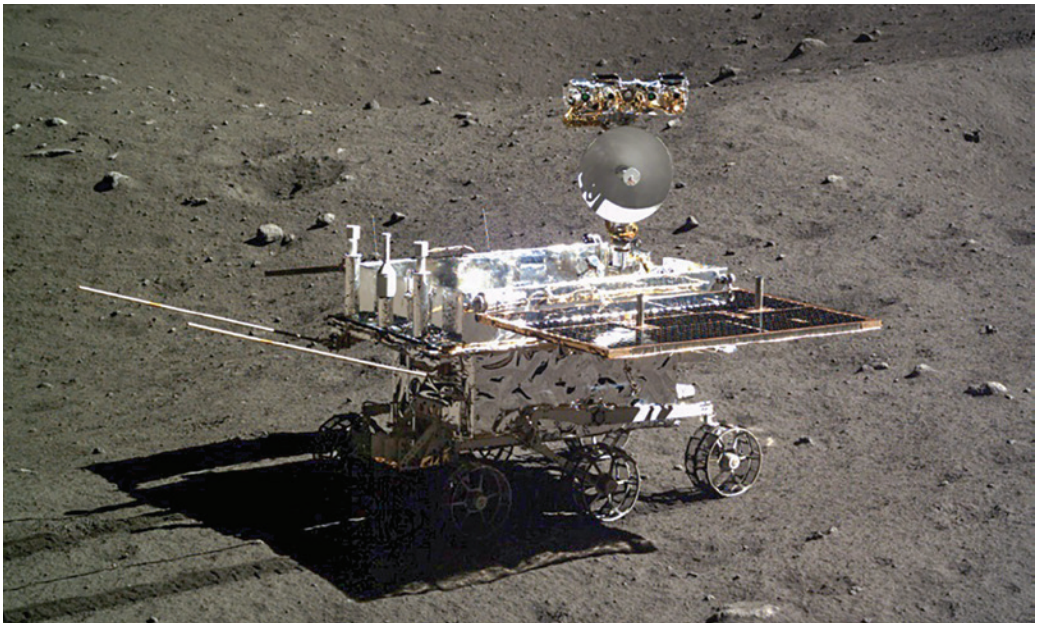
Growing numbers of Planetary Society volunteers are appearing at local Astrofest events to provide physics demonstrations and to raise the profile of space science within the public community. For many of us, promoting astronomy to youth and tackling their inventive questions is the most fulfilling aspect of outreach.

Recently, more than 40,000 people in Australia declared their interest in astronomy in a nationwide endeavor that toppled the Guinness world record for the most people stargazing simultaneously. At the helm were the Australian Broadcasting Corporation and the Australian National University, both of which teamed with astronomy clubs to provide telescopes for the evening. Our members and volunteers championed this event. It was a delight to see so many families captivated by the stars.

Volunteers can have a positive impact on the long-term sustainability of the Australian Space Agency. We can encourage public support and awareness, connect graduates to space careers, and pair science professionals with students. I am delighted to be a part of The Planetary Society's united effort to fuel the imagination of the public and promote Australia's place in space.

Richard Tonello

**LONG XIAO** *is a planetary geoscientist at China University of Geosciences (Wuhan) and Macau University of Science and Technology.*



Chinese Academy of Sciences

# Farside Landing and Nearside Sample Return

## China's New Lunar Missions Are on the Way

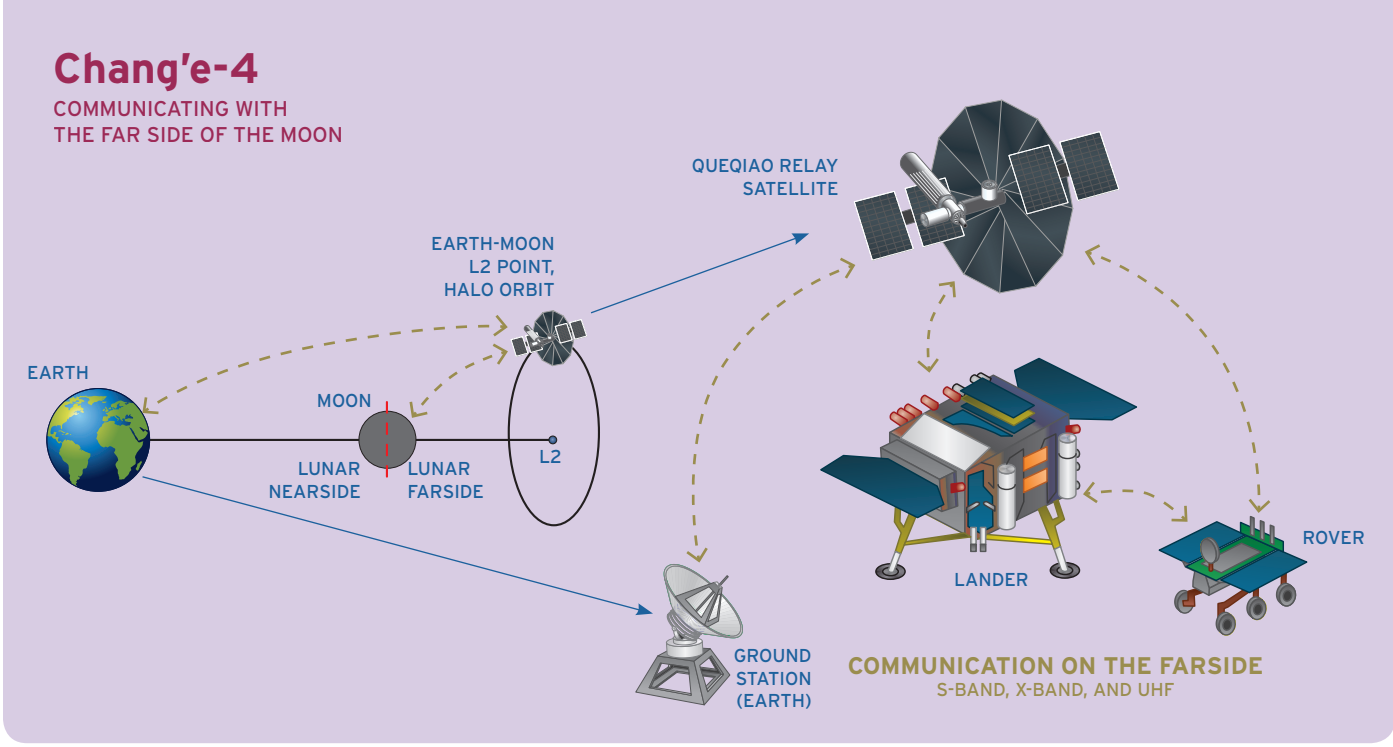
**CHINESE LANDERS** are set to achieve big goals on the Moon in late 2018. One will perform the first-ever landing on the lunar farside, and the other will return samples from the lunar nearside. These two robotic explorers continue a series of successful lunar exploration missions.

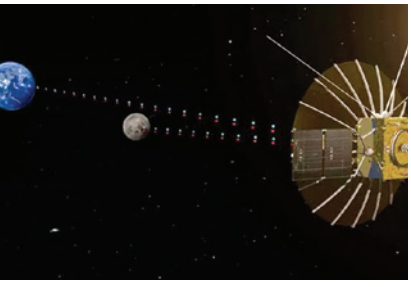
China always planned these missions to be part of a 3-phase robotic lunar exploration program: orbiting (Chang'e-1 and -2), landing (Chang'e-3 and -4), and sample return (Chang'e-5 and -6). The Chinese space agency has produced two spacecraft for each phase, launching one at a time. Chang'e-4 launches in 2018 and Chang'e-5 in 2019.

China's lunar exploration began with the Chang'e-1 and Chang'e-2 orbiters in 2007 and 2010, named for a mythological Moon goddess. These first two missions demonstrated technical success and were China's first explorations beyond Earth's orbit. They acquired high-resolution global images, measured microwave radar properties of the lunar surface and shallow subsurface, mapped elemental composition, and sampled the lunar plasma and radiation environment.

Chang'e-3 followed in 2013. The Chang'e-3 lander and its rover, Yutu ("Jade Rabbit," another resident of the Moon in Chinese mythology), were the first visitors from China to land on an extraterrestrial surface. They also performed the first soft landing on the Moon since the Soviet Union's Luna 24 mission in 1976. The rover explored northern Mare Imbrium, used radar to sense subsurface layering, examined youthful volcanic rocks of a new type, and measured the light-reflecting properties of the regolith (the broken-up rock and dust that make the lunar soil). These achievements produced new knowledge

**ABOVE** *Yutu (or "Jade Rabbit") explores the lunar surface after being deployed by Chang'e-4's predecessor, Chang'e-3. Chang'e-4 will carry a similar rover to the first-ever landing on the lunar farside.*



**ABOVE** *The Chang'e-4 relay satellite, Queqiao, operates in a stable orbit beyond the Moon and is able to see Earth and the lunar farside at the same time. It launched on 21 May 2018 and awaits the lander's arrival.*

about the Moon and also stimulated public enthusiasm, enabling support for further lunar exploration by China.

### CHANG'E-4 TO THE FARSIDE

Chang'e-4 will be humanity's first landed exploration of the lunar farside. The challenge faced by a farside mission is communications. With no view of Earth, there is no way to establish a direct radio link. Thus, the mission will be carried out in 2 steps. On 20 May UTC (21 May in China), China launched a relay satellite toward the Earth-Moon Lagrange Point 2 (L2), located 65,000 kilometers (40,000 miles) beyond the Moon. The Chang'e-4 relay satellite, which is named Queqiao ("Magpie Bridge"), will move in slow circles around the L2 point, remaining visible to both ground stations on Earth and the lander and rover on the lunar farside at all times.

Two microsatellites, Longjiang-1 and Longjiang-2, accompanied Queqiao onto its lunar transfer trajectory. Longjiang-1 failed soon after launch, but Longjiang-2 entered lunar orbit on 25 May. It will perform low-frequency radio astronomy observations, using the Moon to shield its instruments from interference from Earth. It will also take photos of the Moon and Earth using a microcamera contributed by Saudi Arabia.

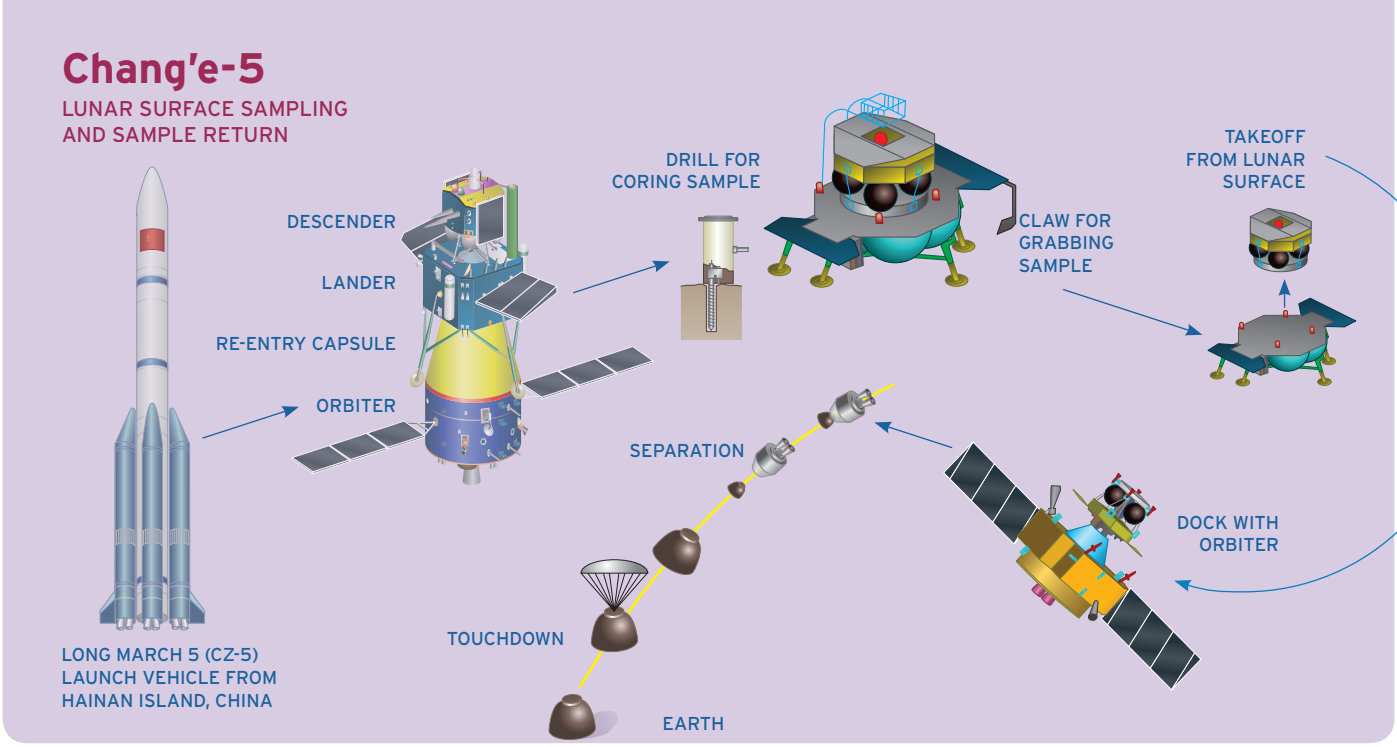
The second part of Chang'e-4, a lander and a rover of similar design to Chang'e-3, will launch in late 2018 or early 2019. The Chang'e-4 mission has 3 scientific goals. It will do low-frequency radio astronomy from lunar orbit with a Netherlands-China Low-Frequency Explorer and also from the surface with a low-frequency radio spectrometer. It will study the shallow structures of the farside landing site using rover ground-penetrating radar. Finally, the rover will examine the geomorphology and mineralogy along its traverse with a visible/near-infrared imaging spectrometer.

The selected landing region for Chang'e-4 is within the South Pole-Aitken (SPA) basin, the Moon's largest, deepest, and oldest impact structure. Its depth and gravity measurements suggest that the huge impact may have exposed the Moon's mantle. Chang'e-4's data will illuminate the history of the SPA basin.

Chang'e-4 is targeting the floor of the Von Kármán crater in its southern portion (45°S - 46°S, 176.4°E - 178.8°E). The Von Kármán crater is an ancient, complex impact crater located within the SPA basin. The science team hopes

**LONG XIAO** *is a planetary geoscientist at China University of Geosciences (Wuhan) and Macau University of Science and Technology. He studies major geological processes of all solid bodies in the solar system, focusing recently on characterizing the geology of China's lunar and Martian landing sites. He also studies Earth analogs of past and present habitable environments on Mars.*

Queqiao image: CNSA




to study the existence and extent of variations in composition of the sheet of melted rock that would have filled the newly formed SPA basin, and we hope to possibly study exposed upper-mantle materials. Scientists also expect to improve understanding of the farside space environment and the evolution of farside regolith, the broken-up rocks and dust that make the lunar surface.

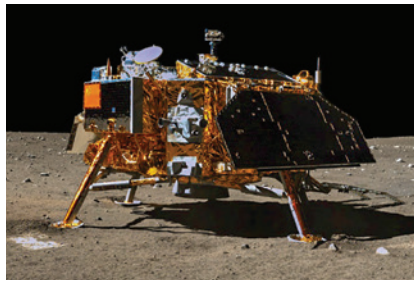
### CHANG'E-5 SAMPLE RETURN

Chang'e-5, scheduled to launch in 2019, is China's first lunar sample return mission. It will provide an opportunity to study new lunar samples in terrestrial laboratories for the first time since Luna 24. Geologists have solved numerous fundamental scientific issues in lunar science with samples returned by the Apollo and Luna missions. The returned samples initiated a golden age of lunar research that continues to this day, as newly developed laboratory techniques allow scientists to perform new science on old samples. However, most of the Moon remains unexplored, and there are still many scientific questions that could be answered with new rocks and soil from the Moon.

Chang'e-5 will launch a large spacecraft stack including an orbiter with a re-entry capsule and a lander. The lander has no rover; instead, it has an arm to grab from the surface and a drill that can sample from a depth of 2 meters. The lander will have cameras and ground-penetrating radar similar to those on Chang'e-3 and 4, plus a lunar mineralogical spectrometer that can take spectra in the visible to infrared range. The spacecraft will collect up to 2 kilograms (4 pounds) of samples, placing them into an ascending craft that will rendezvous with the orbiter and transfer the samples to the re-entry capsule. The orbiter will return the capsule to Earth.

The Chang'e-5 lander is set to land in the Rümker region in northern Oceanus Procellarum (41-45° N, 49-69° W). The Rümker region remains unexplored by robotic or human landing missions carried out earlier by the United States (Surveyor, Apollo) and the Soviet Union (Luna), and no samples have ever been returned from this broad area. The region includes the Procellarum KREEP Terrane, a prominent geochemically anomalous area on the Moon. It is characterized by high concentrations of radiogenic heat-producing elements (such as thorium, uranium, and potassium) in a thin crust. It has also had much more recent volcanic activity than most of the rest of the Moon, the end of a long, complex geologic history. It may include some of the youngest material on the Moon. (For the Moon, "young" means younger than 3 billion years old.)

One of the youngest mare units on the Moon occurs in the Rümker region. The high-titanium basalts are known to be younger

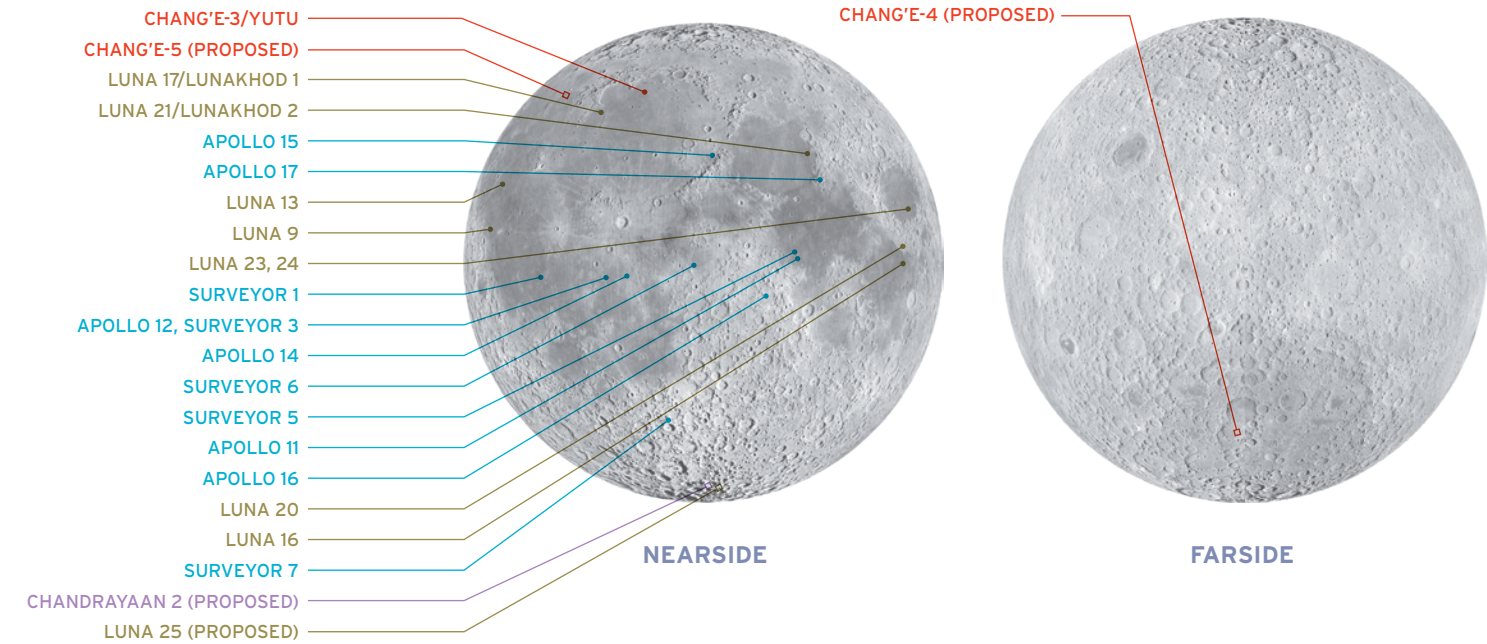


**ABOVE** *This photo of the Chang'e-3 lander was taken by the Yutu rover before the rover's premature failure. The lander is still operating an ultraviolet telescope on the lunar surface more than four years later. Chang'e-4 is nearly the same design, with different science instruments.*

Chang'e 3 lander: Chinese Academy of Sciences

## Chang'e, Yutu, and Queqiao

Chang'e is a Moon goddess in Chinese legend, a central character in the annual Mid-Autumn or Moon festival (which is on 24 September in 2018). Her companion Yutu, the Jade Rabbit, mixes elixirs for the other immortals in his mortar and pestle. Queqiao, or "magpie bridge," features in a different legend, a love story about a flock of magpies that form a bridge crossing the Milky Way once a year to reunite the Cowherd and the Weaver Girl.




Art by Wu Shaoyun; Moon base maps from NASA/Goddard/Arizona State University

than any existing lunar samples, including the youngest lunar meteorites, which are 2.8 billion years old.

These young mare basalt units are a top priority for future lunar exploration. Analysis of these samples in laboratories on Earth will provide exact radiometric dates for some of the Moon's last volcanic events, identifying their age for the first time and improving our understanding of lunar chronology. They will help us understand the nature of the deep source regions that produced the lavas that poured out on the lunar surface. They will permit us to study how radioactive Procellarum KREEP materials played a role in the generation of late-stage mare volcanism, and they will improve our understanding of how the Moon lost its heat over time.

Currently, the only way scientists can determine the ages of these young basalt lava flows is to count craters superposed on top of them. Younger materials have had less time to accumulate impact craters, so they contain fewer craters per unit area. But this is not a precise age-dating method. Returning samples from these young basalts would provide a number for the age of the volcanism.

The Moon is the only cratered terrestrial world from which we have returned samples. Lunar geologists have matched cratering chronology with absolute ages measured from returned lunar samples, building a bridge between crater chronology and absolute ages. The chronology of the rest of the solar system is pinned to lunar chronology. So, Chang'e-5's success will not only teach us more about the Moon; it will also assist in our understanding of the geological evolution of planetary bodies throughout the solar system.

**SRIRAM BHIRAVARASU** *is a postdoctoral fellow at the Lunar and Planetary Institute in Houston. He participated in the science planning process for Chandrayaan-2's radar instrument.*

# Chandrayaan-2

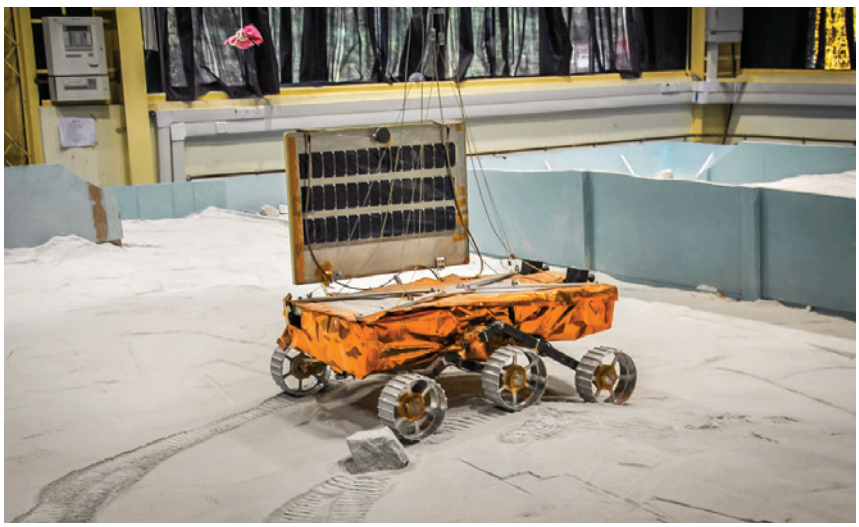
## India's Big Step in Lunar Exploration

**AFTER THE PHENOMENAL** success of the Chandrayaan-1 orbiter, the Indian Space Research Organisation is gearing up for its second lunar mission, Chandrayaan-2, slated to be launched in January 2019. Developed entirely in India, this mission represents a number of technological firsts for the space agency: the heaviest interplanetary launch mass at about 3,890 kilograms (8,580 pounds), the first Indian soft landing, and the first-ever lunar south pole landing, to name a few. The mission aims to address some of the major scientific questions concerning the Moon by studying its topography, polar volatile deposits, mineralogy, elemental abundance, and exosphere.

Some of the orbiter instruments have significantly improved capabilities compared to their Chandrayaan-1 predecessors. The Imaging Infrared Spectrometer characterizes and maps the abundance of hydroxyl ions (OH-, broken from water molecules) and molecular water. The dual-frequency Synthetic Aperture Radar instrument enables us to look into permanently shadowed crater floors in polar regions and detect water ice. Operating in its passive radiometer mode, this instrument will be able to map lunar regolith thickness and electrical conductivity properties at a global scale. Chandra Atmospheric Composition Explorer 2 is a neutral mass spectrometer that will sample atoms in the tenuous exosphere over polar regions of the Moon, complementary to a similar experiment aboard NASA's LADEE mission.

The lander, recently named Vikram after Indian space pioneer Vikram Sarabhai, carries a variety of resourceful instruments. The seismometer will record moonquakes near the landing site and might offer clues about the lunar core if big enough quakes happen while it is measuring. A thermal probe will make the first-ever measurements of the vertical temperature and thermal conductivity profile in the lunar soil (up to a depth of 100 millimeters, or 4 inches) near the polar region. The Langmuir probe will study near-surface plasma density variations to understand the Moon's thin atmosphere. To study how lunar tides affect Earth's ionosphere, a radio-occultation experiment will measure its total electron content. Measuring the major surface constituent elements at different locations on the Moon is very important, as it could constrain various theoretical models of the Moon's origin. The rover will attempt this by carrying two instruments for quantitative elemental analysis: an Alpha Particle X-ray Spectrometer and Laser Induced Breakdown Spectroscope.

The current global consensus is that the next steps in addressing major lunar science objectives will be robotic exploration and return of samples from the surface of the Moon, with a particular emphasis on regions not previously visited. Knowing that there is increased international interest in a human presence on the Moon, the timing of Chandrayaan-2 couldn't be more perfect!



ISRO

**ABOVE** *A model of the small (25-kilogram, or 55-pound) Chandrayaan-2 rover being tested for operations under lunar gravity. The cables atop the rover connect to a large helium-filled balloon that counteracted most of the test rover's weight.*

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

**ABOVE** *PlanetVac Xodiac sampling container following a successful sampling during a Xodiac rocket flight. More than 300 grams (10.5 ounces) of Mars simulant that was collected can be seen in the container. Lens cap for scale.*

**ABOVE RIGHT** *Planetary Society CEO Bill Nye and donors to PlanetVac Xodiac project surround the Xodiac rocket following a successful sampling test flight.*

# Successful Trip

## A Planetary Vacuum Takes a Rocket Ride

**ROCKET SCIENCE MET** planetary science in the California desert when Honeybee Robotics tested PlanetVac, a new planetary surface sampling technique, on a Masten Space Systems Xodiac rocket. During the 24 May test, the Xodiac rocket lifted off, hovered, moved slightly, and then landed PlanetVac in a bed of Mars soil simulant. PlanetVac gathered hundreds of grams of sample, and the rocket lifted off again, moved, and landed. This test advanced The Planetary Society-supported project one step closer to flying in space.

### WHAT IS PLANETVAC?

PlanetVac (Planetary Vacuum) is intended for robotic sample collection from planetary surfaces. PlanetVac uses compressed gas to force dirt and small rocks up into a sampling container or science instrument. It can take advantage of supplies of compressed gas that are usually on landers already (the landers use the gas to pressurize their fuel tanks). PlanetVac sampling devices could be built into the lander legs themselves, as we did in the May tests.

The technology could be used to feed surface dirt to science instruments and/or feed it into sample return rockets on landers on Mars, asteroids, or the Moon. Because of the low pressures on all those bodies, the technique is extremely efficient. The efficiency is related to the ratio of the pressure of the gas used to the ambient pressure. Its use of only one moving part—a valve to release the gas—makes it reliable, and its relatively low mass and cost are big pluses in the planetary exploration game.

In 2013, Planetary Society members funded early tests of PlanetVac in a vacuum chamber at Mars pressures. The test was suc-

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

All photos this spread courtesy of Richard Chute and Bruce Betts for The Planetary Society

cessful, showing that a full prototype could be constructed and operated successfully in a low-pressure environment.

### PLANETVAC XODIAC

NASA sponsored the Xodiac rocket flight through its Flight Opportunities program. Planetary Society members and donors came together to provide the additional funding needed for Honeybee Robotics to adapt PlanetVac to the Xodiac. This involved creating a version of PlanetVac that would replace one of the Xodiac lander's feet.

Several Planetary Society staff members and PlanetVac donors had the opportunity to witness one of the test flights. The flight took place at the Mojave Air and Space Port in the southern California desert. The rocket launch was a spectacular sensory experience with a magnificent rocket plume and big sound. Half a minute later, it landed a few meters away with the PlanetVac leg in the Mars simulant. Sampling itself took only 10 seconds. The rocket flew back to its starting point and landed.

Honeybee engineers were very excited when they retrieved the sampling container. They had targeted 100 grams (3.5 ounces) of sample but actually obtained more than 300 grams (more than 10.5 ounces). It was a big success and a great experience.

The activity demonstrated that PlanetVac could be adapted to a planetary lander, in this case replacing a landing foot of a Xodiac rocket. It also demonstrated that PlanetVac could survive and thrive in the hot, shaking environment of a rocket firing. The successful demonstration advanced the technology's readiness for a future space flight, making PlanetVac more likely to be selected to fly on future space missions.

Thanks to all of The Planetary Society supporters and members who made this possible! You can learn more about PlanetVac Xodiac and watch a video covering its flight at **planetary.org/planetvac**. You can also listen to a Planetary Radio episode covering the event at **planet.ly/PlanetVacPlanRad**.

**TOP** *PlanetVac Xodiac in the midst of sampling Mars soil simulant during a flight test in May 2018. PlanetVac is the far foot of the lander in this picture. The sampling process causes the dust cloud visible near the lander foot.*

**MIDDLE** *Justin Spring removes the sample collection container from PlanetVac Xodiac following a successful test flight.*

**BOTTOM** *Team members are all smiles after the successful PlanetVac Xodiac test. Shown left to right: Justin Spring (Senior Project Engineer, Honeybee Robotics) holds the sample collection container, Mat Kaplan* (Planetary Radio *Host and Producer, The Planetary Society), Kathryn Luczek (Project Engineer, Honeybee Robotics), and Bruce Betts (Chief Scientist, The Planetary Society). The Xodiac rocket stands behind.*

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


# Why Start A Space Program?

## Watching Australia Take A Bold Step Forward

**ABOVE** *The Planetary Society has provided expertise and support for Australia's new space initiatives. In January 2018, CEO Bill Nye hosted a delegation of Australian civic and political leaders at our headquarters as part of the Australian-American Leadership Dialogue, a private diplomatic initiative. Aided greatly by Senior Government Relations Manager Matt Renninger, who worked at the Australian embassy before joining The Planetary Society, and our Australian volunteer network, we plan to provide ongoing outreach to build public support for space in both hemispheres.*

**THE FACT THAT** so many countries seem to want a space program implies an inherent value to exploring space, but what is it? Last year, Australia became the latest country to announce the formation of its own space agency. The process took a significant step forward in March with a new report recommending goals and focus for its space agency. The report also provides insight about why Australia sees space as a valuable enterprise.

The report highlights several areas where the country could leapfrog others by strategically investing in specific capabilities (for example, artificial intelligence or quantum computing) and sets out a goal of tripling the size of the Australian space industry by 2030. One of the keys to succeeding in this new effort, the report declares, will be international partnerships.

International partnerships provide the means for countries to participate in the exploration of space without having to create expensive, enabling infrastructure from the ground up. They can leverage the space capabilities of other nations while providing unique contributions to the benefit of their own industry and scientific base. This is the opposite of a zero-sum, competitive mentality of international relations; a rising rocket lifts all spacecraft, if you will. The European Space Agency's very existence relies on this model. Its BepiColombo mission—as you will read in this issue—includes contributions from 13 European member states, the United States, and Japan. This coalition of nations is deeply invested in the success of the mission, spreading out the cost and also the political support.

The United States recognized the value of international engagement in its space program from the beginning. NASA's charter

The Planetary Society

directs it to pursue a "program of international cooperation" and "cooperation by the United States with other nations and groups of nations." This is often cited as one of the most practical benefits of the space program in the United States and has been used to great effect in the past for both human and robotic space projects. Cassini, with its major contributions from ESA, Italy, and others, survived the budget axe in the early 1990s in part due to the existence of international partnerships. The Shuttle-Mir program and then the International Space Station brought together former Cold War adversaries, creating an ongoing line of communication and cooperation even as formal relationships between Russia and the U.S. have strained. Now, lunar exploration is being positioned as an opportunity to cooperatively engage a large number of nations.

Australia's nascent space program will find itself with a plethora of partnership opportunities and not only with established programs like those of NASA, ESA, and Japan. Many other countries are developing productive space programs. China has ambitious goals to return samples from the Moon and Mars and has issued an open call to nations around the world to participate in its planned space station. India is also making great strides with its probes to the Moon and Mars. The United Arab Emirates plans to launch its own robotic mission to Mars in 2020, which could begin a new program of ongoing exploration as well.

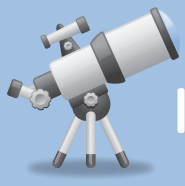
There is also the unknown, alluring opportunity for exploration and profit promised by the private space sector. Countries can work with non-state international partners, as Luxembourg has demonstrated by investing in a number of companies to position itself as a future leader in space resources.

The benefits of strategic research and development, scientific discovery, and the strong relationships formed through the cooperative exploration of space are likely why so many countries have decided that space is a worthy cause for national investment.



**ABOVE** *This photo of the total solar eclipse was taken by David Morrison on March 9, 2016 during the Society's Indonesia Total Solar Eclipse Expedition.*

## WHAT'S UP? *by Bruce Betts*



### IN THE SKY

In the early evening in late September and into October, 4 planets can be seen stretching across the sky. Bright Venus is very low in the west, getting lower as days pass. Jupiter is above Venus. Farther east in the sky are yellowish Saturn and Mars. Mars is bright but fades as the weeks pass and it grows farther from Earth in its orbit. At the end of October, Mercury is near Jupiter, low in the west shortly after sunset. Soon into November, both have left the evening sky, but Saturn and Mars remain there. By November, Venus is in the pre-dawn east and is joined by Mercury and then Jupiter in December. The Geminids meteor shower peaks on 13 and 14 December. The best viewing will be after midnight, when the Moon has set. Often the best meteor shower of the year, 100 meteors per hour may be seen from a dark site.

### RANDOM SPACE FACT

If you lived on Mercury (not recommended), one Mercury day would last two Mercury years.

### TRIVIA CONTEST

Our March Equinox contest winner is Mike Shaw of Edmonds, Washington. Congratulations! The question was: ***Which planet in our solar system has the highest average density?*** The answer: ***Earth at 5.515 grams per cubic centimeter. Mercury is 5.427 grams per cubic centimeter.***

Try to win a Planetary Society Venn Diagram tee and a signed copy of Emily Lakdawalla's book, *The Design and Engineering of Curiosity*, by answering this question:

***What was the first human-made object to hit another world besides 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 November 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*.

# Where We Are

## An At-A-Glance Spacecraft Locator

**WHEN I FIRST CAME** to The Planetary Society in 2001, there were few solar system spacecraft actively operating their science missions. That year, it was just Mars Global Surveyor, Deep Space 1, Stardust, and the tail end of the Galileo mission. The current decade has been a different story. It's gotten so busy that I had to write down a list and make a point of checking each active mission every month or two, just to be sure I hadn't missed any momentous events. I used to do this only at *planetary.org/blog*, but now I'm initiating a regular column in *The Planetary Report* called Where We Are, your guide to humanity's active robotic emissaries across the solar system and beyond.

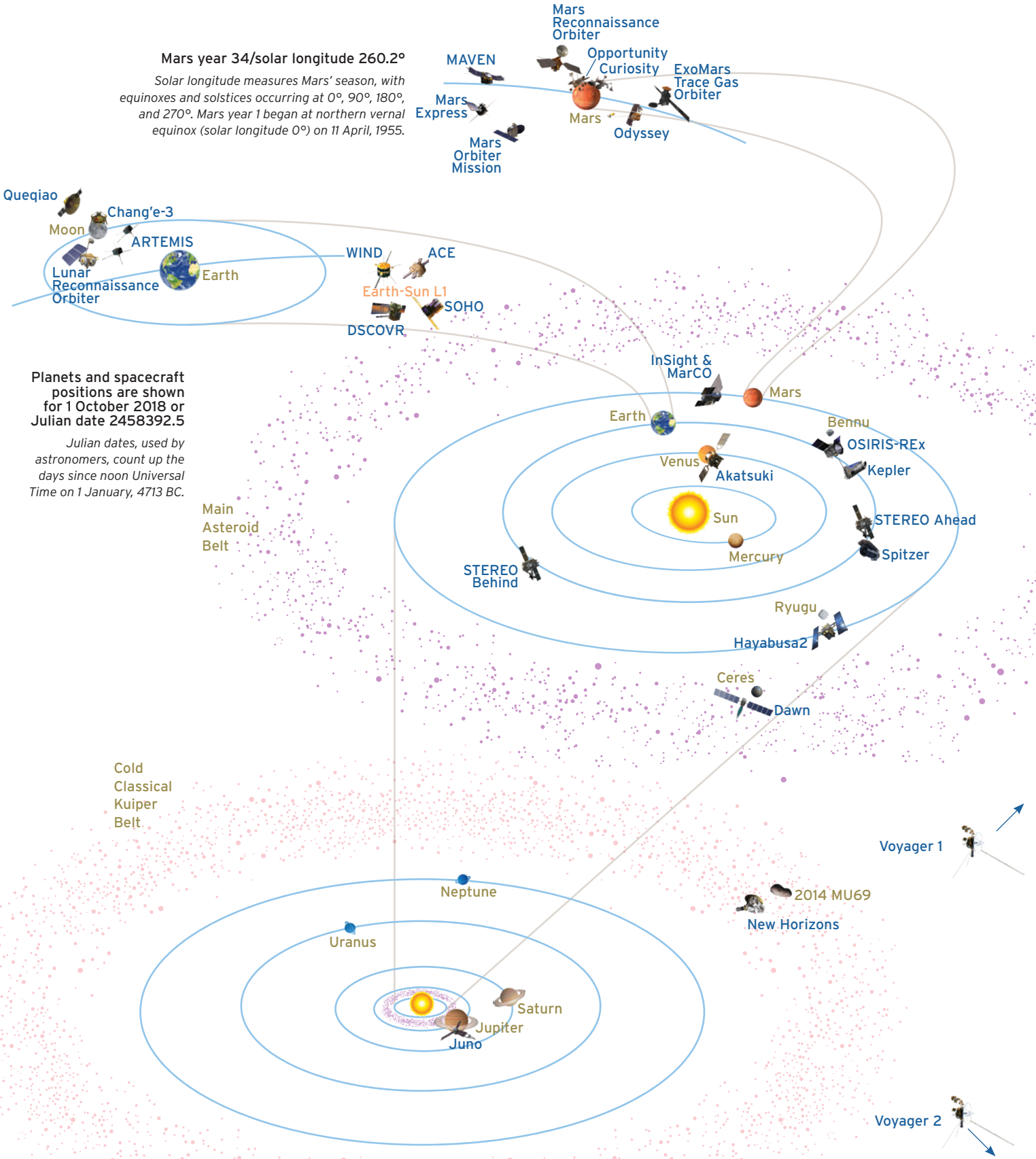
On the facing page, you'll see two wide solar system views: one focused on the inner solar system through the main asteroid belt, and one zoomed out to encompass the outer planets and the Kuiper belt. The layout is based on diagrams produced by space fan Olaf Frohn for *planetary.org* since 2009. Insets show you the exploration action at Mars, at our Moon, and at L1, a gravitationally stable point between Earth and the Sun. I don't show spacecraft in Earth orbit. You'll see all the deep-space robots that are currently in routine communication with Earth—plus one, Opportunity, that is not actively communicating with us as we go to press. Let's hope that the silent Mars rover wakes up before you receive the next issue of *The Planetary Report*.

What else will change before January? As you've read in this magazine, BepiColombo should set off for Mercury via Earth and Venus in November, and Chang'e-4 will launch toward a landing on the lunar farside in December. OSIRIS-REx is slowly approaching its target asteroid Bennu, which will transform from a point of light into a unique-looking world by December. Hayabusa2 is expected to deploy its landers, touch down, and grab a sample from Ryugu. Kepler, running on fumes, may not last out the year.

Out at Mars, InSight will land on November 26 and begin to set up its geophysical experiments, bringing the total number of Mars spacecraft to 9 (assuming Opportunity is still with us).

Beyond Mars, our fleet has suffered expected losses in the last couple of years. We're down to Juno, patiently orbiting Jupiter; Dawn, nearly out of fuel at Ceres; and New Horizons, fast approaching an exciting New Year's Day flyby of classical Kuiper belt object 2014 MU69. Far beyond everything else, Voyager 1 and 2 continue to send us messages from interstellar space.

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



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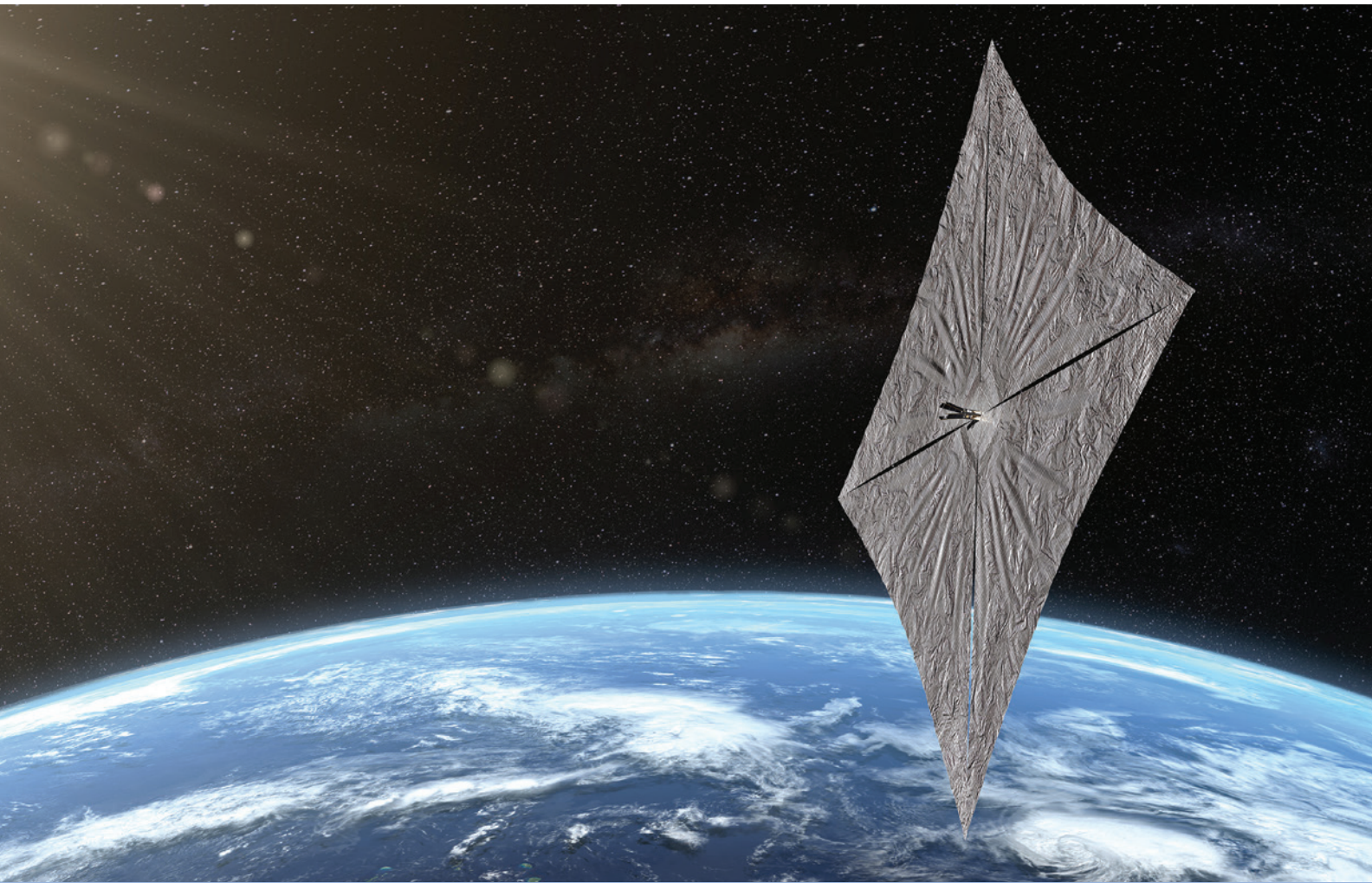

# LightSail 2 Launch – You're Invited!

As we go to print on The Planetary Report, LightSail 2's launch date is set for no earlier than 30 November, 2018. All members are invited to join us at Kennedy Space Center to experience Planetary Society history being made. Details are still being finalized, but we will offer members a number of opportunities that may include meet-up-style meals at local restaurants, a members-only mission briefing, and access to tickets to see the launch from the Kennedy Space Center Visitor Center. Our family-friendly events will be scheduled over a 2-day period.

For more information and tips on launch viewing, go to sail.planetary.org. Can't wait for November and want to grab some LightSail 2 swag now? Head over to planetary.org/store to check out T-shirts, patches, pins, and more.

Josh Spradling / The Planetary Society