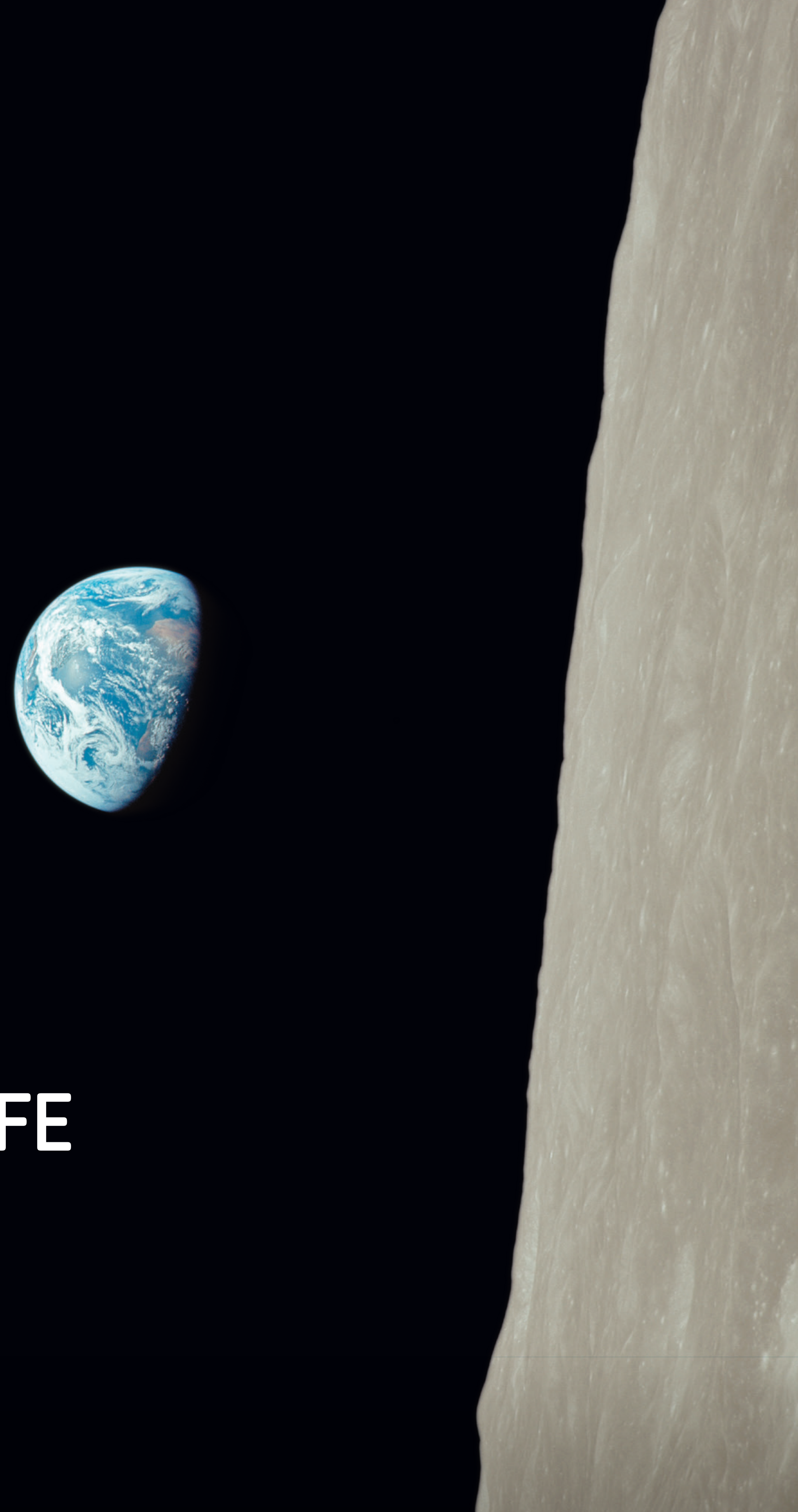
THE PLANETARY SOCIETY

THE PLANETARY REPORT

DECEMBER SOLSTICE 2018
VOLUME 38, NUMBER 4
planetary.org



WHERE LIFE BEGAN

SPACE EXPLORATION SEARCHING FOR LIFE'S ORIGINS BRINGS US BACK TO EARTH

TESTING OSIRIS-REx • SPACECRAFT EARTH • THE FUTURE OF SOLAR SAILING

CASEY DREIER *is chief advocate and senior space policy adviser for The Planetary Society.*

Total Immersion in the Heavens

Why Earthrise Resonates 50 Years Later

THE QUARTER EARTH FLOATS suspended, crisp above a horizon of dull gray. Pale blues are interrupted by smears of bright clouds, with primal black everywhere else. The photo of Earthrise over the Moon, taken in an impromptu moment by Bill Anders, brought home the fact that we'd really traveled beyond the Moon for the first time 50 years ago. Apollo 8 commander Frank Borman, a no-nonsense military man, later reminisced that looking back at our home planet was like a "total immersion in the heavens."

ABOVE *Astronaut James A. Lovell Jr. pilots the Apollo 8 spacecraft command module, December 1968. The Apollo 8 mission produced the iconic Earthrise photo on the cover of this magazine 50 years ago this month.*

The photo appeared on the front page of *The New York Times* on 30 December 1968, 3 days after the command module splashed down in the Pacific. *Life* magazine devoted a 2-page spread to the photo that January. The Apollo 8 crew gave copies to political leaders around the world during their goodwill tour. It briefly occupied a prominent spot on the wall of the Oval Office.

Perhaps no other image of Earth has been as famous. Apollo 17's whole Earth image, taken 4 years later, became the go-to representation of our home planet in textbooks for decades, but it lacked the social and cultural impact of Earthrise. Voyager 1's view of Earth as a pale blue dot captured the public imagination, but that arguably had more to do with Carl Sagan's poetic words than the grainy photo itself. Many other spacecraft photographed their planet of origin over the years, but none have dislodged Earthrise from its cultural pedestal. (For some of these photos, read "Spacecraft Earth," page 12.)

Why is this image so iconic? Timing, for sure. It was the first taken by humans so far from Earth. It arrived at the end of an ugly year marred by warfare, assassination, and cultural upheaval. Its depiction of a delicate Earth ensured its adoption by the nascent environmental movement.

However, there is more to it than timing. The photo resonates because we know that human hands held the camera, that human eyes were looking through the lens, and that a human being was capturing a picture of his home. The subject of this photo is not only Earth; it is our relationship to Earth as seen through the eyes of Anders, Borman, and Lovell.

Tension permeates this photo. Blue Earth contrasts with black cosmos and the living planet with the lifeless moonscape. We, the Earthbound viewers, see it first as a photo of Earth—of us—but then through the eyes of the astronaut himself—of Earth without us—and snap back. Earthrise vibrates with this tension because of the human being who took it.

The Moon and other destinations continue to call to us. Perhaps we will once again respond to that call and allow ourselves the grand perspective we so desperately need.

NASA

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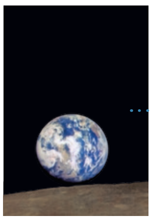

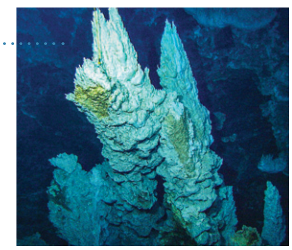

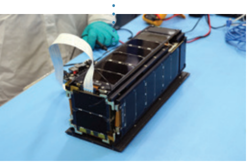

ON THE COVER: When Apollo 8 astronauts Bill Anders, Frank Borman, and Jim Lovell rounded the farside of the Moon, they became the first humans to witness an Earthrise above an alien surface. The iconic image was first published on 30 December 1968, 50 years ago this month. *Credit: NASA/Seán Doran*

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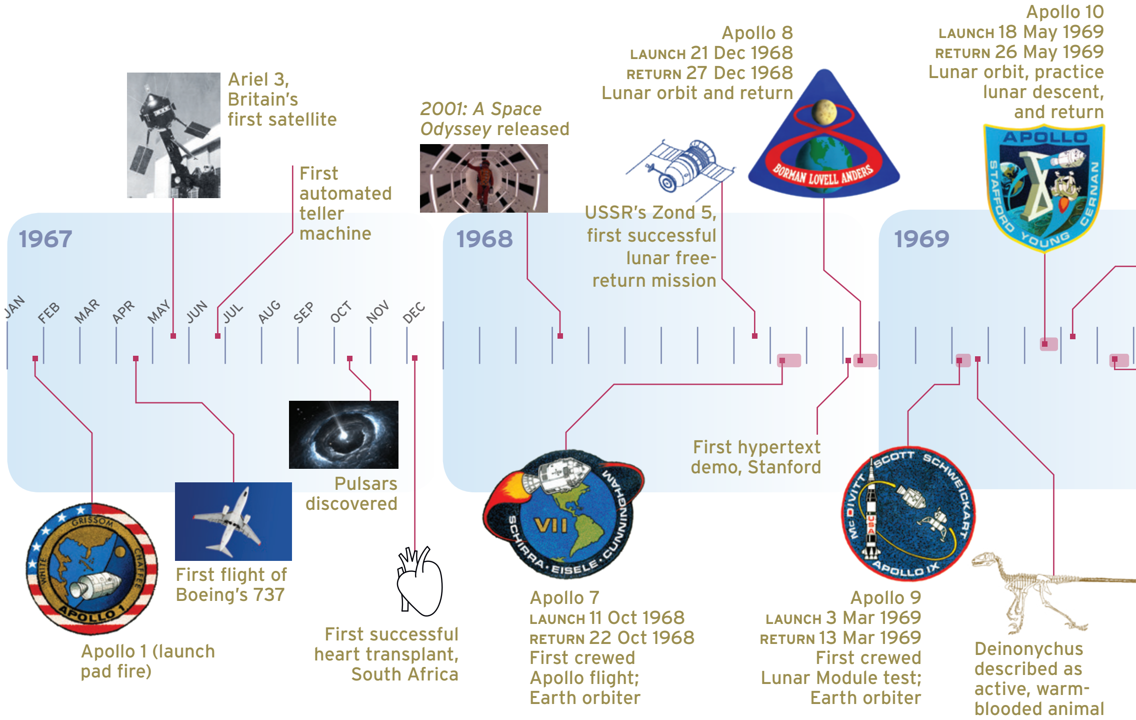
The Planetary Report (ISSN 0736-3680) is published quarterly at the editorial offices of The Planetary Society, 60 South Los Robles Avenue, Pasadena, CA 91101-2016, 626-793-5100. It is available to members of The Planetary Society. Annual dues are $50 (U.S. dollars) for members in the United States as 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.

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



Assembled by Loren A. Roberts for The Planetary Society; The Planetary Society

No Place Like Home Planet

Exploring Space to Learn About Ourselves

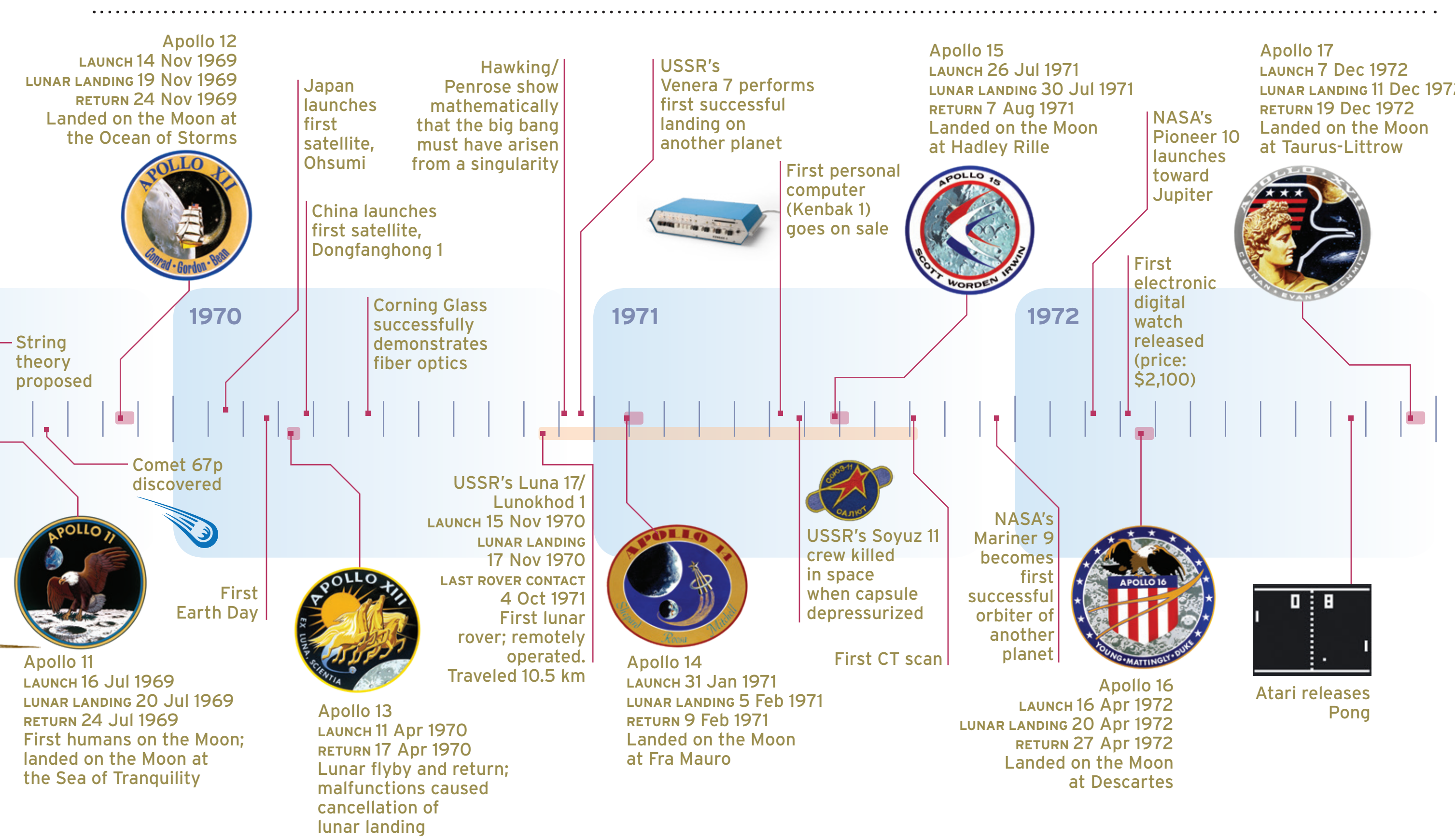
BY EXPLORING SPACE, we learn more about our planet and ourselves. On the cover, we celebrate Earthrise, the famous photo of our blue marble of a planet taken by astronaut Bill Anders on 24 December 1968. (Some disclosure: I remember it well as an 8th grader.) Viewing Earth from the Moon changed the way people everywhere viewed Earth and our place in the cosmos. Seeing Earth from space was a powerful reminder that humankind—in fact, all life as we know it—is united here on this beautiful yet fragile world.

In the coming year, we will celebrate and reflect on the groundbreaking achievements of Apollo. Check out the Apollo timeline right here on this page and read Casey Dreier's essay inside the front cover on the cultural significance of the 50th anniversary of humans on the Moon.

In these 50 years since Apollo, humankind has explored farther away from home. As we venture out, we continue to look back at our home world. In this issue, Emily Lakdawalla showcases some of the best self-portraits taken by robotic explorers, and Vicky Hamilton describes how OSIRIS-REx used its instruments to examine Earth during a flyby on its way to asteroid Bennu.

As we continue to explore, we seek answers to the fundamental questions about the origin of life and the origin of species—like you and me. In "The Making of Life," Michael Wong explains how life may have developed here on Earth and elsewhere.

These quests to find life in the cosmos and to understand our place in space are deep within us. We're curious, we're tenacious, and we're explorers. The Planetary Society was founded to keep humankind exploring. Through your passion, you prove public support for space exploration. Members like you are not only passionate about space; you're willing to act to advance exploration by spreading the word on social media, partici-



pating in letter-writing campaigns, volunteering, and financially supporting our projects and programs.

Because of you, we're ready to fly LightSail 2, our solar sail spacecraft that is 100 percent funded by members and supporters (see Bruce Betts' update on LightSail in this issue). Because of members like you, I am able to communicate with you here in *The Planetary Report*.

Your support also enables us to directly advocate for continued exploration to government agencies. A recent example of this was my participation in a Washington Post Live event with NASA Administrator Jim Bridenstine. Unlike my previous informal discussions with the administrator, this one was in public with a large in-person audience and a live webcast. Planetary Society Vice President Heidi Hammel and I were on a panel with the administrator, and we talked about what we see as the opportunities in space today and in the near future. Heidi described the great value of planetary exploration: the more we learn about other worlds, the more we learn about our own. We agreed that discovering life elsewhere would be astonishing. Deflecting an incoming massive rock or block of ice (asteroid or comet) could be vital. Also, the International Space Station has a unique role in international engagement and diplomacy. We discussed the key to the future: the money (NASA's budget). I managed to remind everyone there that a big reason the world's largest nongovernmental space organization (your Planetary Society) exists is to help lawmakers make the right decisions about missions and funds.

In the 50 years since Apollo and the 38 years since the founding of The Planetary Society we have accomplished a great deal, but the best is yet ahead. I am delighted you all have joined us. Let's explore!

Bill Nye

ABOVE *While Apollo astronauts were taking their first steps into space, it was a period of rapid scientific and technological progress back on Earth, as this timeline illustrates. Robotic spacecraft were also fanning out toward multiple solar system destinations for the first time. The Apollo program's flight phase spanned just 6 years, from 1967 through 1972. Each crewed mission made incremental progress toward the goals of reaching the Moon, landing on it, and performing scientific exploration. We will be celebrating the 50th anniversaries of each of the Apollo milestones over the next 4 years.*

VICKY HAMILTON *is the head of OSIRIS-REx's Spectral Analysis Working Group.*

ABOVE *OSIRIS-REx returned to Earth a year after launch for a gravity assist, flying south of Earth to adjust its path toward asteroid Bennu. Following the encounter, it looked back and tested many of its science instruments on the familiar targets of Earth and the Moon.*

NASA/Goddard Space Flight Center/University of Arizona

Flying By Home

Testing OSIRIS-REx's Tools on the Way to Asteroid Encounter

EVERY TIME a planetary spacecraft turns to take a picture of Earth on its way to a new destination, it's a reminder of how spectacular a place our home planet is. When NASA's OSIRIS-REx mission flew past Earth on its way to the asteroid Bennu in September 2017, we observed a planet primarily covered by water, whose atmosphere included water vapor, carbon dioxide, ozone, and methane. If we were an alien species, we might infer from the atmospheric temperature and the presence of water and carbon dioxide that Earth is a habitable planet. Of course, we're not an alien species, and we knew these things about Earth already. Why would you take a spacecraft designed to study a distant world, launch it on an interplanetary trajectory, and then point its instruments at Earth?

As many spacecraft do, OSIRIS-REx returned to Earth a year after launch for a gravity assist. For OSIRIS-REx, the Earth gravity assist was a critical part of the journey to Bennu, enabling the spacecraft to leave the plane of Earth's orbit and enter that of Bennu's so that we could ultimately rendezvous with this tiny bit of rock.

Just being in the neighborhood isn't a good enough reason to take data on Earth. OSIRIS-REx stands for Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer. The top priority of the OSIRIS-REx mission is to return a pristine sample of carbonaceous material. Observations of Earth are not a mission requirement, nor were they even in the original mission plan. The science team engaged in lengthy discussions with the spacecraft engineering team about whether we could collect such data.

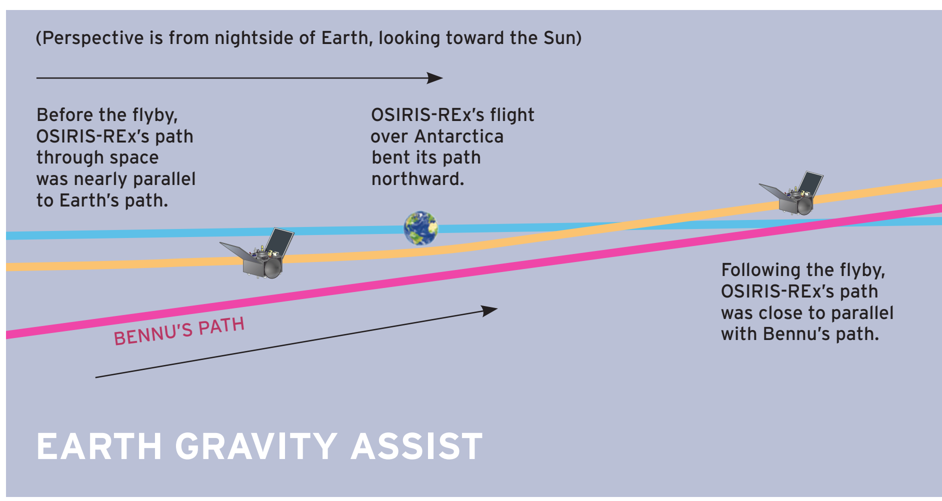
There is a significant—albeit collegial and professional—tension between the scientists who want to make such measurements and the engineers whose job it is to ensure the health and safety of the spacecraft. The spacecraft engineering team was understandably reluctant to add any unnecessary activities ahead of and during the critical Earth flyby maneuver in order to avoid anything that might put the spacecraft's arrival at its ultimate destination at risk.

On the other hand, as the scientists who built the instruments that will make the measurements at Bennu, we had not had an opportunity to assess how the instruments performed after launch. We also wanted to verify the alignment of the instruments relative to each other and to the spacecraft so we could correct any differences in pointing. Together, the OSIRIS-REx scientists and engineers worked out a plan that would allow for safe passage by Earth, followed shortly after that by an opportunity to turn on the science instruments and collect data on our home planet.

OSIRIS-REx'S INSTRUMENTS

Our spacecraft carries five science instruments to map the topography, geology, mineralogy, and chemical composition of the asteroid, providing context for the returned sample and comparison data for similar asteroids. They also identify hazards to the spacecraft and sampling system and help determine the optimal location for collecting a sample.

Two of the 5 instruments did not operate during the Earth gravity assist. The Regolith X-ray Imaging Spectrometer (REXIS), which will map chemical elements on Bennu, launched with a cover that had not yet been opened. The OSIRIS-REx Laser Altimeter (OLA) will inform our understanding of the detailed shape of Bennu; it needs to be within 7 kilometers (4 miles) of its target to collect data. Unfortunately for the OLA team, the Earth flyby distance of

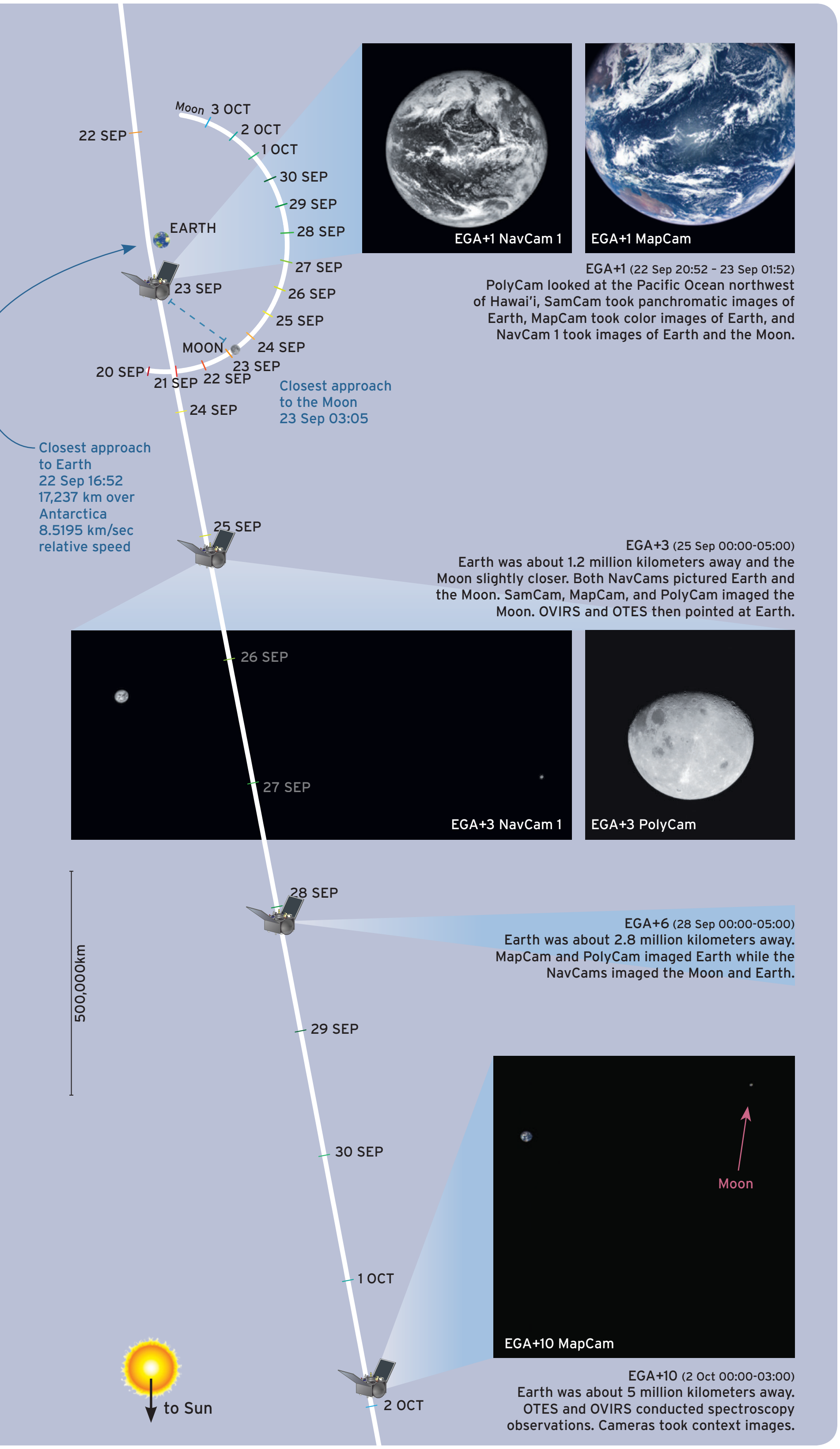


TOP *OSIRIS-REx's MapCam looked at the Pacific Ocean through color filters just hours after the flyby when Earth filled its field of view.*

BOTTOM *Bennu's path around the Sun is inclined to Earth's path.*

NASA/Goddard Space Flight Center/University of Arizona/Björn Jónsson; EGA graphic: Loren A. Roberts/Emily Lakdawalla for The Planetary Society

VICKY HAMILTON *is the head of OSIRIS-REx's Spectral Analysis Working Group and the deputy instrument scientist for the OTES spectrometer. At the Southwest Research Institute, she studies the composition of planetary surfaces and operates a laboratory devoted to thermal infrared spectroscopy of planetary materials.*



Loren A. Roberts for The Planetary Society/Emily Lakdawalla/NASA/Goddard Space Flight Center/University of Arizona/Arizona State University

17,237 kilometers (10,711 miles) was too large.

The OSIRIS-REx Camera Suite (OCAMS) will take pictures of Bennu so we can identify any geologic features on the asteroid as well as perform a detailed inventory of hazards such as boulders that could prevent successful sampling. The Earth observations provided an opportunity to characterize the cameras' performance and to exercise the image-processing techniques for mosaicking and color-image production.

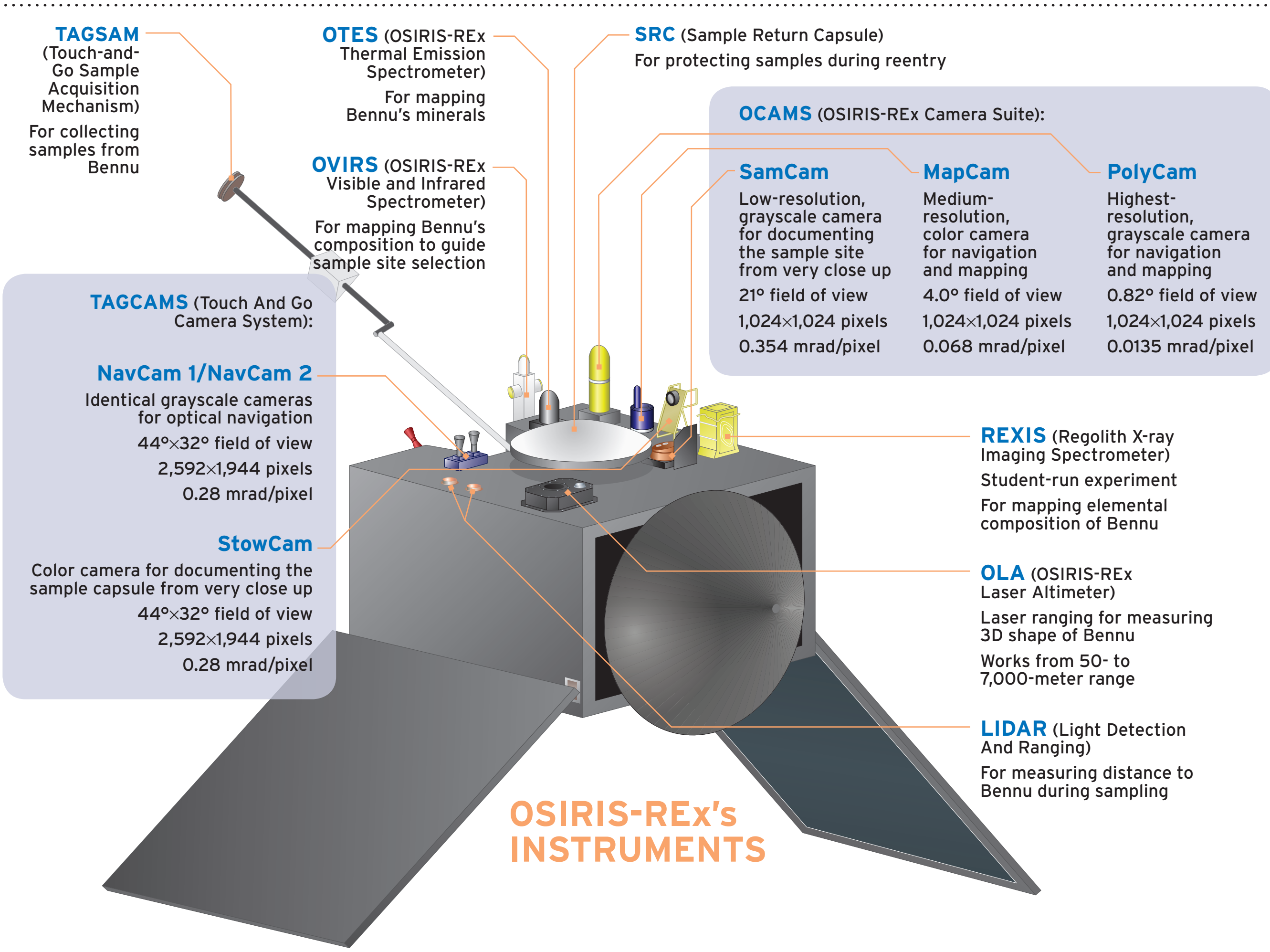
Complementing the visual images, the OSIRIS-REx Visible and Infrared Spectrometer (OVIRS) and the OSIRIS-REx Thermal Emission Spectrometer (OTES) will map the mineralogy and chemistry of Bennu. OVIRS and OTES looked at deep space during our cruise to Bennu. However, space has no spectral features, so those data only show that the instruments are operational. To really understand the post-launch quality of the spectral data (radiometric and spectral calibration) and the alignments of the instruments (to the spacecraft and to each other), we needed to look at an object that has spectral features. The best extended object along our path to Bennu was Earth because we already knew what we should see. Ultimately, that was the justification for capturing data on Earth following our gravity-assist flyby.

POST-FLYBY SCIENCE

We scheduled our Earth and Moon observations for 4 different periods across the 10 days after the flyby, in part to hedge against any anomalies that might preclude making observations immediately after the closest approach to Earth.

The gravity assist went smoothly. A few hours after our closest approach to Earth, the camera suite and spectrometers turned on to warm up. All of the instruments are fixed to the spacecraft—they're not steerable—so the spacecraft has to move to point us at different locations on Earth.

Starting about 6 hours after the flyby, the spacecraft scanned east to west and north to south across Earth. We called these the "EGA+1" observations, where "+1" signifies the first day after the Earth gravity assist. For



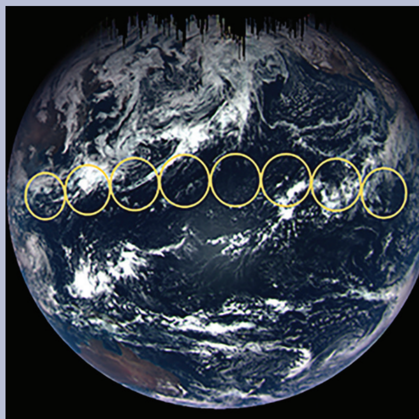
EGA+1, the spacecraft was still quite close to Earth (still inside the orbit of the Moon), and Earth completely filled the fields of view of the spectrometers. The scanning motions allowed us to use the limb or "edge" of Earth (which is very different than looking at deep space) to verify whether the pointing of each instrument was consistent with what was measured before launch and also to compare the pointings of the instruments to each other. We did not observe the Moon because while we could see Earth nearly fully lit, the Moon was only a thin crescent.

As Earth receded from view, we made additional observations on days EGA+3, EGA+6, and EGA+10. As EGA+3 began, we were 1.2 million kilometers (750,000 miles) from Earth, and we could see the sunlit farside of the Moon. The Moon was far enough away that it only filled 15 to 25 percent of our instruments' fields of view, making the signal weaker. Still, these observations allowed us to verify the alignments and performance of the OCAMS, OVIRS, and OTES instruments.

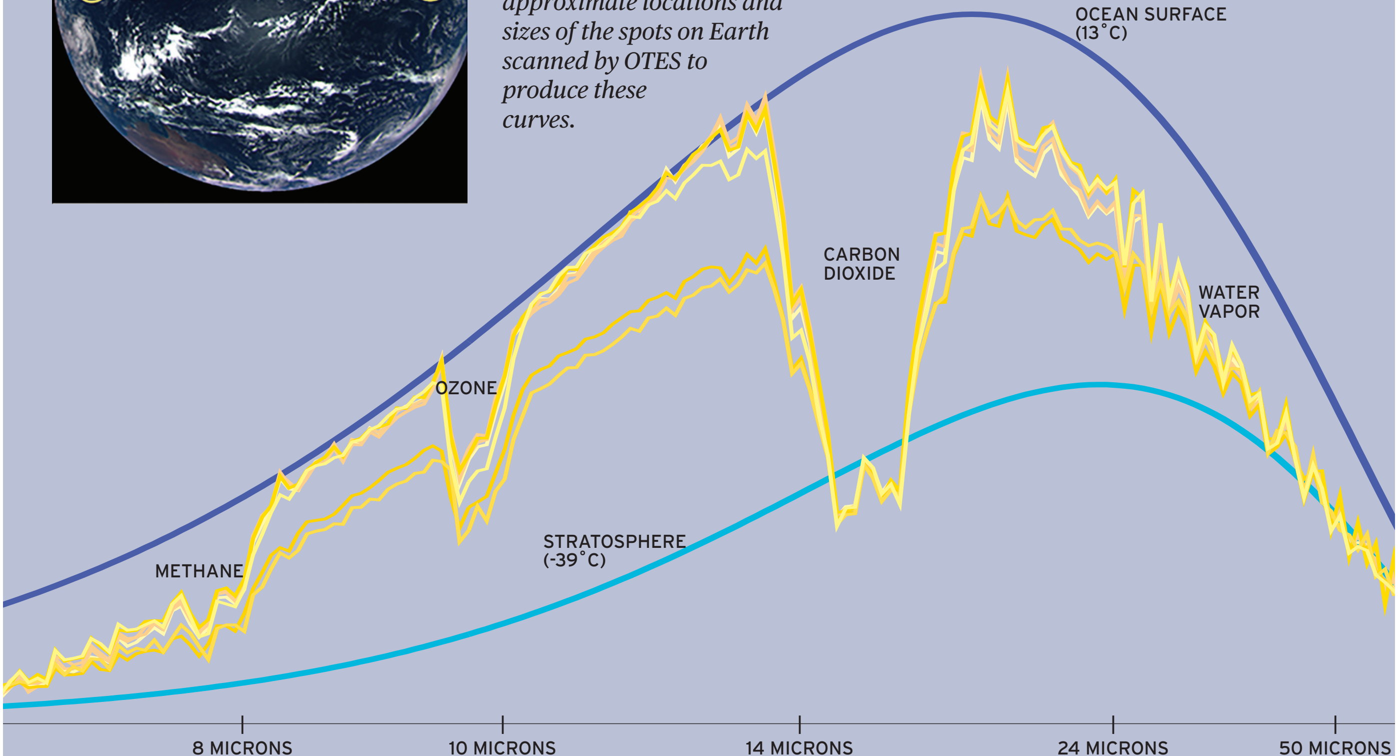
OCAMS can take pictures of stars during our cruise to Bennu to demonstrate that it is working well, but Earth observations allowed OCAMS to fully exercise MapCam's color filters. Our perspective on Earth after the flyby was dominated by the Pacific Ocean. Looking at Earth, OCAMS saw what we recognize from daily weather satellite images as deep-blue water, hints of brown or greenish land masses around the edges, and contrasting bright, white water-vapor clouds. In fact, Earth's clouds are so bright that they challenged our camera because we designed OCAMS to be sensitive enough to take photos of Bennu, whose dark surface reflects at most 4 percent of incoming sunlight. Even though we used short exposures, parts of some of the OCAMS images of Earth are overexposed. They are, nonetheless, beautiful.

OVIRS will measure how Bennu reflects visible and near-infrared wavelengths of sunlight (see sidebar). Like OCAMS, OVIRS was designed to look at dark Bennu, not

ABOVE *OSIRIS-REx's instrument deck is crowded. Most are science instruments, including OCAMS, OLA, OTES, OVIRS, and REXIS, but TAGCAMS and LIDAR are for navigation purposes. OSIRIS-REx was able to test OCAMS, the NavCams, OTES, and OVIRS on Earth and the Moon during the encounter.*



LEFT *The OTES instrument gathered its spectral data at nearly the same time that MapCam took this photo. The yellow circles, each 800 kilometers (500 miles) in diameter, show the approximate locations and sizes of the spots on Earth scanned by OTES to produce these curves.*



SQUIGGLY LINES

OVIRS generates spectra, measurements of how much of each wavelength of sunlight a spot reflects. OVIRS measures reflected sunlight in wavelengths ranging from 0.4 to 4.3 micrometers (visible light spans 0.4 to 0.7 micrometers). In this region, inorganic materials and organic molecules preferentially absorb some of the light wavelengths. These absorptions create dips in the spectra. Spectroscopists read those dips to determine what minerals or chemicals are present. Because of the Pacific point of view during the flyby, our EGA+1 spectra mostly show spectral features signaling the presence of water and carbon dioxide. Unlike OVIRS, OTES does not need sunlight to work; it takes spectral readings in thermal infrared wavelengths, where materials radiate heat, from 5.6 to 100 micrometers. Like OVIRS, OTES measured absorptions due to water vapor and carbon dioxide gas, and we also saw absorptions due to ozone and methane in the spectra. The depths and widths of the absorption features could tell us the abundances of each atmospheric gas, but extracting that information requires computer modeling that we do not plan to do because it's not applicable to Bennu science. OTES is also sensitive to temperature, and the radiance (intensity) of different locations on Earth increases or decreases with temperature. At wavelengths where we could see the ocean's surface (8 to 9.5 micrometers), OTES measured temperatures of about 13 degrees Celsius (55 degrees Fahrenheit). At other wavelengths where there are atmospheric absorptions, we measured the lower temperatures in the atmosphere. Bennu won't have an atmosphere to complicate our interpretations of the thermal infrared spectra, thankfully.

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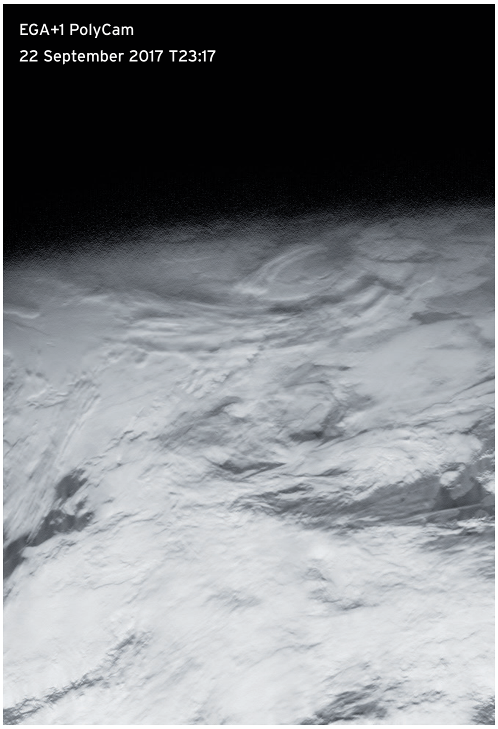
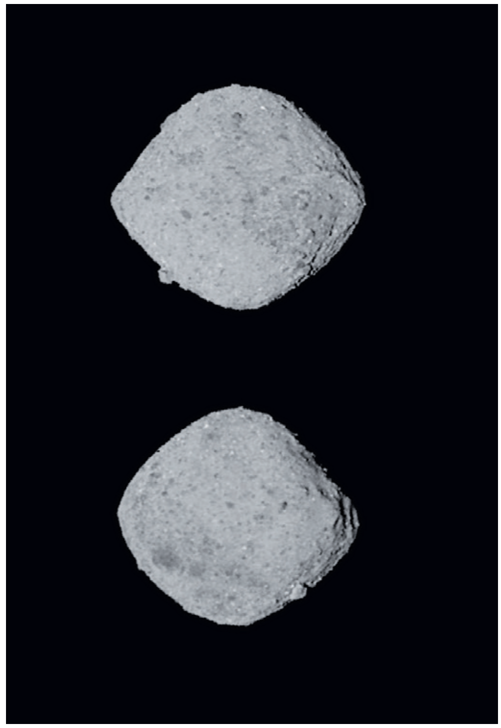




LEFT *When MapCam could see all of Earth, the higher-resolution PolyCam saw just a part of Earth. This image shows parts of Canada's Northwest Territories, including Great Bear Lake right of and below center. High clouds cast shadows, blurring the distinction between cloudy skies above and snow-covered surface below.*

RIGHT *As this article went to press, OSIRIS-REx was approaching its asteroid target, Bennu. These two photos were taken with PolyCam on 1 and 2 November 2018. Overall, the asteroid is very dark in tone, but these early images show dark spots and bright rocks, hinting at colorful diversity of the surface that will soon be revealed by MapCam.*

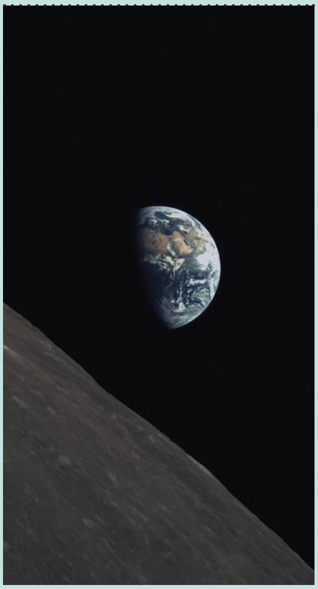
NASA/Goddard Space Flight Center/University of Arizona/Björn Jónsson

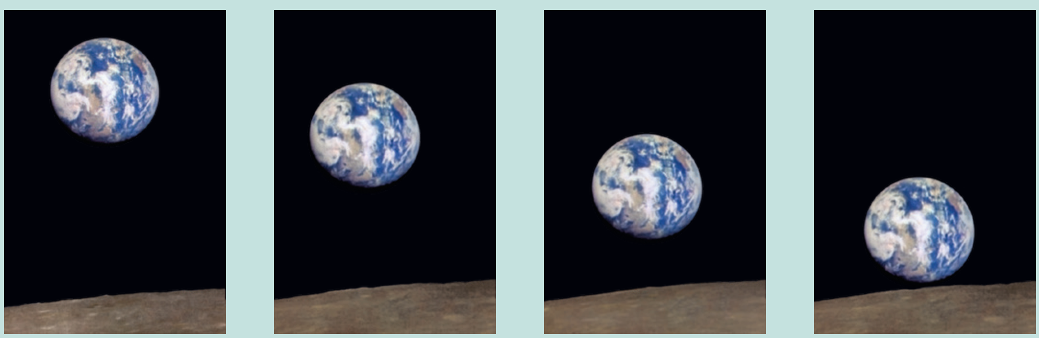
bright Earth, so we commanded OVIRS to take spectra rapidly. Although OVIRS could have detected minerals on Earth's surface, our field of view at midnight UTC contained almost entirely ocean. Our EGA+1 data primarily show atmospheric constituents: water vapor and carbon dioxide.

OTES will measure the energy emitted by Bennu in thermal infrared wavelengths (see sidebar). It can detect a wide array of minerals as well as provide information about the temperature of the asteroid's surface. Surface temperature—and how rapidly it changes from asteroid days to nights—can tell us about the size of particles in the uppermost surface. Earth's atmosphere also has spectral features in this wavelength region from water vapor, carbon dioxide, ozone, and methane gases, which means that OTES also saw spectral features we don't expect to see at Bennu.

Scientists studying Earth's climate use remote-sensing measurements similar to these to track changes in the spatial distribution and abundance of atmospheric constituents over time. For both OVIRS and OTES, we successfully used the known spectral features of Earth's atmosphere to verify our radiometric and spectral performance. Because our spectrometers are designed to measure the spectral features of minerals and organics that typically have much wider absorption bands than atmospheric gases, we can't use our data to say much that is new about Earth's climate.

For my part, I was most excited to see the first post-launch data from our spectrometers where they had a real target to measure. OSIRIS-REx is the first planetary spacecraft to carry both visible-to-near-infrared and thermal infrared spectrometers, and it's immensely gratifying to see that the quality of the data from both spectrometers is superb and bodes well for our future observations of Bennu. Many scientists and engineers worked long, hard hours to make these instruments as good as they could be, and these data prove their effort was successful. Now OSIRIS-REx is approaching Bennu, and I can't put into words how much I'm looking forward to seeing an entirely new body in our solar system through the eyes of our spectrometers.





ABOVE *This tiny image of Earth over the Moon was acquired in June 2018 by the first CubeSat to have entered lunar orbit. Longjiang-2 launched toward the Moon with Queqiao, the relay satellite for the Chang'e-4 lander.*

ABOVE RIGHT *The HiRISE camera on Mars Reconnaissance Orbiter captured significant detail in Earth's clouds from Mars orbit, 142 million kilometers (88 million miles) away, on 3 October 2007.*

RIGHT *Zond 7 flew past the Moon, taking this sequence of images of Earth setting behind the lunar limb on 9 August 1969. The sequence actually consists of only three images; the second one was simulated from data in the others to even out the Earthset sequence.*

Spacecraft Earth

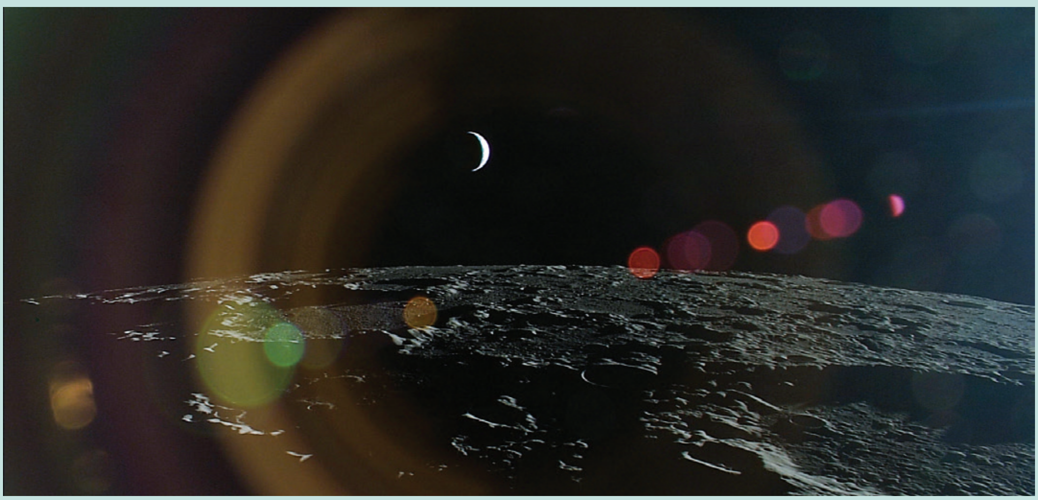
Looking at Our Home Planet From Outside Its Atmosphere

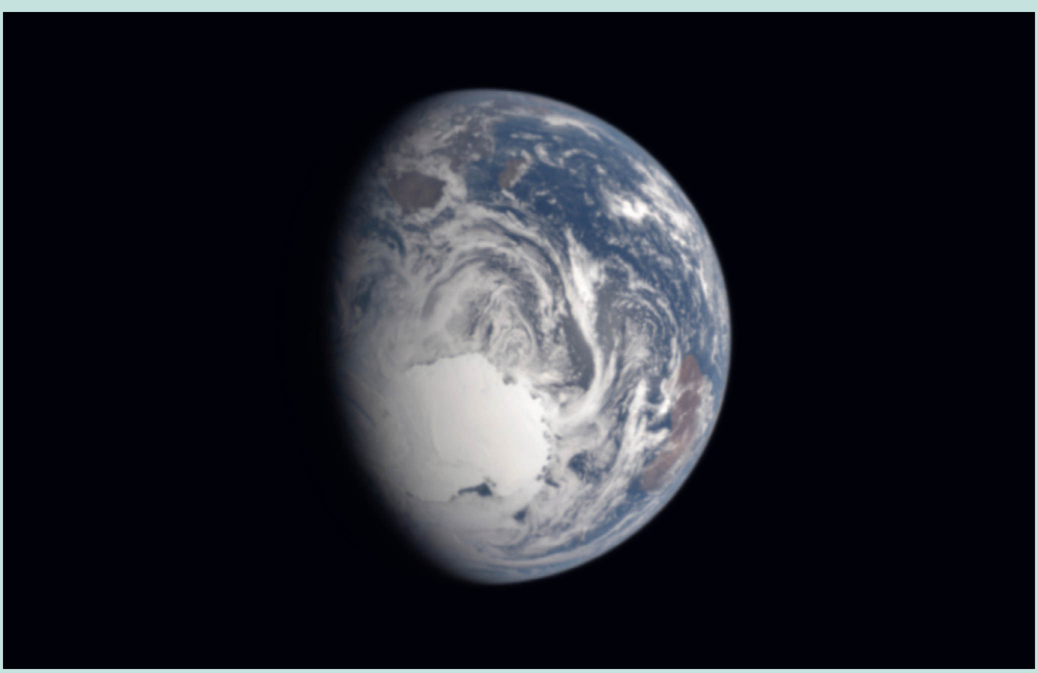
THE EARTHRISE PHOTO that graces the cover of this magazine was the first color photo taken in space to include Earth and the Moon in the same frame, but it was far from the last. Many other lunar orbiters and landers have photographed both worlds. Some spacecraft turned to look at our home planet as they departed it. Others came in from the vast blackness of space to revisit Earth on a gravity-assist flyby. A few have even looked back toward home from distant reaches of the solar system.

Seeing Earth afloat in space imparts a dramatic shift in perspective; Earth is no longer solid ground but just another spacecraft, one that carries every living thing we know of into an unknown future.

Here are a few rarely printed examples of these dramatic images of our home planet and moon. You can find more on our website at **planetary.org/spacecraftearth**.

Longjiang-2: Harbin Institute of Technology; MRO: NASA/JPL/University of Arizona; Zond 7: Russian Academy of Sciences/Ted Stryk





TOP *In this unusual farside perspective from a Chinese lunar sample return test vehicle named Chang'e-5 T1, the Moon looms much larger than the more distant Earth. It was taken on 28 October 2014.*

MIDDLE *The Kaguya lunar orbiter carried a high-definition video camera that frequently viewed Earthrises and Earthsets at a variety of phases as it orbited over the lunar poles, as in this view from October 2008.*

BOTTOM *This was Hayabusa2's view of Earth during its 4 December 2015 flyby. Ice-covered Antarctica is at the center of the image, and Australia is near the right. This photo has been specially processed to portray Earth's colors as the human eye would perceive them.*

Chang'e-5 T1: CNSA; Kaguya: JAXA/NHK; Hayabusa2: JAXA, courtesy Hidehiko Suzuki

MICHAEL L. WONG *is a research associate in the Univeristy of Washington's Astrobiology program.*

Loren A. Roberts for The Planetary Society

The Making of Life

Grappling With the Emergence of Life on Earth Helps Researchers Understand How to Search for It Elsewhere

ABOVE *A future mission to Jupiter's moon Europa may deploy an autonomous submarine to explore Europa's subsurface ocean to look for signs of life, concentrated either at ocean-floor hydrothermal vents or clinging to the ice-ocean interface.*

OPPOSITE *The solar system is full of "ocean worlds." Their surfaces are inhospitable—frozen and fried by solar and galactic radiation—but deep inside, they contain large volumes of liquid water. At least two of these worlds, Jupiter's moon Europa and Saturn's moon Enceladus, very likely have hydrothermal vents sprouting from hot rocks at their ocean floors, providing a possible habitat for life.*

ARE WE ALONE?

This question looms larger with every passing year of envelope-pushing space exploration. For the first time in human history, we have the potential to find unambiguous signs of extraterrestrial life.

Liquid water is the most fundamental requirement for life as we know it. The physical and chemical properties of H_2O control the molecular processes that underpin how life works. Water molecules dissolve ions and enable organic reactions that drive the essential functions of biology. Wherever we find liquid water on Earth, we find life. It's no wonder that NASA adopted "follow the water" as the theme for its Mars exploration program.

It turns out that water is everywhere in the solar system. A stable lake might hide beneath Mars' south polar cap. Jupiter's moon Europa houses perhaps twice as much liquid water as Earth. Tiny Enceladus squirts free samples of its ice-covered ocean into Saturn's orbit. Titan has two kinds of fluids: a global layer of liquid water sloshes deep beneath a thick ice crust and the hydrocarbon seas on its surface. Add to this list the theoretical subsurface oceans of far-flung Pluto and Eris, and it seems that almost every world is staking its claim to habitability.

We now realize that about as many extrasolar planets exist as there are stars. Given the 100 billion stars in our galaxy and the trillions of galaxies in the observable universe, our cosmos should contain countless water-rich habitats.

But are they teeming with life?

HABITABLE VS. INHABITED

We used to believe that life spontaneously appeared wherever the conditions were right. In 1861, French scientist Louis Pasteur performed an experiment that refuted this concept of spontaneous generation, showing that life would only arise when a habitable but sterile environment was seeded by life from elsewhere. Life can only arise from life, Pasteur concluded.

In the present age of interplanetary exploration, Pasteur's experiment serves as an important reminder that "habitable" is not synonymous with "inhabited." Yet, if life is common across the cosmos, then abiogenesis—a synonym for spontaneous generation that doesn't bear the latter's historical baggage—must happen often enough to initiate life on worlds separated by vast tracts of sterile space.

The fact that you are reading *The Planetary Report* is proof that abiogenesis happened at least once in the universe's history. However, until we find other such occurrences, we are forced to base our entire understanding of life on a single sample: us. Solving the mystery of how life emerged on Earth from nonliving processes is how astrobiologists hope to connect the concept of habitability to the reality of inhabitation.

CLUES FROM THE PAST

Almost every environment on Earth has been infected by—or at least affected by—biology, from microbes to humans. Life gave us an oxygen-rich atmosphere, introduced thousands of new minerals to Earth's crust, broke rocks apart, held sediment together, sent the world into a global deep freeze, and is now steadily warming the climate.

Despite Earth's incredible capacity to host life, there is no evidence that spontaneous generation has happened more than once. Just as Pasteur surmised, the life that exists today arose from life that came before it, which came from older life made by even older life, on and on and on. We know this because we can connect the dots between every living thing that we have discovered on a phylogenetic tree. Thanks to our ability to read the instructions written in DNA and RNA, we can compare genetic codes across every domain of life and draw a map of evolution stretching back to our last universal common ancestor, charmingly referred to as "LUCA." The identity of LUCA has been lost to history, but through fossil evidence, we know that life has persisted on this planet in one form or another for roughly 4 billion years.

Thus, the very first life form on Earth emerged about one third the age of the universe ago. The conditions of the early Earth—which were nothing like what we experience now—might have been much more conducive to the emergence of life.

IT CAME FROM THE DEEP

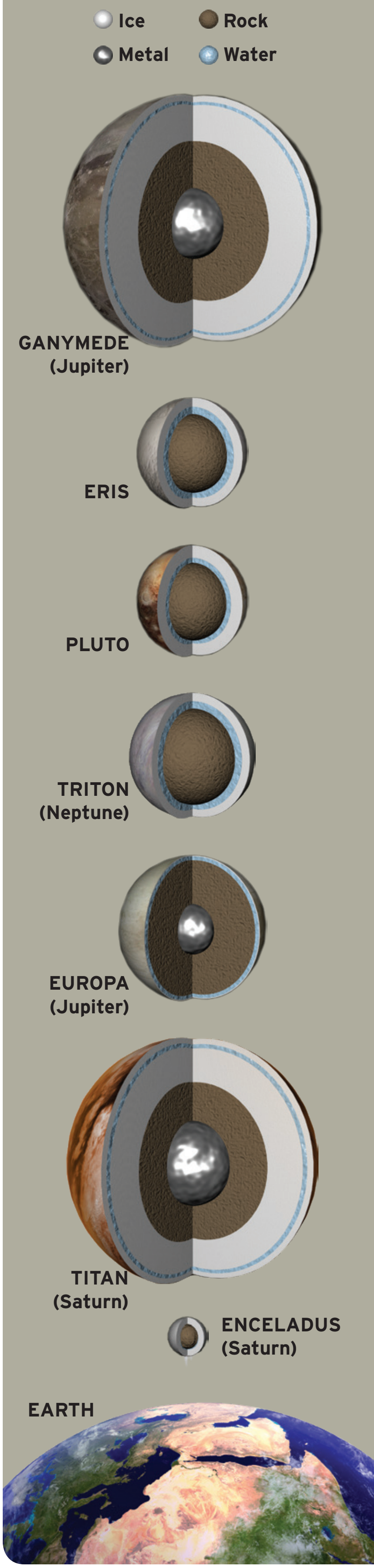
You would die instantly if you were transported back in time by 4 billion years, asphyxiating in an oxygen-free environment and succumbing to high doses of ultraviolet radiation from the young Sun. Even if you circumvented those calamities, you'd eventually drown if you didn't have the foresight to bring a boat because there were probably no landmasses on the infant Earth.

How could anything resembling life possibly originate at the surface of such a treacherous world? The short answer is: it probably didn't. Instead, a growing body of scientific work has come to suggest that life emerged at hydrothermal vents at the bottom of the ocean.

Let's say your time machine was also a submarine, one that could dive to the base of Earth's early ocean. There, you would find spires resembling the chimneys of the Atlantic Ocean's Lost City hydrothermal field.

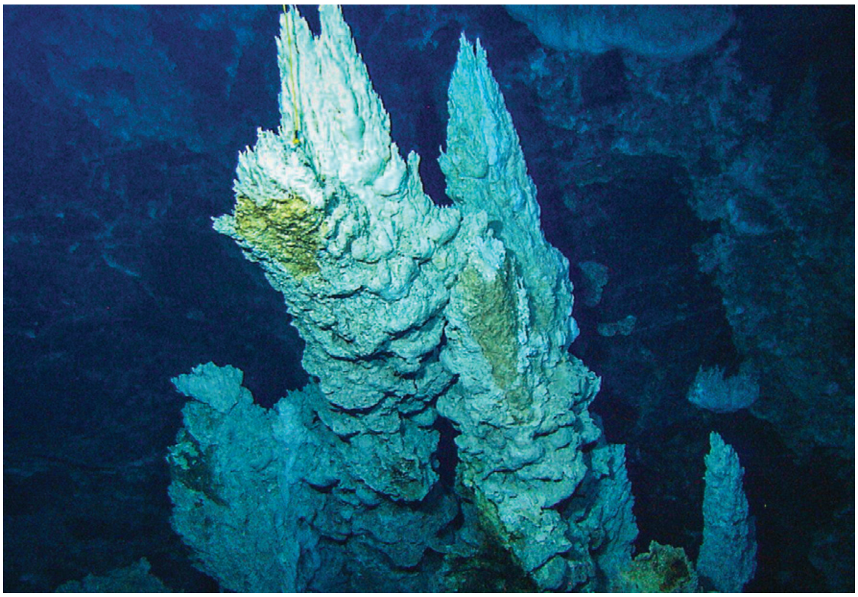
MICHAEL L. WONG *is a research associate in the Univeristy of Washington's Astrobiology program studying planetary atmospheres, habitability, biosignatures, and the emergence of life. He also hosts a podcast called* Strange New Worlds, *which examines science, technology, and culture through the lens of* Star Trek.

OCEAN WORLDS



Doug Ellison, Emily Lakdawalla, and Bob Pappalardo. Internal models based mostly on Hauke Hussmann, Frank Sohl, and Tilman Spohn, 2006, except for Titan (Giuseppi Mitri et al., 2010) and the Galilean moons (Bob Pappalardo, personal communication)

These massive structures, some more than 50 meters tall, were created by the precipitation of iron-bearing minerals when two very different kinds of water met.



ABOVE *At the Lost City hydrothermal field in the Atlantic Ocean, the reaction between seawater and oceanic crust produces calcium carbonate spires up to 60 meters tall. Today, these alkaline vents host diverse biological communities, but roughly 4 billion years ago, they may have been the location for the emergence of life itself.*

RIGHT *The Cassini orbiter observed Enceladus jetting water ice and other materials into orbit around Saturn. That material spreads and becomes the E ring, the band across the image against which Enceladus is silhouetted. By examining particles from the jets and the E ring, Cassini discovered evidence for hydrothermal activity at the floor of an internal Enceladus ocean.*

The majority of Earth's ancient ocean was acidic like a lightly carbonated soft drink, thanks to an overlying carbon dioxide-rich atmosphere. Just beneath the ocean floor, seawater and rock interacted in a process called serpentinization. This chemical reaction changed the water's pH, rendering it alkaline (the opposite of acidic). It also heated the water and infused it with molecular hydrogen, a valuable chemical fuel for life.

When this alkaline groundwater seeped into the ocean, it found itself out of equilibrium with the surrounding colder, acidic, carbon dioxide-rich seawater. "Out of equilibrium" is just jargon for "unbalanced," but its ramifications for life are enormous. An out-of-equilibrium situation is full of untapped energy—the potential to enact change and create complexity.

ELECTRONS AND PROTONS POWER LIFE

Consider how disequilibria power humans. We eat and breathe to gain energy, but what does that really mean? At its heart, it's all about electrons. Our bodies take electrons from the electron-rich food that we eat and transfer them to the electron-greedy oxygen in the air that we breathe.

This electron transfer, mediated by a series of chemical reactions that happen inside of our cells' mitochondria, releases useful energy. Proteins in our mitochondria use this energy to pump protons across an inner membrane, transforming what used to be an imbalance in electrons into an imbalance in protons. A protein called ATP synthase uses the potential energy stored in the imbalance of protons to create adenosine triphosphate (ATP) molecules. Actually, ATP exists as part of yet another imbalance: that between its wholesome self and its broken pieces, adenosine diphosphate and a lone phosphate. ATP is often thought of as the "energy currency of life," and now the origin of that stored energy is clear: it's the useful energy derived from a disequilibrium.

It's not just our cells that harness these disequilibria to create ATP. Almost all the other living things on Earth do too, down to the most primitive single-celled organisms. It's so universal, in fact, that these disequilibria might even be related to how life started.

Lost City: IFE/URI-IAO/UW/Lost City Science Party/NOAA/OAR/OER; Enceladus: NASA/JPL/SSI/Emily Lakdawalla

A HYDROTHERMAL HATCHERY OF LIFE

Back in your time-traveling submarine 4 billion years in the past, you put a microscope up against a hydrothermal chimney. You find that this colossal tower is built like a high-rise apartment building with trillions of tiny mineral rooms, or vesicles, each roughly the size of a biological cell.

Inside these vesicles, H_2 from serpentinization and CO_2 from the surrounding seawater swirl in chemical disequilibrium. In this case, H_2 is the fuel (electron donor) and carbon dioxide is the air (electron acceptor). There's a second disequilibrium present between the alkaline vent fluid and the acidic seawater. The contrast in pH is a natural proton imbalance that resembles the proton imbalance created in modern-day cells.

We don't know how life really began, but here's a plausible scenario involving the untapped geochemical energy present in these ancient hydrothermal chimneys. Travel forward through time and you might see H_2 and CO_2 react with each other, aided by the catalytic metals in the vesicle's walls. They would not only form organic molecules but release pent-up energy as well, and if some organic-mineral precursor to ATP synthase could use the natural proton gradient to bind phosphates together, an energy currency is within the realm of possibility. Incorporating nitrogen- and sulfur-bearing molecules dissolved in the surrounding water, these processes could lead to the first metabolic network: a web of reactions that reinforces itself, growing more stable and more complex with time.

Eventually, this network might lead to information-carrying and self-replicating molecules like RNA, allowing for greater adaptive abilities to changing conditions. It might also construct lipid membranes to replace the inflexible and immutable mineral walls and build ion pumps to regulate its own proton imbalance, thereby effecting the ability to escape these hydrothermal confines.

In the end, it would be a fully functional cell—a product of its geochemical past afloat in the formerly sterile abyss of this ancient sea, soon to encounter new places to thrive and evolve into new ways of being.

ABOVE *Banded iron formations formed billions of years ago when the ocean was full of iron and the atmosphere lacked oxygen.*

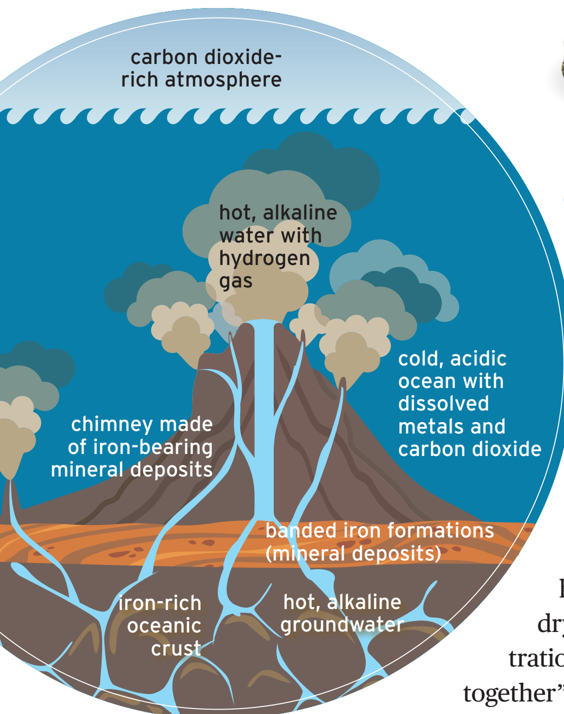
LEFT *Chemical garden experiments simulate the chemistry of active hydrothermal vents. In the experiments, two fluids that are in chemical disequilibrium react with each other, and then mineral precipitates grow. These precipitates are analogous to the hydrothermal chimneys that form at sea-floor vents. Chemical gardens illustrate how non-equilibrium systems can drive the emergence of self-assembly and complexity.*

Michael L. Wong; James St. John

AN EVER-EVOLVING FIELD

For all of its attractive aspects, nobody knows whether this story represents primordial reality. As you read this, scientists are testing various aspects of the hydrothermal-vent hypothesis. Some are learning more about how chemical disequilibria create complex structures by making hydrothermal analogs in the lab. Others are conducting experiments on the catalytic properties of metal-bearing minerals. Still others are investigating how the temperature disparity between the vents' hot interiors and cold exteriors could help concentrate the organic components of life. A few are even trying to come up with clever ideas for the structure of ATP synthase's precursor and how proto-metabolic networks stored and carried information.

Some scientists are investigating completely different hypotheses for the origin of life. Many of these involve prebiotic soups of complex organic molecules. These organic medleys sunbathe on Earth's surface until just the right combination of them find each



ABOVE *Beneath the ocean floor, iron-rich crustal materials like olivine and pyroxene react with water in a process called serpentinization. The reaction produces a green mineral called serpentine along with hydrogen gas and methane and also releases heat. Alkaline groundwater circulating through the fractured rock picks up the heat and gases along with metal ions; under pressure, it flows toward the surface. Where it spews out of the ocean floor, the contrasts in chemistry and temperature cause minerals to precipitate into smoky plumes and mineralized chimneys.*

Loren A. Roberts for The Planetary Society; Rocks: James St. John

other to form life. In the vast expanse of Earth's primitive ocean, the chance encounters between potential molecular collaborators would be rare. So, most researchers suspect that the organic matchmaking must have occurred at tidal pools along the seashore or in freshwater hydrothermal pools, where periodic drying episodes promoted the concentration and polymerization (or "sticking together") of life's building blocks.

Origin-of-life research doesn't lack in "far out" ideas either. One camp argues that life on Earth began as self-replicating clay minerals. Another group claims that nuclear-powered geysers—formed by the decay of radioactive uranium—enabled the prebiotic reactions that formed life.

Then there's the notion that we're all Martians, insisted upon by those who consider early Mars a likelier place to start life than early Earth. In this scenario, primitive Martian microbes hitched a ride deep inside an impact-ejected rock and seeded our planet in a process known as lithopanspermia.

If any of these ideas proves correct, what would that imply about our loneliness in the cosmos?

SEEKING OUR COSMIC NEIGHBORS

If life originated because of the physical and chemical disequilibria at hydrothermal vents, then countless wet, rocky planetoids should provide the basic requirements to start life. Hydrothermal systems can result from water meeting rock on any tectonically active world. Martian rocks examined by the Spirit rover bear the mineral byproducts of ancient hydrothermal systems, and Cassini identified the telltale signs of hydrothermal activity on the Saturnian moon Enceladus. Thus far, the hydrothermal-vent hypothesis is the only scheme that could plausibly lead to independent abiogeneses on both Earth-like planets and ice-covered ocean worlds.

However, if the emergence of life requires surface environments that undergo wet-dry cycles and are directly exposed to air and radiation, then Mars would be much more conducive to life than Europa or Enceladus are. In this case, the icy satellites of Jupiter and Saturn—as well as their analogs across the cosmos—would be habitable but sterile, barring the unlikely scenario that some rock ejected from an inhabited world like Earth seeded them.

If life can arise in a chemical soup without the aid of catalytic minerals or tectonic activity, then that raises the possibility of exotic life on the surface of Titan. This moon of Saturn produces complex organic molecules in its atmosphere that collect on its surface and in its hydrocarbon seas. Scientists look to Titan for potential analogs to the organic-rich soups that were present on Earth's first landmasses.

At present, there is no consensus in the scientific community on the requirements for the origin of life. Perhaps none of our hypotheses are correct, or perhaps the answer is "all of them." We just don't know yet.

Finding life on any neighboring world would tell us which—if any—of our origin hypotheses are more likely than the others. Not finding life would also teach us that habitability alone is an insufficient condition for life. Now that we know that such a diverse array of astrobiological candidates exist in our own cosmic backyard, the question begs: is anyone out there?

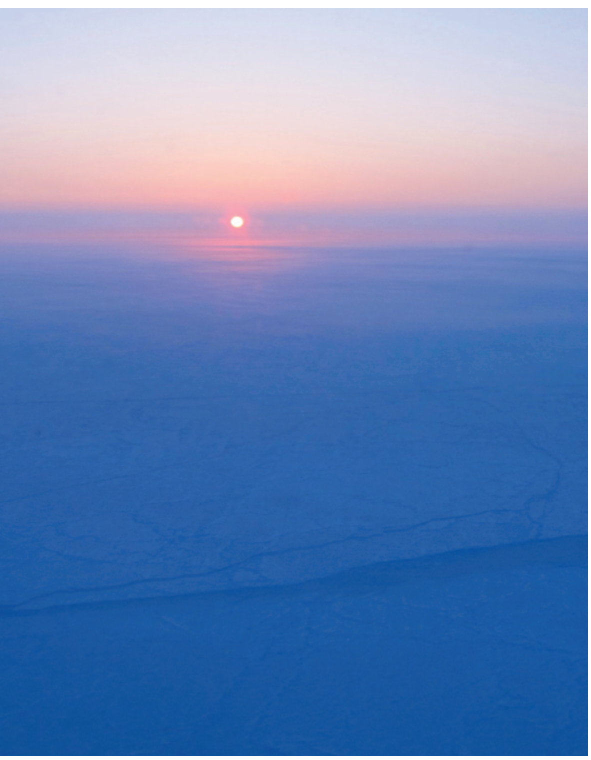
RICHARD CHUTE *is The Planetary Society's chief development officer.*

Timing Is Everything

Year-End Gifts to Support Space Exploration

THE TRADITION OF giving to charities like The Planetary Society at year's end often brings up questions about how to make those gifts, as well as their tax implications.

A gift of cash is the simplest way to make a gift, and gifts may be sent to us in the form of a check via the mail (sent to my attention at 60 S. Los Robles Ave., Pasadena, CA 91101) or via a credit/debit card on our secure website at **planetary.org/donate**. While you are making your gift, we make it easy for you to see if you work for a company that will match it. Our confirmation page and email both include links to our look-up tool, which allows you to see if your employer participates. You may also check in advance by going to **planetary.org/workplace**.



NASA/James Yungel

For our members who are United States taxpayers, some changes were enacted in the Tax Cuts and Jobs Act of 2017 which impact when and how charitable deductions may be taken. The most significant change was the increase in the standard deduction to $12,000 for individuals and $24,000 for married couples filing jointly. Gifts to charities are deductible only if you itemize, so these increases will reduce the number of people who will qualify for charitable deductions, especially middle-income families.

While fewer people will benefit from deductions, the tax savings for donors who itemize will increase. The limit on the amount of charitable deductions that can be taken in a single year increased from 50 percent to 60 percent of adjusted gross income, and those who give more than 60 percent of their adjusted gross income may carry forward the excess contribution for an additional 5 years.

For U.S. taxpayers, there are other ways to make gifts to The Planetary Society. Members may want to consider a direct transfer of appreciated stock. This allows you to avoid the capital gains tax that occurs if you sell the stock and recognize the income from the sale.

For those who have individual retirement accounts and are over age 70.5, another taxwise method is to make a qualified charitable distribution. Gifts made this way allow you to avoid paying any tax on the income and also count toward your required minimum distribution up to a maximum of $100,000. If the new standard deduction levels mean you won't itemize, this could be a sensible approach to making charitable gifts. We have also found that many of our members give through a donor-advised fund, which is a valuable tool for those looking to carefully manage their charitable giving.

IMPORTANT DEADLINES

For U.S. tax purposes, gifts must be received on or before the last day of the year. Here are some common methods of making a gift and their associated deadlines.

ONLINE CREDIT CARD GIFTS: transaction completed by 11:59 p.m. EST (8:59 p.m. PST), 31 Dec

CHECKS SENT VIA U.S. MAIL: postmarked on or before 31 Dec

CHECKS SENT VIA THIRD-PARTY SHIPPING (SUCH AS FEDEX OR UPS): delivered on or before 31 Dec

CREDIT CARD GIFTS VIA U.S. MAIL: received and processed on or before 31 Dec

STOCK TRANSFER: broker-to-broker instructions issued in time for completed transfer on or before 31 Dec

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

A Busy Summer

LightSail 2 and Solar Sailing Updates

WHILE LIGHTSAIL 2 waits out launch delays, the LightSail 2 team and even the spacecraft have been busy. Since our last update in *The Planetary Report* (June Solstice 2018), the spacecraft has been shaken (not stirred) and has made its way back to San Luis Obispo, and team members participated in a workshop to investigate using exotic metamaterials in future solar sails.

ABOVE *The LightSail 2 mission readiness review team at Cal Poly San Luis Obispo on 17 July 2018. Back row: John Bellardo, Cal Poly; Dave Spencer, Purdue. Middle row: Barbara Plante, Boreal Space; Bruce Betts, The Planetary Society. Front row: Alicia Johnstone, Cal Poly; Alex Diaz, Ecliptic Enterprises Corporation. Not pictured: Darren Garber, NXTRAC.*

MRR/ORT A-OK

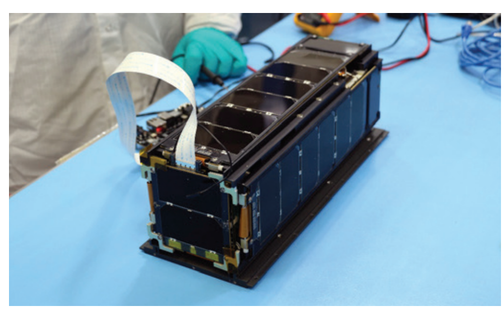
During the summer, the LightSail 2 team held a mission readiness review (MRR) and an operational readiness test (ORT). In the MRR, the team reviewed various aspects of the mission, from flight rules to spacecraft idiosyncrasies to flight modes.

Since the MRR, we have visited our ground communication stations at Cal Poly San Luis Obispo and Georgia Tech, and we have traveled to Purdue University and Kauai Community College in hopes of bringing them on as ground stations as well. Kauai would be particularly valuable for us. It is at a longitude far west of our current ground stations and is also much closer to the equator (useful because LightSail 2 will have an orbital inclination of 24 degrees).

The ORT was a mission rehearsal. The team simulated key mission events using the actual Cal Poly ground station and Benchsat, a tabletop mockup of LightSail that contains clones of the LightSail 2 software and most of its hardware. We will hold one more ORT shortly before launch.

SUCCESSFUL SHAKE-UP

In July at the Air Force Research Laboratory (AFRL) in Albuquerque, New Mexico, engineers put LightSail 2 through a series of vibration tests to simulate rocket launch conditions. LightSail 2 had already gone through similar tests on its own, but now the whole Prox-1 bundle (including LightSail 2's P-POD deployer inside the Georgia Tech Prox-1 spacecraft) had to be tested. Afterward, LightSail 2 was removed from the P-POD and tested. All systems performed well.



RIGHT *LightSail 2 undergoing health checks following vibration testing at the Air Force Research Laboratory.*

Group photo: Jason Davis/The Planetary Society; LightSail 2: Air Force Research Laboratory

BACK HOME TO RECHARGE

The testing of LightSail 2 after the vibration testing revealed that during the 4 months it had been stored, its batteries had dropped in charge more than we would have liked. LightSail 2 is designed to work even if it comes out of Prox-1 low on charge, but we'd prefer

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

a higher level of charge. In late October, we flew the spacecraft back to Cal Poly so we could recharge the batteries at regular intervals. When a firm launch date gets closer, we'll top off the batteries and fly LightSail 2 back to AFRL for reintegration with Prox-1 before it is shipped to Florida for integration into the Falcon Heavy rocket.

ARE METAMATERIALS IN SOLAR SAILING'S FUTURE?

Also in October, I presented about solar sailing and the LightSail program at an Optical Society of America (OSA) workshop in Washington, D.C. It brought together members of the solar sailing community with members of optics and materials communities, specifically experts in metamaterials. Metamaterials in this context are materials that combine and arrange different substances in extremely clever ways to generate unusual optical properties. Often laid down as thin films (metasurfaces), they can actively control the polarization of transmitted light, actively change diffraction patterns, bend light around objects, and cause physical material to bend in response to exposure to light.

In the workshop, participants began the discussion of how these materials might assist future solar sails. Ideas included integrating small patches of metamaterials as part of a large reflective sail to assist with control of the orientation of the spacecraft. In the longer term, perhaps one could make whole sails out of transparent diffractive metamaterials. They could in theory adjust the thrust direction of the sail without rotating the sail by adjusting the angle at which light is diffracted through the sail.

AWAITING LAUNCH

At the time of this writing, the launch date for the Falcon Heavy on which LightSail 2 will ride is still uncertain but is anticipated to occur in early 2019. For updates on the launch date and to read blogs with more details, visit **sail.planetary.org**.

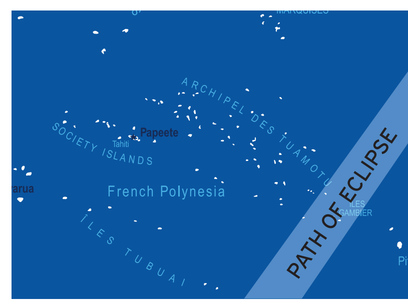
Total Solar Eclipse Adventures for Society Members & Friends!

ALASKA AURORA BOREALIS
28 MARCH–3 APRIL 2019
You'll see Alaska's wildlife—from grizzlies to musk oxen—in their winter habitat. Then, you'll travel by train from Talkeetna—past 20,310-foot Mt. Denali—to Fairbanks, where you'll delight in the night sky's dazzling aurora borealis!

TAHITI TOTAL SOLAR ECLIPSE
25 JUNE–4 JULY 2019
WITH OPTIONAL BORA BORA EXTENSION TO 7 JULY
With leadership by popular Planetary Society and Betchart leader Bob Nansen
French Polynesia is one of the most beautiful places on Earth. Discover the magic of these islands and see the total solar eclipse on 2 July from our chartered aircraft near the remote Gambier Islands. Enjoy this marine wonderland of coral reefs, exquisite islands, and hardy Polynesian people who have learned to exist in this ruggedly beautiful environment!

CHILE TOTAL SOLAR ECLIPSE
26 JUNE–6 JULY 2019
WITH OPTIONAL EASTER ISLAND EXTENSION 21–26 JUNE
With leadership by another popular Planetary Society and Betchart leader, Dr. Tyler Nordgren
Join us as we explore Chile, where the total solar eclipse path will cross on 2 July 2019. Visit the historic capital city of Santiago, Chile's largest city and one of the most beautiful cities in South America. Explore an archeological site in the Valle del Encanto, and discover the unique cloud forest and coastal beauty of Parque Nacional Fray Jorge. Visit astronomical observatories and see the 2019 total solar eclipse!

We invite you to join these wonderful eclipse adventures! Space is limited, so please contact us right away for reservations. Phone Betchart Expeditions Inc. at (800) 252-4910 or email: *betcharttaunya@gmail.com.*



Observatorio Cerro Mamalluca: Miguel Carvajal

IN THE SKY

On 21 January, there will be a total lunar eclipse visible throughout most of North America, South America, the eastern Pacific Ocean, the western Atlantic Ocean, western Europe, and western Africa. A partial lunar eclipse will be visible in other parts of Africa, Europe, and Asia. On 6 January there will be a partial solar eclipse visible in parts of eastern Asia and the northern Pacific Ocean. Very bright Jupiter is below extremely bright Venus in the pre-dawn East until it passes Venus in the sky on 22 January. At that point dimmer, yellowish Saturn is below the other two but passes above Venus in the sky on 18 February. Reddish Mars continues to fade in the early evening West as Mars and Earth grow farther apart in their orbits.

RANDOM SPACE FACT

Besides being the first humans to witness an Earthrise (see cover), the Apollo 8 crew (Borman, Lovell, and Anders) were also the first to travel beyond low Earth orbit, the first to orbit the Moon, and the first to see the farside of the Moon with their own eyes.

TRIVIA CONTEST

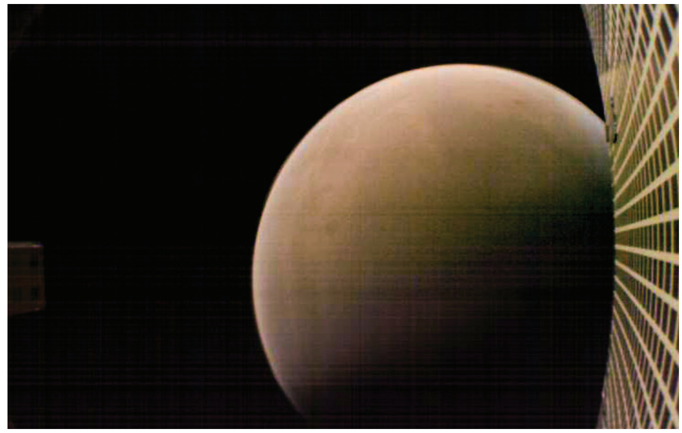
Our June Solstice contest winner is Nicholas Green of Waterloo, Iowa. Congratulations! The question was: ***By volume, about how many of Mars would fit inside Earth?*** The answer: ***About 6.64 of Mars would fit inside Earth.***

Try to win a copy of *The Penguin Book of Outer Space Exploration: NASA and the Incredible Story of Human Spaceflight* by John Logsdon and a *Planetary Radio* T-shirt by answering this question:

Who were the final members of the backup crew for the Apollo 8 mission?

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 March 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 *On 26 November, the first interplanetary CubeSats, Mars Cube One (MarCO), relayed news of InSight's successful Mars landing. Afterward, one of them took this farewell photo of Mars, looking across its solar panel. Flight controllers will maintain contact with the MarCOs as they continue on heliocentric orbits.*

Where We Are

An At-A-Glance Spacecraft Locator

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 Kuiper belt. I have added colored arrows to the orbits of the planets to demonstrate where in each orbit the seasons shift.

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 robots that are currently in routine communication with Earth, plus 3 others. The Kepler and Dawn missions ended on 30 and 31 October. Opportunity's status remains uncertain.

I have to apologize for leaving out two interplanetary spacecraft from the inaugural version of this column. I've now added in NASA's Parker Solar Probe, on its way to pass through the solar atmosphere, and China's Longjiang-2, the first CubeSat to enter lunar orbit. We had to print this magazine before China's Chang'e-4 lander was scheduled to launch on 8 December; optimistically, I've placed it on the lunar farside. By now, you'll know if my guess was correct.

The final quarter of 2018 has had a lot of comings and goings. The first quarter of 2019 looks to be less momentous, with only India's Chandrayaan-2 slated for launch toward the Moon.

MarCO: NASA/JPL-Caltech; Loren Roberts for The Planetary Society after a concept by Olaf Frohn

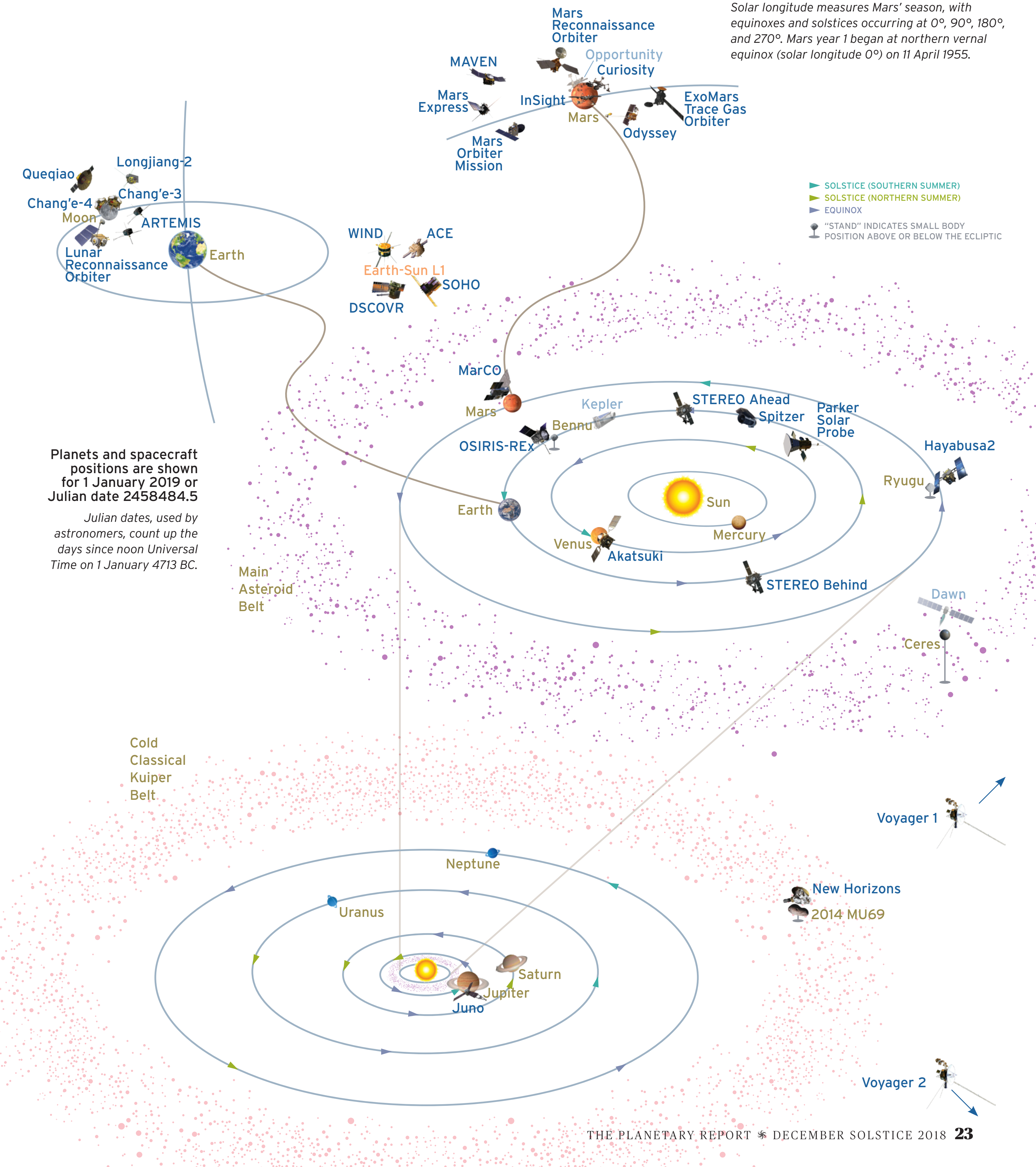
EMILY STEWART LAKDAWALLA *is The Planetary Society's senior editor and planetary evangelist.*

Mars year 34/solar longitude 316.3°

Solar longitude measures Mars' season, with equinoxes and solstices occurring at 0°, 90°, 180°, and 270°. Mars year 1 began at northern vernal equinox (solar longitude 0°) on 11 April 1955.

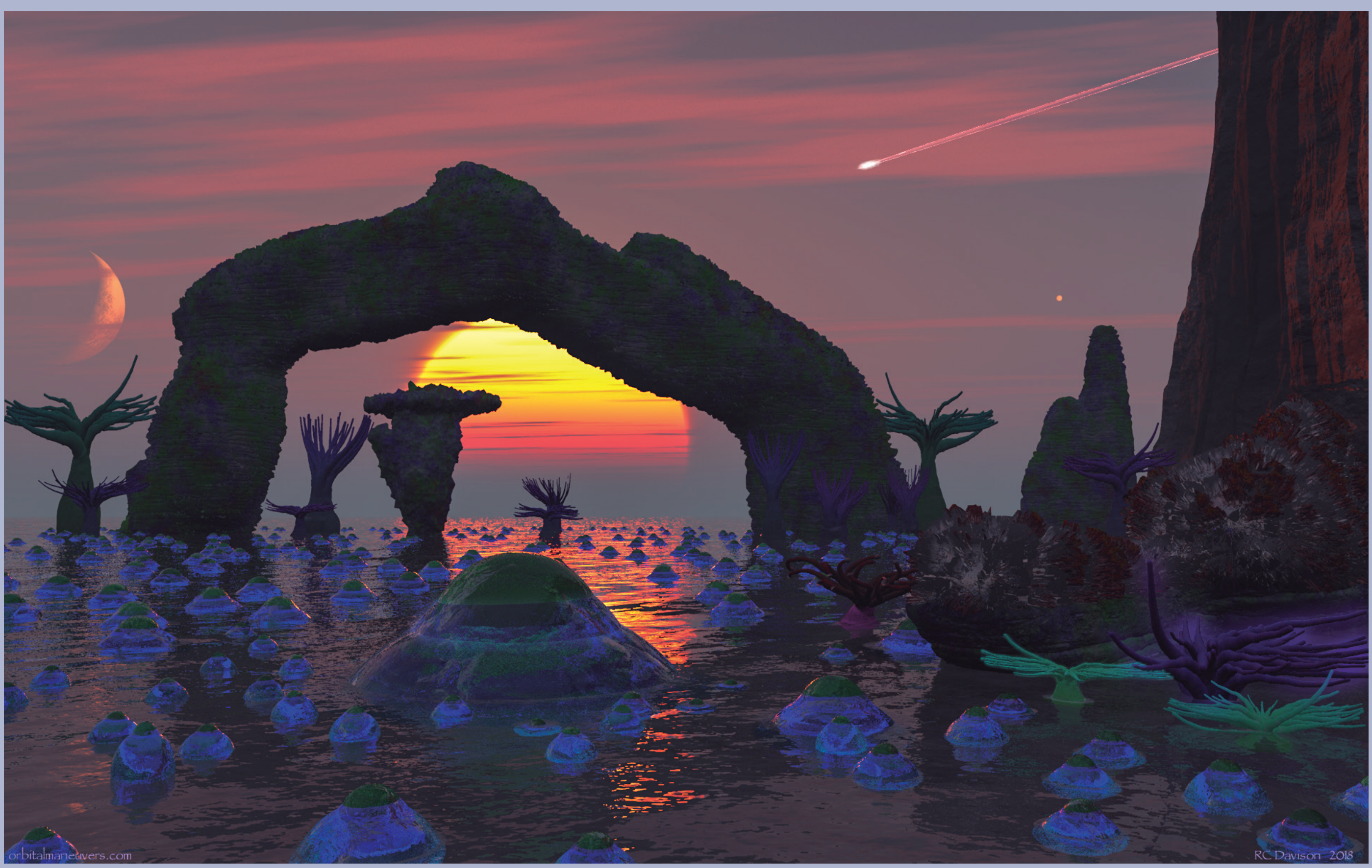
Planets and spacecraft positions are shown for 1 January 2019 or Julian date 2458484.5

Julian dates, used by astronomers, count up the days since noon Universal Time on 1 January 4713 BC.



THE PLANETARY SOCIETY
60 SOUTH LOS ROBLES AVENUE
PASADENA CA 91101-2016 USA

astronomical art



RC Davison
Primordial Sunset

With help from the International Association of Astronomical Artists, The Planetary Society is returning to the tradition of featuring space artists on the back cover of *The Planetary Report*. This issue asks how life might have begun on Earth or elsewhere and views our Earth from a planetary perspective. *Primordial Sunset* touches all these themes. It depicts an imagined early Earth when multicellular life existed only in the oceans.

About this work, artist RC Davison says: "Life started in the seas. Water provided the medium and all the nutrients needed for life to form, but perhaps it didn't evolve spontaneously. Perhaps it was seeded by comets, asteroids, and meteors from other inhabited planets."

RC Davison