The Planetary Society

THE PLANETARY REPORT

DECEMBER SOLSTICE 2019
VOLUME 39, NUMBER 4
planetary.org

LOOKING BACK, LOOKING AHEAD

WE FOLLOWED WATER
FOUND HOT SPRINGS, RIVERS, AND LAKES
NEXT, WE SEARCH FOR LIFE

SPACE LIFE GOALS ✲ CELEBRATING 40 YEARS ✲ PLUTO ON EARTH

University of Arkansas

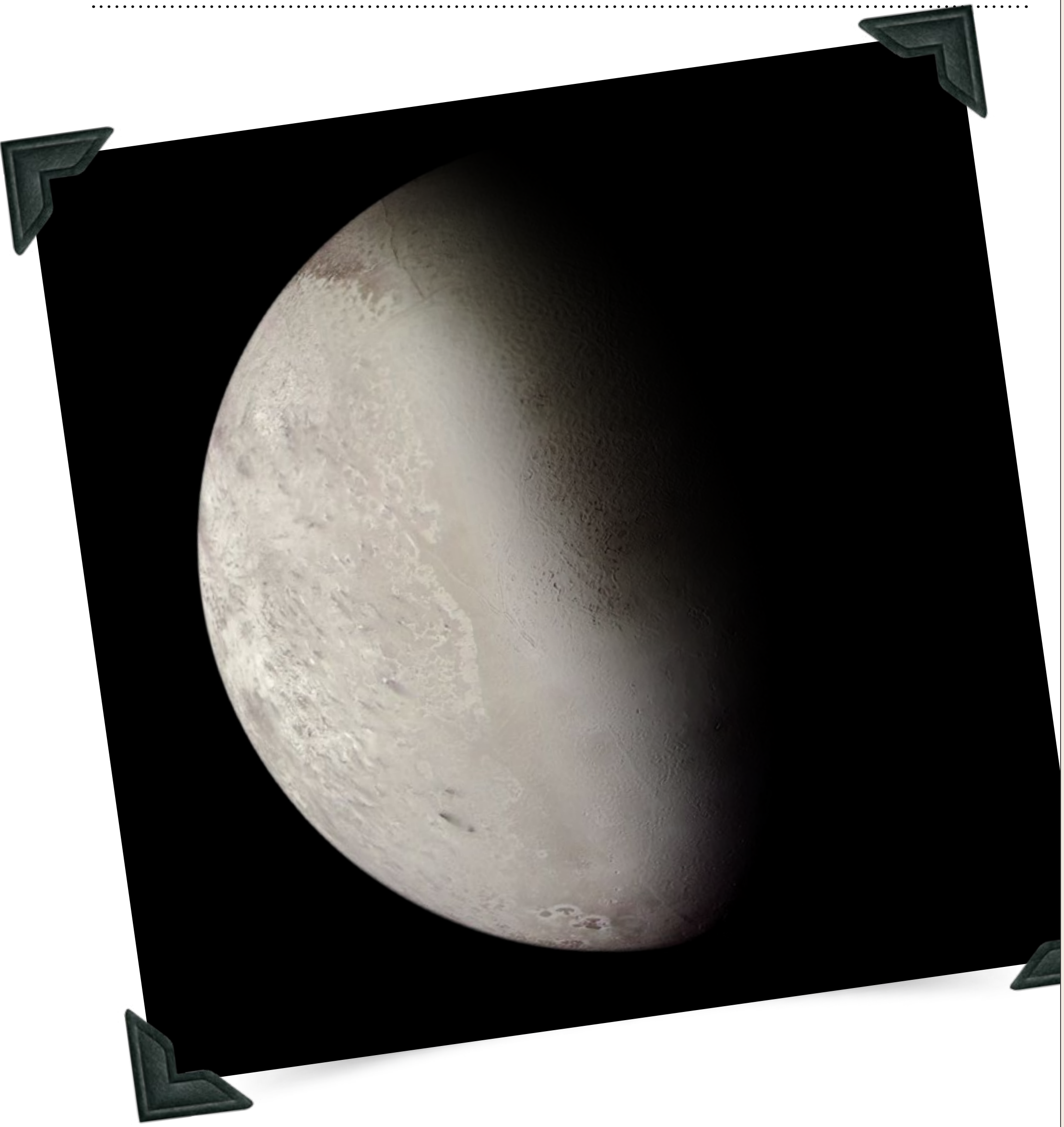
Deep Freezer

Simulating Chemical Processes on Far-Away Worlds

DOCTORAL STUDENT Caitlin Ahrens works in the Pluto lab at the University of Arkansas. The machine can simulate Pluto's surface temperature (34 to 54 kelvins, or -239 to -219 Celsius, or -398 to -362 Fahrenheit) and pressure (14 microbars, or 14 millionths of Earth surface pressure). It has a separate chamber for mixing carbon monoxide, methane, and nitrogen gases in different proportions before Ahrens introduces them to the Pluto chamber to observe how they would behave on Pluto, helping scientists to interpret New Horizons' observations of Pluto's surface composition. While scientists have studied the behavior of the individual ices before, how they interact with each other is not well understood.

Pluto has a huge variety of surface textures with large, blotchy regions of different kinds of ices. In the Pluto lab, investigating these ices helps to understand how they form crystals and how those crystals change with temperature and pressure. Spectrometers can see how light of different wavelengths interacts with the crystals, so Pluto lab experiments will help Ahrens and her coworkers to interpret the data from spacecraft and Earth-based telescopes. They can also study how shifts in Pluto's climate affect its ices. Eventually, the work with this Pluto lab will lead to other experiments investigating how these different ices behave as the geologic materials that form Pluto's diverse landforms.

SNAPSHOTS FROM SPACE



NASA/JPL/Ted Stryk

NEPTUNE'S MOON TRITON, nearly as large as our own moon, probably began its existence in the Kuiper belt. It's covered by the same kinds of ices as Pluto: solid forms of water, methane, nitrogen, and carbon-rich gunk. It's been 30 years since Voyager 2 flew past, seeing only its southern hemisphere. If Earth were to begin developing a Neptune orbiter mission soon, we could arrive in the 2040s, when the Neptune system would be near equinox, and the entire surface of the moon would be sunlit over the course of its day.

–Emily Stewart Lakdawalla

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

SEE MORE EVERY DAY! PLANETARY.ORG/BLOGS

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

ON THE COVER: The Sun sets below a fan of blue in a brown sky over the mountainous rim of Gusev crater, Mars. The Mars Exploration Rover Spirit took this photo on 19 May 2005. *Credit: NASA/JPL/Cornell/Texas A&M* ✻ *The Planetary Report* (ISSN 0736-3680) is published quarterly at the editorial offices of The Planetary Society, 60 South Los Robles Avenue, Pasadena, CA 91101-2016, 626-793-5100. It is available to members of The Planetary Society. Annual dues are $50 (U.S. dollars) for members in the United States as well as in Canada and other countries. Printed in USA. Third-class postage at Pasadena, California and at an additional mailing office. Canada Post Agreement Number 87424. ✻ Viewpoints expressed in articles and editorials are those of the authors and do not necessarily represent positions of The Planetary Society, its officers, or its advisers. © 2019 by The Planetary Society. All Rights Reserved. The Planetary Society and *The Planetary Report*: Registered Trademarks ® The Planetary Society. Planetfest™ The Planetary Society.

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DECEMBER SOLSTICE 2019

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

People. Passion. Planets.

Celebrating 40 Years of Space for Everyone

LIKE SPACECRAFT, time flies. Forty years ago, our founders Carl, Bruce, and Lou had a hypothesis. They believed that public support for space exploration was strong but was unrecognized and unfocused. Their idea was to form a grassroots organization dedicated to advancing planetary exploration.

Carl wrote in the first issue of *The Planetary Report*: "If we are as successful as at least some experts think we are likely to be, we may be about to accomplish not only our initial goal of demonstrating a base of popular support for planetary exploration, but also to provide some carefully targeted funds for the stimulation of critical activities."

Over and over again, you have proven that the founding hypothesis was correct. Public support for space and fascination about space are stronger than ever. People everywhere have a renewed interest in exploring Mars, searching for life, protecting against an incoming asteroid, visiting the Moon, and watching what commercial companies like SpaceX and Blue Origin are accomplishing.

Looking back on our 40-year history, it's clear that 2019 has been extraordinary. Your very own LightSail 2 spacecraft has proven that a solar sail can maneuver and raise its altitude in Earth orbit for one twentieth the cost of a government-built mission. Your efficient PlanetVac regolith sampling system now has a chance to go to the Moon. Your advocacy efforts continue to pay off: New Horizons maneuvered and flew by another fantastically distant Kuiper belt object, Europa and Titan missions are in development, and NASA has committed to a new space telescope to help us detect dangerous asteroids.

It's amazing to see what we can do when we work together to advance space exploration.

We have a new 5-year strategic framework: Space for Everyone. We want more people taking action for space, enabling humankind to explore worlds, search for life, and defend Earth from asteroids. We aim to increase our membership to 75,000 and to engage a broader community of many millions more around the globe.

Navid Baraty for The Planetary Society

You can help. Share the adventure of space with others. Pass on *The Planetary Report*, give a gift membership, and share videos, podcasts, and stories from our website.

You're reading this because not only do you support space exploration but you also take action to shape our future in space. Thank you indeed.

Onward! The best is yet ahead!

Bill Nye

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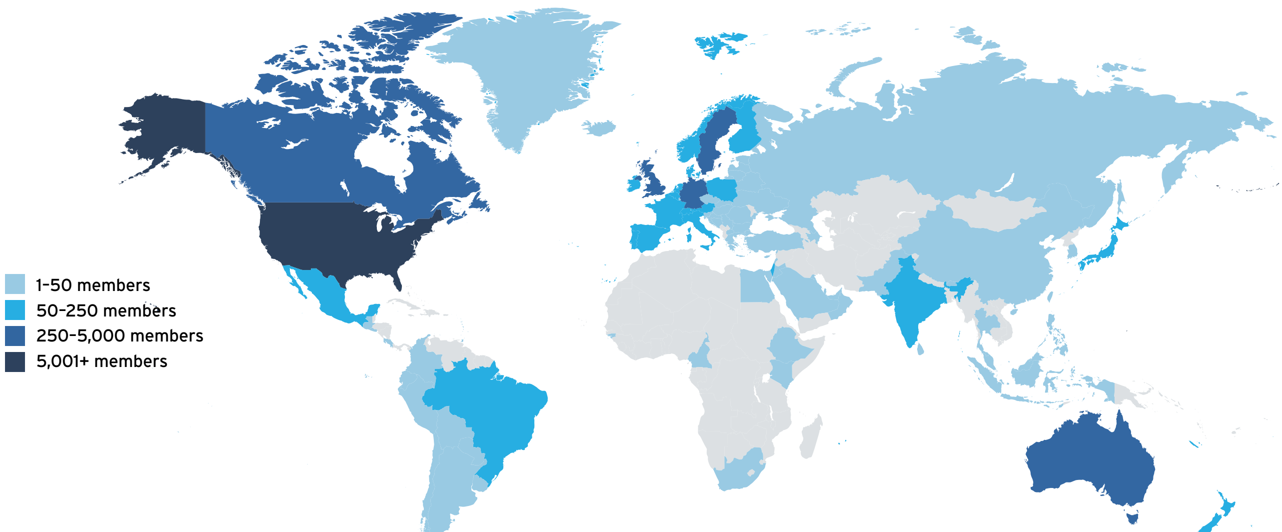
YOUR YEAR ADVANCING SPACE EXPLORATION



LEFT *Members celebrate together at Kennedy Space Center just before watching the launch of LightSail 2.*

Global Collaboration

HOW YOU'VE CULTIVATED A GLOBAL VOICE FOR SPACE IN 2019

The Planetary Society is at its core a community. Working together across our pale blue dot, we advance space science and exploration. In 2019, our community grew.

Antonio Peronace for The Planetary Society

46,996 members in **107** countries

5,700 volunteers in **111** countries

1.5M social media community

Your membership helps sponsor events like the biannual Planetary Defense Conference, which brings together the world's leading experts in planetary defense.

ABOVE *CEO Bill Nye addresses the attendees of the Planetary Defense Conference's public event on 1 May 2019 in Washington, D.C.*

Education

HOW YOU EXPANDED PUBLIC KNOWLEDGE ABOUT SPACE IN 2019

Thanks to you, millions of people have learned about the importance of space exploration through educational resources, powerful storytelling, and human connection.

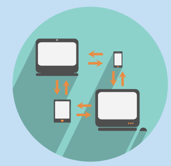
RADIO

2.5 million worldwide *Planetary Radio* listeners tuned in to **69 new episodes**

VIDEO

60 new videos garnered **3.15 million views**

WEB



Planetary.org received **6.5 million page views** from **2.8 million website visitors**

All Aboard the Spacecraft

We believe that the best way to educate people about a space mission is to make them a part of it. In 2019, your name and those of fellow members flew past Kuiper belt object 2014 MU69 aboard New Horizons, orbited asteroid Bennu aboard OSIRIS-REx, and landed on asteroid Ryugu as part of Hayabusa2. Learn more about the names on these and other missions at planetary.org/membernames.

ABOVE *On 17 September 2019, Hayabusa2 dropped a baseball-sized target marker toward asteroid Ryugu. Etched onto foil wrapped around the target marker are names collected by The Planetary Society and the Japan Aerospace Exploration Agency in 2013.*

ABOVE *Illinois volunteer Sathwik Palwai shares the LightSail 2 story with his community.*

Learn, Share, Connect

The Planetary Society's free online course offerings grew this year, giving you the knowledge you need to advocate for space and share your passion with others. Thanks to your support, we also added new online tools for community outreach that equipped volunteers to organize more than 100 events and activities, reaching more than 30,000 people in their communities.

Hayabusa: JAXA, Chiba Inst. Tech and collaborators; classroom: Jyothsna Palwai

ABOVE *Members listen to a presentation by New Horizons team member and Planetary Society charter member Ralph McNutt during the 2019 Day of Action.*

A Day of Action in Washington, D.C.

In February 2019, 100 Planetary Society members from 25 states in the United States came together in Washington, D.C. for the first annual Day of Action. They represented members worldwide in 127 meetings with congressional representatives, advocating for funding for space science and exploration.

Advocacy

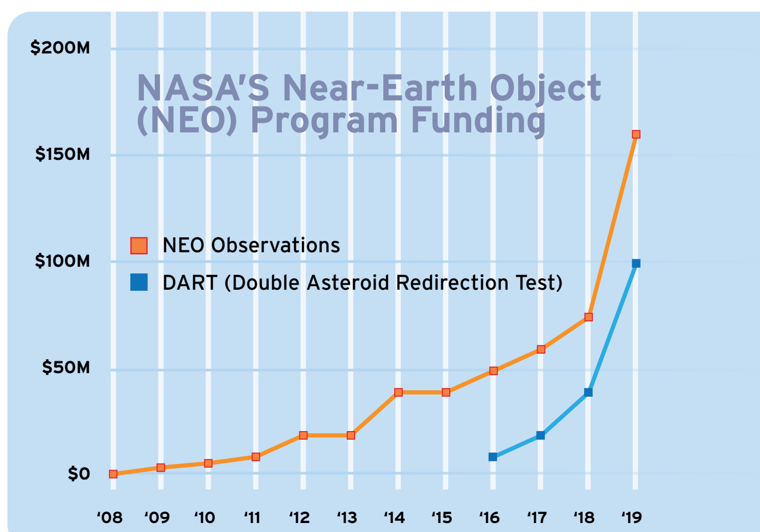
HOW YOU SHAPED SPACE POLICY AND FOUGHT FOR EXPLORATION IN 2019

Bringing Space Exploration to Capitol Hill

This year, your support led to the reestablishment of the Planetary Science Caucus in the 116th U.S. Congress. The caucus, which unites members of Congress from both parties who are passionate about promoting the scientific exploration of space, currently boasts 20 members and continues to grow.

Seeing the Results of Your Work

Thanks to your many years of advocacy for planetary defense (protecting our planet from asteroid and comet impacts), real progress is being made. NASA has increased its planetary defense budget by 4,000 percent over the past decade. This year, NASA announced that it will build an asteroid-hunting space telescope as part of a new, multipronged approach to planetary defense.



ABOVE *The budget for NASA's Near-Earth Object Observations Program (renamed Planetary Defense in 2019) grew from less than $4 million in fiscal year 2009 to more than $150 million in 2019. It now supports regular planetary defense missions, beginning with the Double Asteroid Redirection Test (DART), launching in 2021.*

Antonio Peronace for The Planetary Society; chart: Casey Dreier/Loren A. Roberts

Innovation

HOW YOU'VE INVESTED IN INNOVATIVE SCIENCE AND TECHNOLOGY IN 2019

ABOVE *In 2018, The Planetary Society awarded its first-ever Shoemaker grant to an observatory in Africa, the Morocco Oukaïmeden Sky Survey (MOSS). In recent years, our asteroid hunters have helped NASA confirm a rare double asteroid, observed a fast-spinning asteroid that rotates every 3.5 minutes, and imaged the interstellar asteroid 'Oumuamua that visited our solar system in 2017.*

Defending Earth

Thanks to you, the Gene Shoemaker Near-Earth Object (NEO) Grant Program is now in its twenty-second year. This year, 696 donors gave $76,633 to support work by amateur and professional astronomers that is critical to the defense of our planet. As we go to press, we're about to announce a new set of winners. Get the latest information at planetary.org/neogrants.

PlanetVac on Its Way to the Moon

In 2019, NASA selected PlanetVac, a streamlined, less-expensive method for gathering samples from planetary surfaces, for its Commercial Lunar Payload Services Program. Your support funded 2 crucial tests for PlanetVac: lab testing of PlanetVac in 2013 and a field test in the Mojave desert onboard a Xodiac rocket in 2018.

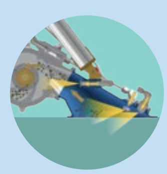
LightSail 2 Mission Success

This year, The Planetary Society's LightSail 2 spacecraft launched into Earth orbit and succeeded in its mission to demonstrate controlled solar sailing. With this mission, you showed the world that groundbreaking space exploration technologies can be made possible entirely by crowdfunding.

SHOEMAKER

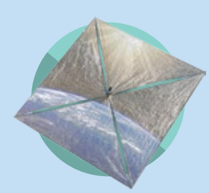
56 grants awarded in **18 countries** on **6 continents**

PLANETVAC



1,389 members gave **$124,465** to support the development of PlanetVac

LIGHTSAIL 2



LightSail 2 was funded by **49,426 donations** totaling **$7 million** over **10 years**

MOSS; The Planetary Society

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

WHAT ARE YOUR SPACE LIFE GOALS?

In 2020, join us in building the ultimate list of life goals for space enthusiasts. Have you ever witnessed a rocket launch or observed Jupiter's moons through a telescope? If not, do you want to? You can help give space enthusiasts a way to track their experiences and be inspired to share their excitement, whether they're a lifelong space geek or a newfound fan.

The Planetary Society; NASA; Getty Images

What are the greatest space things you've seen and done? What experiences caused your interest in space? What are the absolute must-sees and must-dos for a space fan like you?

Between now and 31 January 2020, send us your creative ideas for ways to experience space. Share your space life goal suggestions at **planetary.org/spacegoals**.

YOUR GUIDE TO YEAR-END GIVING FOR SPACE EXPLORATION

You can make a difference in our mission by making a gift to advance space science and exploration.

Give cash: use your credit or debit card at **planetary.org/donate** or mail a check in the provided envelope.

Corporate gift matching: use our lookup tool to see if your company participates.

Get a tax break: make an IRA-qualified charitable distribution.

Give stock: contact *richard.chute@planetary.org* for instructions for your broker.

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

Planetary Society Member Adventures

ALASKA AURORA BOREALIS
27 FEBRUARY–4 MARCH 2020
Come see the aurora dance across the night sky in this perennially favorite expedition!

ARIZONA SKIES AND NEW DISCOVERIES
19–26 APRIL 2020
Discover the desert and astronomical wonderland around Tucson and Flagstaff.

Annular Eclipse 2020

You can see the "ring of fire" of an annular eclipse as the 21 June 2020 eclipse crosses from Ethiopia to Tibet on 2 different expeditions:

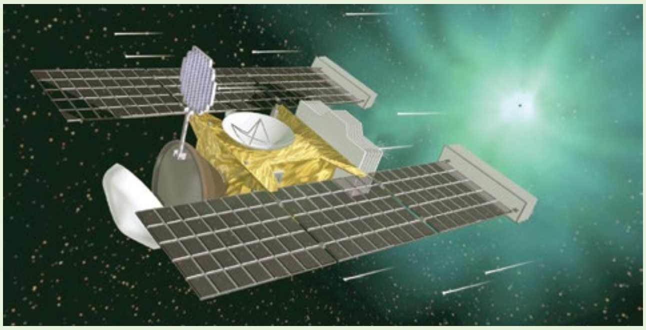
ETHIOPIA, 9–23 JUNE 2020
Including the source of the Blue Nile

TIBET, 10–23 JUNE 2020
See the eclipse at the "top of the world"

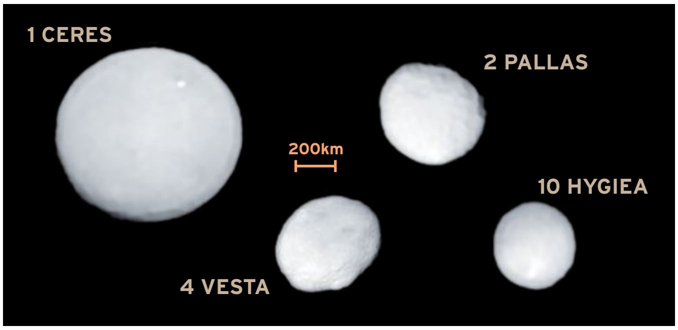
ARGENTINA TOTAL SOLAR ECLIPSE 2020
8–19 DECEMBER 2020
With optional Peru or Easter Island pretrips, 2-8 December 2020

ANTARCTICA TOTAL SOLAR ECLIPSE 2021
23 NOV–15 DEC 2021
A once-in-a-lifetime opportunity!

For detailed brochures, please contact Betchart Expeditions Inc. at 800-252-4910 or go to *betchartexpeditions.com*.



ABOVE *Stardust was the first spacecraft to return a cometary sample and extraterrestrial material to earth from outside the orbit of the Moon. In 2004, Stardust made a close flyby of comet 81P/Wild (Wild 2), collecting comet and interstellar dust in a substance called aerogel.*



ABOVE *The Very Large Telescope in Chile has an instrument named SPHERE, designed to image extrasolar planets, which can also resolve details on minor planets within our solar system. In October, scientists announced that SPHERE images revealed fourth-largest asteroid 10 Hygiea to be round, implying that it is a dwarf planet. All 4 images above were taken with SPHERE.*

IN THE SKY

The Quadrantids, an above-average meteor shower, peak on the night of 3 to 4 January. From a dark site, one may see as many as 40 meteors per hour. The best viewing occurs after the Moon sets around midnight. Super-bright Venus dominates the West after sunset. Dimmer Mercury is to its lower right in early February. Reddish Mars is in the East before dawn. By February, bright Jupiter and yellowish Saturn have joined it to Mars' lower left. In March, the 3 planets dance close together with Mercury to their lower left. On 18 March, the crescent Moon joins Jupiter, Mars, and Saturn in a tight grouping.

RANDOM SPACE FACT

The distance from Earth to the Moon is about the same as the distance traveled around Earth 10 times.

TRIVIA CONTEST

Our June solstice contest winner is David Lee Summers of Mesilla Park, New Mexico. Congratulations! The question was: ***What was the first spacecraft mission to return samples from a comet?*** The answer: ***The Stardust mission***.

Try to win a copy of *Super Cool Space Facts: A Fun, Fact-filled Space Book for Kids* by Bruce Betts and a *Planetary Radio* T-shirt by answering this question:

In January 2019, Chang'e-4 became the first spacecraft to soft-land on the far side of the Moon, but what was the first spacecraft to impact on the far side of the Moon?

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 2020. 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

IN THE FIRST QUARTER of 2020, there will be one interplanetary launch—ESA's Solar Orbiter, which is planned to go up on an Atlas 5 rocket from Cape Canaveral on or after 5 February. It will travel close to the Sun to study the inner heliosphere. While it won't get as close to the Sun as Parker Solar Probe does, Solar Orbiter will enjoy an unusual polar orbit.

We'll lose one interplanetary spacecraft this quarter when the great Spitzer Space Telescope ends its mission with a planned shutdown on 30 January.

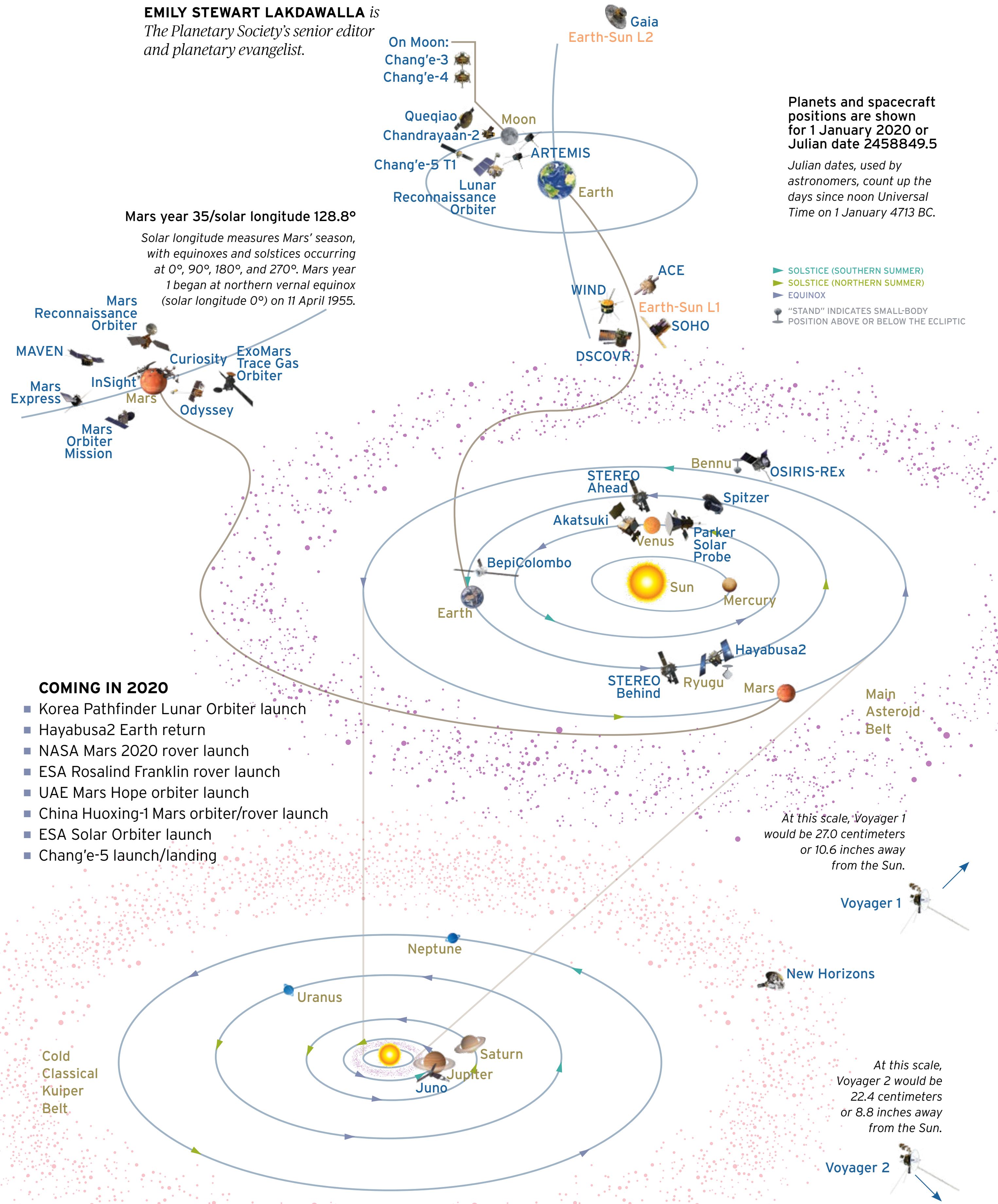
Sadly, the Indian Space Research Organisation (ISRO)'s Vikram lander crashed on 6 September, but it did successfully test a number of new technologies before it tumbled out of control. The Chandrayaan-2 orbiter is operating well and could last for as many as 7 years at the Moon, ISRO said.

Orbiters are sending science data from Venus, the Moon, a near-Earth asteroid, Mars, and Jupiter. There are two active Mars landers and two active lunar landers. Hayabusa2 departed asteroid Ryugu on 15 November to return its samples to Earth. Parker Solar Probe flies past Venus on 26 December. BepiColombo is catching up with Earth on the inside track toward a 13 April flyby.

Back on Earth, space agencies around the world are scrambling to prepare for the opening of the summer 2020 Mars launch opportunity. Three rovers (NASA's Mars 2020, ESA's Rosalind Franklin, and China's Huoxing-1) are undergoing final preparations for launch. Last-minute problems could delay the launch until 2022, so the stakes are high.

NASA/JPL; ESO/P. Vernazza et al./MISTRAL algorithm (ONERA/CNRS); Loren A. Roberts for The Planetary Society after a concept by Olaf Frohn

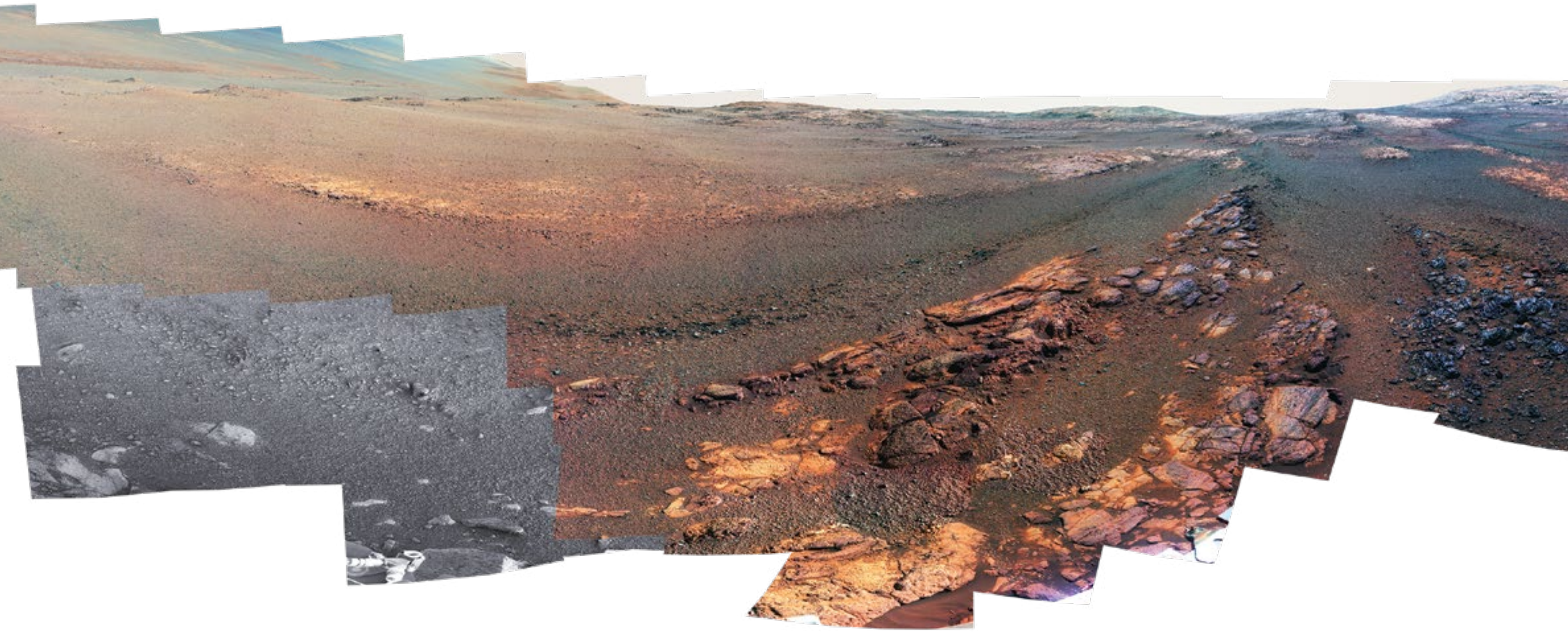
EMILY STEWART LAKDAWALLA *is The Planetary Society's senior editor and planetary evangelist.*



COMING IN 2020

- Korea Pathfinder Lunar Orbiter launch
- Hayabusa2 Earth return
- NASA Mars 2020 rover launch
- ESA Rosalind Franklin rover launch
- UAE Mars Hope orbiter launch
- China Huoxing-1 Mars orbiter/rover launch
- ESA Solar Orbiter launch
- Chang'e-5 launch/landing

ABIGAIL FRAEMAN *is a planetary scientist at NASA's Jet Propulsion Laboratory.*



A New Understanding

How Spirit and Opportunity Changed Our View of Mars

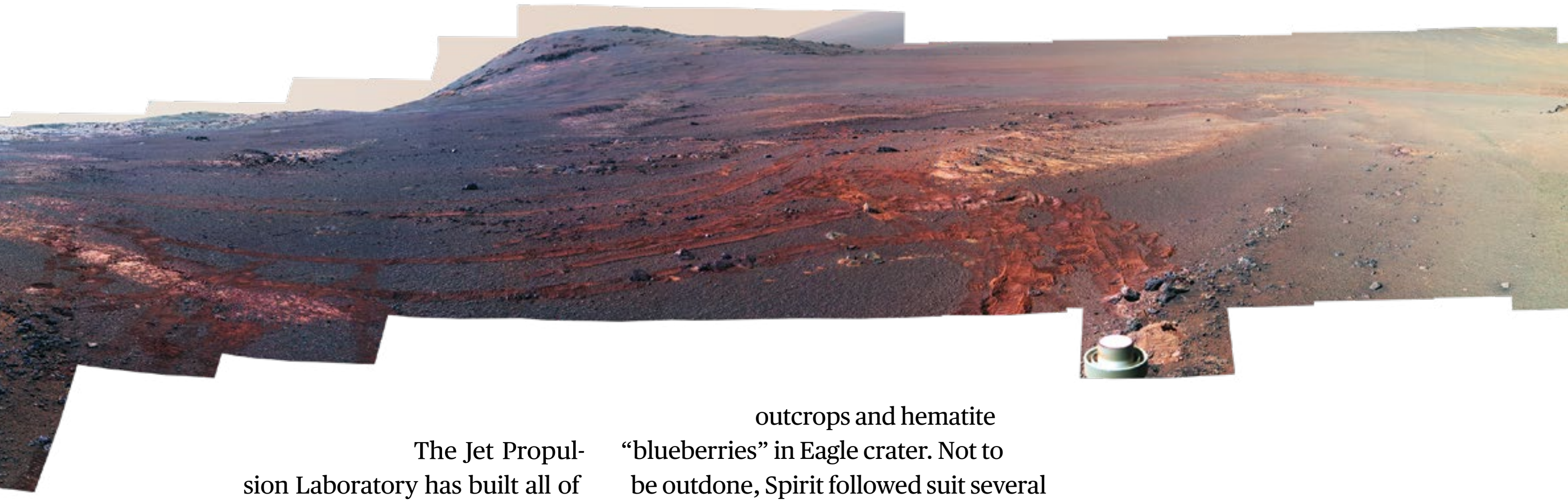
ABOVE *Opportunity's last Martian field site was Perseverance valley, a 200-meter-long channel that cut into Endeavour crater's rim. Like Earth field geologists, the Opportunity team sought out places like crater rims—and channels cut into them—to expose layered bedrock that illuminates Mars' history in this spot. The exaggerated colors of this panorama emphasize the diversity among rocks and soils that Opportunity encountered at Endeavour. The black-and-white frames in the lower left are portions Opportunity was still planning to image in color when the mission-ending dust storm hit.*

NASA/JPL-Caltech/Cornell/ASU

THE MARS EXPLORATION Rover science team gathered in Pasadena, CA for our final meeting on 11 June 2019, and I wondered if I had ordered enough Thai food. I had been the deputy project scientist for the Mars Exploration Rover Opportunity for 3 years, capping 15 years of involvement with the mission as a graduate, an undergraduate, and even a high school student. That night, I was responsible for organizing an evening celebration bringing together engineers and scientists to toast the end of the surface mission. For all of us, the rovers had been a part of our daily lives for years or even decades, and this group was just a small subset of the thousands of people who had contributed to making the mission a reality. It was important that we marked the achievement appropriately.

NASA launched the identical rovers Spirit and Opportunity in July 2003. At the time, our strategy for studying Mars was summarized by the mantra "follow the water" because liquid water is an essential ingredient for life. Today, it may seem like there's a news story every few months reporting that water was discovered on Mars, but things were different 2 decades ago. We had known that Mars had frozen water ice in its poles and water vapor in its atmosphere, but we could only hypothesize that there had been liquid water on the planet in its past. Mars-orbiting spacecraft had imaged channels that seemed to have been carved by water, and they had spotted evidence of minerals that could have formed in water, but we really needed to get down onto the surface to test these hypotheses.

Geologists had dreamed of roving on Mars ever since images that were returned from the Viking landers in the 1970s showed tantalizing rocks that were just out of reach of the landers.

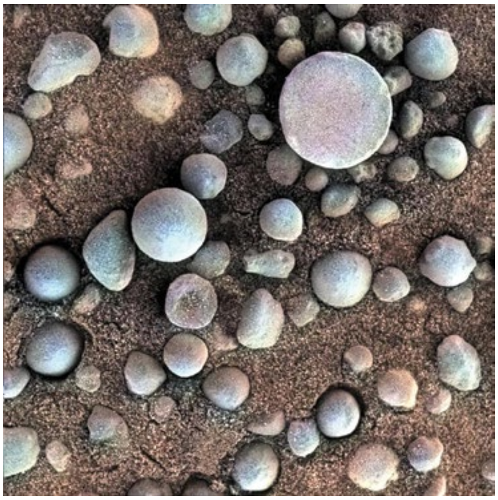


The Jet Propulsion Laboratory has built all of NASA's Mars rovers. In 1997, the Pathfinder rover Sojourner had demonstrated that it was possible to drive on Mars, and Spirit and Opportunity were the first mobile rovers with a fully capable payload. Spirit and Opportunity's instruments were designed to collect clues about how Martian rocks and soils formed and could see if their elements and minerals had ever been altered by liquid water. The rovers were each designed to drive at least 600 meters over 90 Martian days (sols). It was anyone's guess as to how well the mission would work or if it would even succeed at all.

Of course, most of us know the ending of the story. By the time NASA Associate Administrator Thomas Zurbuchen declared the mission complete on 13 February 2019, Spirit had traveled more than 7.73 kilometers (4.80 miles) over 2,208 sols of operation, while Opportunity drove more than 45.16 kilometers (28.16 miles) in 5,111 sols. The data the 2 rovers returned from their adventures changed our view of Mars. Spirit and Opportunity not only followed and found evidence for liquid water but also discovered that Mars was wet many different times in the past and in many different environments, both on and beneath its surface.

WATER ON MARS

Although it landed second, Opportunity was the first of the rovers to find evidence of past liquid water, locating it in the sedimentary outcrops and hematite "blueberries" in Eagle crater. Not to be outdone, Spirit followed suit several years later when it detected minerals that form in water, including goethite and carbonate, in the Columbia Hills. By mission's end, the rovers had driven through 5 different geologic settings. Four of the 5 settings

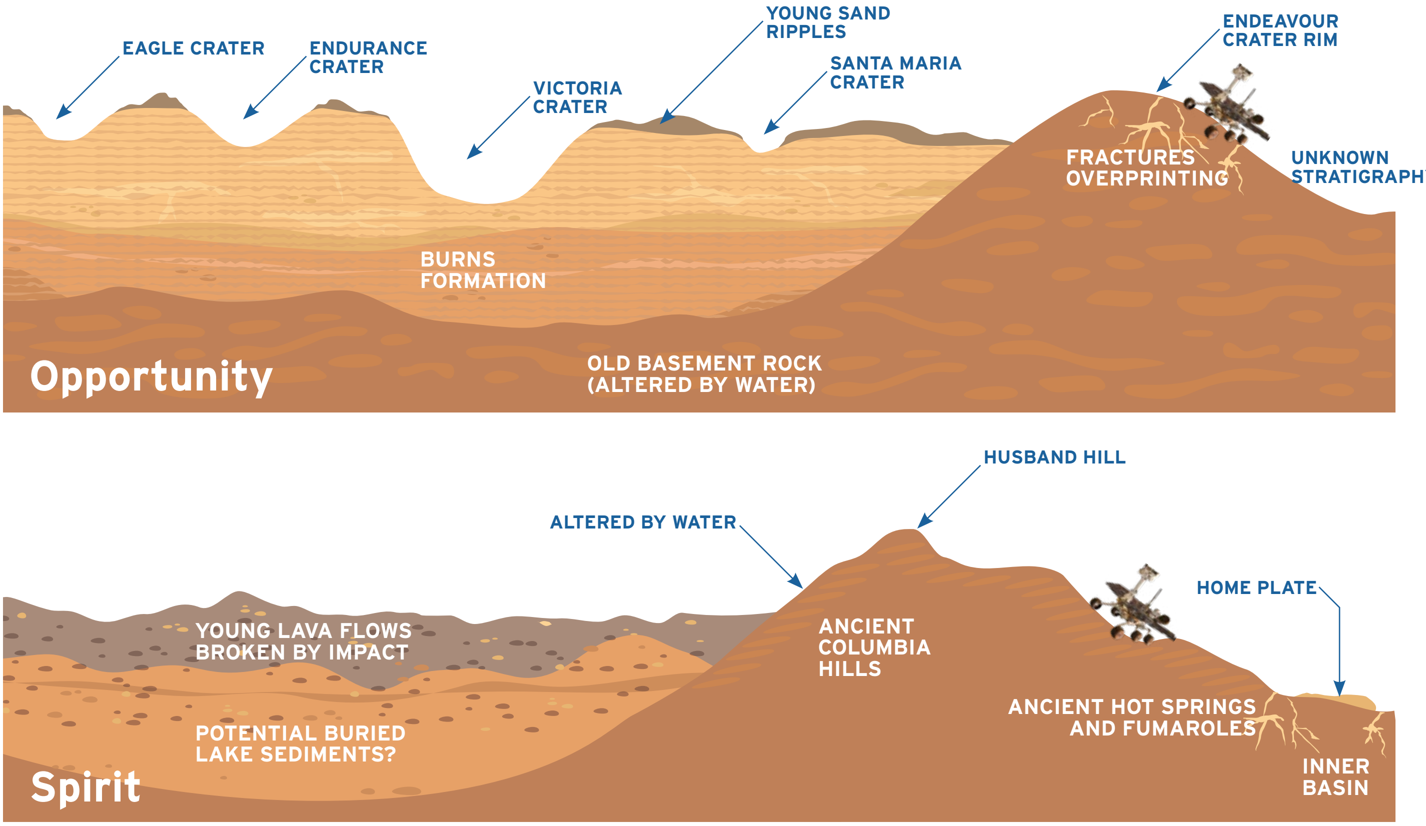


LEFT *The small spherules on the Martian surface in this close-up image are near Fram Crater, visited by NASA's Mars Exploration Rover Opportunity during April 2004. The area shown is 1.2 inches (3 centimeters) across. The view comes from the microscopic imager on Opportunity's robotic arm, with color information added from the rover's panoramic camera.*

NASA/JPL-Caltech/Cornell/USGS

preserved evidence of at least a dozen unique times when liquid water had interacted with the Martian surface and subsurface (see infographic on page 14).

In the plains of Meridiani Planum, Opportunity roved atop ancient acidic playas where very salty water had been exposed to the atmosphere, evaporating to leave its salts behind. Once dried, the salts had been eroded, transported, and deposited into sand dunes that were later cemented into rock when ground-



DRAWINGS NOT TO SCALE

ABOVE *Spirit and Opportunity explored 5 major geologic environments. THE LAVA FIELDS OF GUSEV CRATER, where Spirit landed, showed no evidence for water. THE COLUMBIA HILLS, much older than the Gusev plains, contained rocks altered by groundwater. HOME PLATE, an extinct volcano, had hot springs and fumaroles. MERIDIANI PLANUM contained sedimentary rocks laid down in water and later altered by groundwater. ENDEAVOUR CRATER RIM had fractures that acted as conduits for groundwater multiple times.*

Abigail Fraeman, Emily Lakdawalla, and Loren A. Roberts for The Planetary Society

water rose from beneath them, dissolving and redepositing salts into the pore spaces between the sand, gluing the grains together. The acidic, salty environment would not have been especially friendly to life, but later in Opportunity's mission, it found that pH-neutral groundwater had flowed many different times through fractures in the ancient rocks that made up the rim of Endeavour crater.

On the other side of the planet, Spirit found different kinds of watery environments. At the base of Home Plate within the Columbia Hills, Spirit roved where ancient fumaroles had left thick deposits of silica and sulfate salts centimeters below the surface, and extinct hot springs had left behind finger-shaped nodules made of nearly pure silica. On Earth, similar structures are always associated with biology. Spirit's findings were so exciting to astrobiologists that the Home Plate site was one of the top 3 finalists for a landing site for a future sample return mission.

EYES IN THE SKY, HANDS IN THE DIRT

Spirit and Opportunity conclusively demonstrated the value of operating landed missions in synergy with science orbiters. For example, in 2009, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on the Mars Reconnaissance Orbiter discovered that clay minerals were present at several locations along the rim of Endeavour crater. On Earth, clay minerals most commonly form when volcanic minerals are altered by liquid

ABIGAIL FRAEMAN *is a planetary scientist at NASA's Jet Propulsion Laboratory. She was the deputy project scientist for the Mars Exploration Rover mission and one of The Planetary Society's student astronauts.*

water. The rover science team directed Opportunity to the exact CRISM-detected spots. The journey took more than 3-and-a-half years, but it paid off in science. In one spot, the rover discovered clays that formed when there was lots of water flowing through a fracture. In another area, Opportunity discovered different clays, also in fractures, that probably formed by a very small amount of stagnant water. Now, geologists can return to the CRISM data set and find spots all over Mars where similar environments probably existed.

Spirit and Opportunity also confirmed to us that there are some things you just can't see from orbit and that there's no substitute for wheels on the ground. For instance, Spirit was sent to Gusev crater because we thought it was an ancient lake based on its shape in orbital images, yet the rover landed on top of young lava flows that buried any geologic evidence of an ancient Lake Gusev. The science team dubbed the plains of Gusev crater a "basalt prison" out of a mixture of frustration and affection. It wasn't until Spirit escaped the prison by ascending into the Columbia Hills that it found minerals that form in watery environments. Spirit's discoveries at Home Plate could never have been predicted from orbital data but were just as compelling as an ancient lake would have been in the search for life. The evidence was just below the surface or too small to be seen by even the highest-resolution cameras. Every place we land, we are almost certain to learn something new and potentially paradigm-shifting.

THE LEGACY OF SPIRIT AND OPPORTUNITY

The findings from the Mars Exploration Rovers allowed the Mars science community

NASA/JPL-Caltech/Cornell/ASU

LEFT *The light-colored material in the center of this exaggerated-color image is a vein called "Esperance." The chemical data Opportunity collected from this target showed that a large amount of nearly neutral-pH groundwater flowed through it in the past, leaving behind aluminum-rich clay minerals. Of all sites Opportunity visited, this site has the best potential to have supported ancient Martian life.*

TOP *Spirit landed on a field of volcanic rocks at Gusev crater. Scientists had hoped to find evidence of an ancient lake there, but the volcanic materials covered any such evidence. However, the chemical and textural measurements Spirit made here still provided important information about the volcanic evolution of Mars. Many of the rocks in this image have pointy, jagged shapes. The shapes could result from them being broken by impacts or from erosion by Martian winds over billions of years.*

BOTTOM *A subset of the Mars Exploration Rover science and engineering teams gathered at Caltech for a team meeting in 2015. Over the 30-plus years of the mission's existence, thousands of people were involved.*

NASA/JPL-Caltech/Cornell/ASU/Daniel Crotty/Emily Lakdawalla; Keck Institute for Space Sciences/Michele Judd to develop our strategy for Mars exploration beyond "follow the water" to the more complicated question of whether these watery environments were ever habitable. Very loosely defined, a habitable environment is one that has the 2 other essential requirements in addition to liquid water that are needed to support life as we know it: a source of carbon and a source of energy. The Mars Science Laboratory mission's Curiosity rover, which landed on Mars in 2012, carried a larger and more complicated payload than the Mars Exploration Rovers. Curiosity is capable of finding evidence of all 3 of these requirements. In fact, it has succeeded: within its landing site at Gale crater, Curiosity found ancient river and lake deposits that preserved carbon-containing compounds as well as evidence for water chemistry that could power microbial metabolism. Today, we not only know that Mars was once wet—it was also habitable.

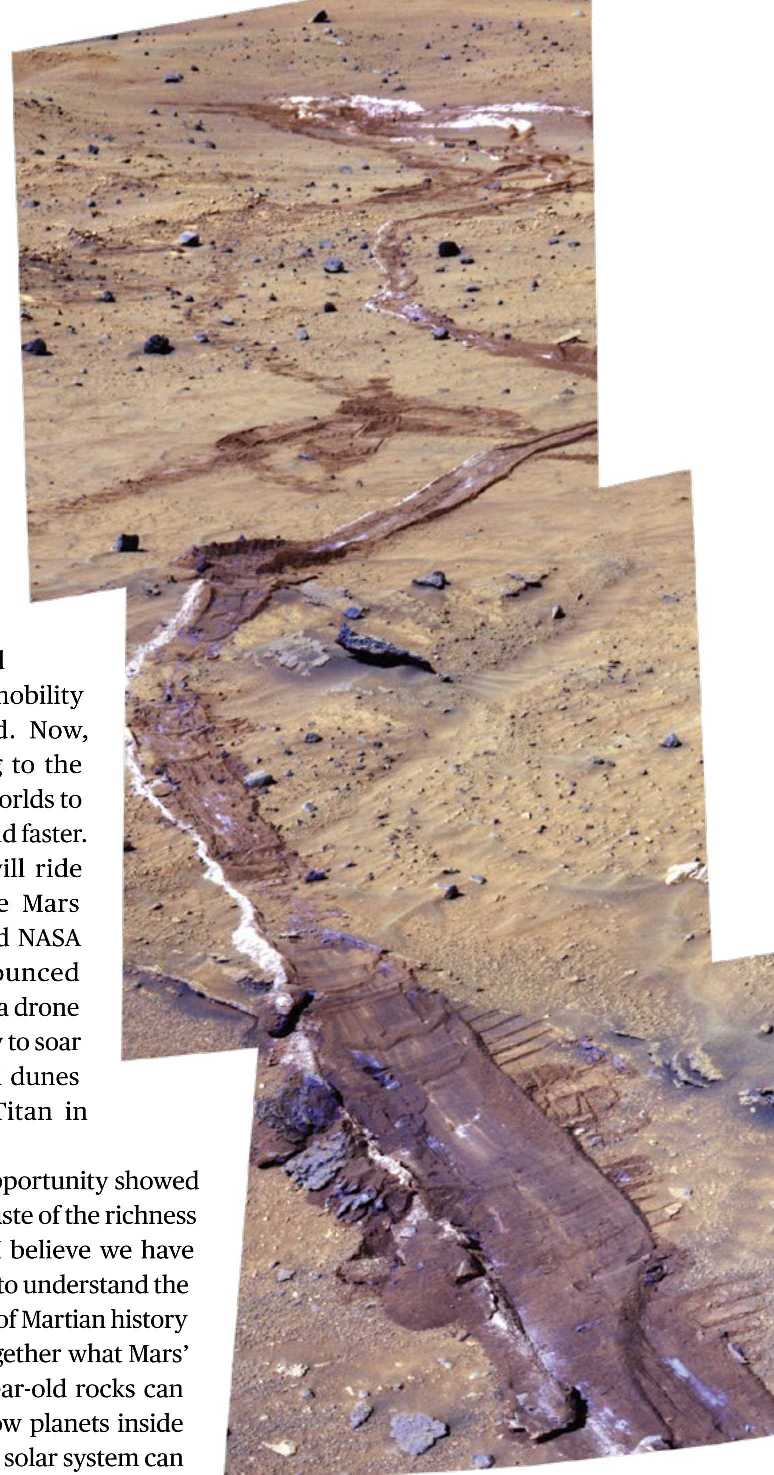
Almost 2 decades after Spirit and Opportunity and a decade after Curiosity landed, NASA's Mars 2020 rover and ESA's ExoMars rover are now poised to address the most challenging question in our search for life on Mars when it lands in February 2021: did it exist? The designs of these missions and the selections of their landing sites rest on what we learned from Spirit and Opportunity.

At the Thai-food-fueled, end-of-mission celebration, people were in a reflective mood. They told stories about their experiences during mission development and reminisced about the escapades that had occurred over 14 years of operations. For all this looking back, there was just as much anticipation of the road ahead: "What are you working on now?" "Can you tell me more about your new mission concept?"

Spirit and Opportunity took humanity on a great adventure and set the bar extremely high for what we can accomplish with robotic space exploration. Although the rovers leave big wheel prints to fill, they have also opened the door to dreams of even greater voyages. We've demonstrated the power of mobility on the ground. Now, we are looking to the skies of other worlds to travel farther and faster. A helicopter will ride along with the Mars 2020 rover, and NASA recently announced that it will send a drone called Dragonfly to soar above the sand dunes and lakes of Titan in the 2030s.

Spirit and Opportunity showed us just a small taste of the richness of Mars' past. I believe we have only just begun to understand the full complexity of Martian history and to piece together what Mars' 3-to-4-billion-year-old rocks can tell us about how planets inside and outside our solar system can evolve into habitable worlds. As the mission's principal investigator Steve Squyres said at the end of the final science team meeting, "The biggest stuff is still ahead, and I think [enabling] that in large measure may be the greatest legacy that this project has."

(For those wondering, the Thai food I had ordered for the celebration exceeded mission-success criteria, like Spirit and Opportunity. We ended up with abundant leftovers that were consumed by eager Caltech grad students the next day.)



NASA/JPL-Caltech/Cornell/ASU

ABOVE *When one of Spirit's front-wheel motors failed, the rover had to drive backward and drag along the stuck wheel, creating shallow trenches. Near Home Plate, the trenches exposed nearly pure silica, a probable sign of fumaroles and hot springs that could've been a habitat for life.*

JAVIER GÓMEZ-ELVIRA *is the principal investigator of the REMS weather sensor instrument on the Curiosity rover and coinvestigator of the similar MEDA instrument on the Mars 2020 rover.*

What Comes Next on Mars?

Planning the Search for Life on the Red Planet

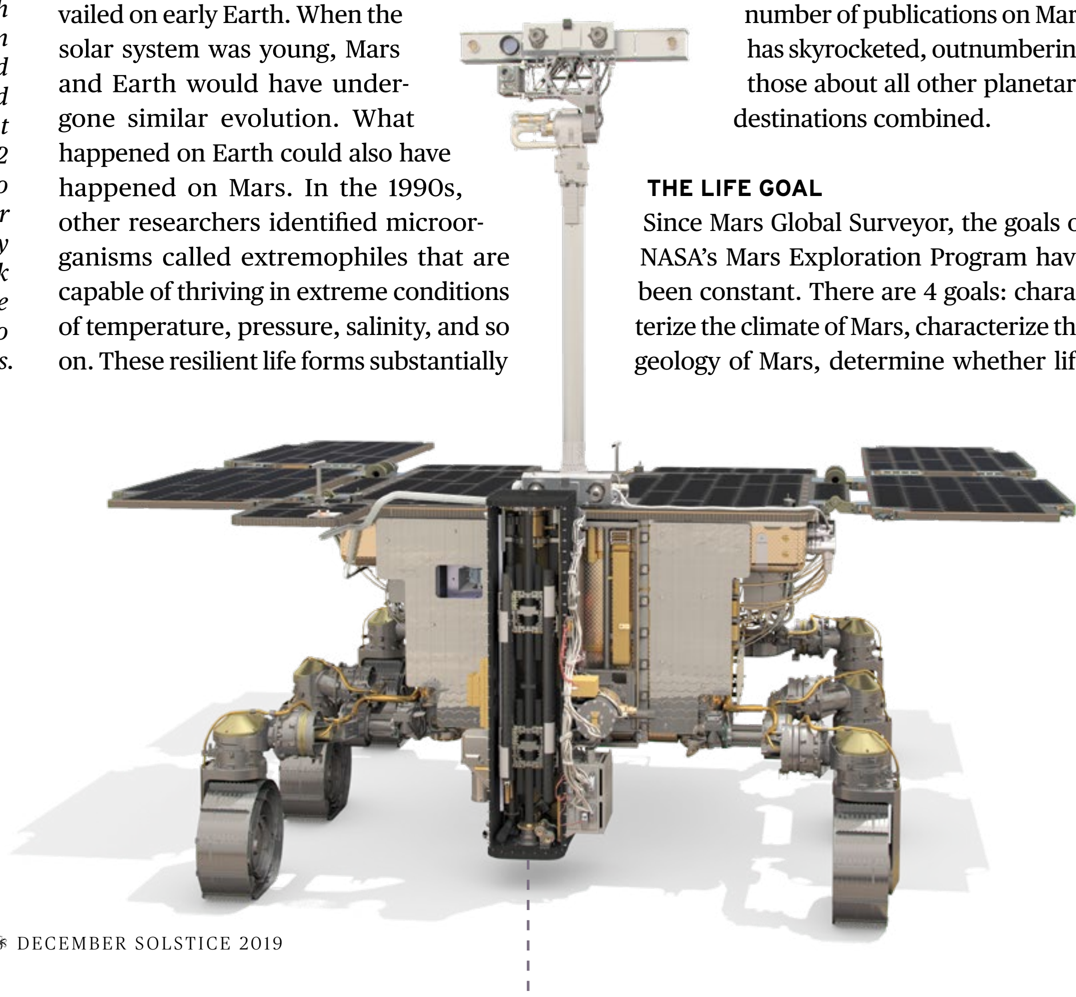
THE SEARCH FOR LIFE has been a goal of Mars exploration since its beginning. However, more than 50 years of work have failed to answer the basic question: is or was there life on Mars? The next missions to Mars seek to address this question directly.

In the 1950s and 1960s, work by Stanley Miller, Joan Oro, and others demonstrated that the building blocks of life could form through naturally occurring chemical reactions under specific environmental conditions. These conditions could have prevailed on early Earth. When the solar system was young, Mars and Earth would have undergone similar evolution. What happened on Earth could also have happened on Mars. In the 1990s, other researchers identified microorganisms called extremophiles that are capable of thriving in extreme conditions of temperature, pressure, salinity, and so on. These resilient life forms substantially increased the variety of environments we thought capable of hosting life and therefore the chances of finding life elsewhere in the solar system.

The Viking lander missions sought to discover life on Mars in 1976, and their fruitless results had a negative impact on the enthusiasm for funding Mars missions. Twenty years later, a new stage of Mars exploration began with Mars Global Surveyor, which arrived in orbit in 1997. Since then, community interest has increased so much that the number of publications on Mars has skyrocketed, outnumbering those about all other planetary destinations combined.

THE LIFE GOAL

Since Mars Global Surveyor, the goals of NASA's Mars Exploration Program have been constant. There are 4 goals: characterize the climate of Mars, characterize the geology of Mars, determine whether life



RIGHT *ESA's ExoMars rover, named Rosalind Franklin, is in final preparations for a July 2020 launch and March 2021 landing in Oxia Planum, where Martian rivers once flowed. Its goal is to search for signs of ancient life. In addition to cameras and spectrometers, Rosalind Franklin carries a drill that can penetrate as many as 2 meters beneath the surface to retrieve samples and deliver them to analytical laboratory instruments. In the artwork at right, the cover of the drill has been removed to show its internal workings.*

ESA/ATG medialab; ESA/DLR/FU Berlin

ever arose on Mars, and prepare for human exploration. ESA's Mars mission goals are similar.

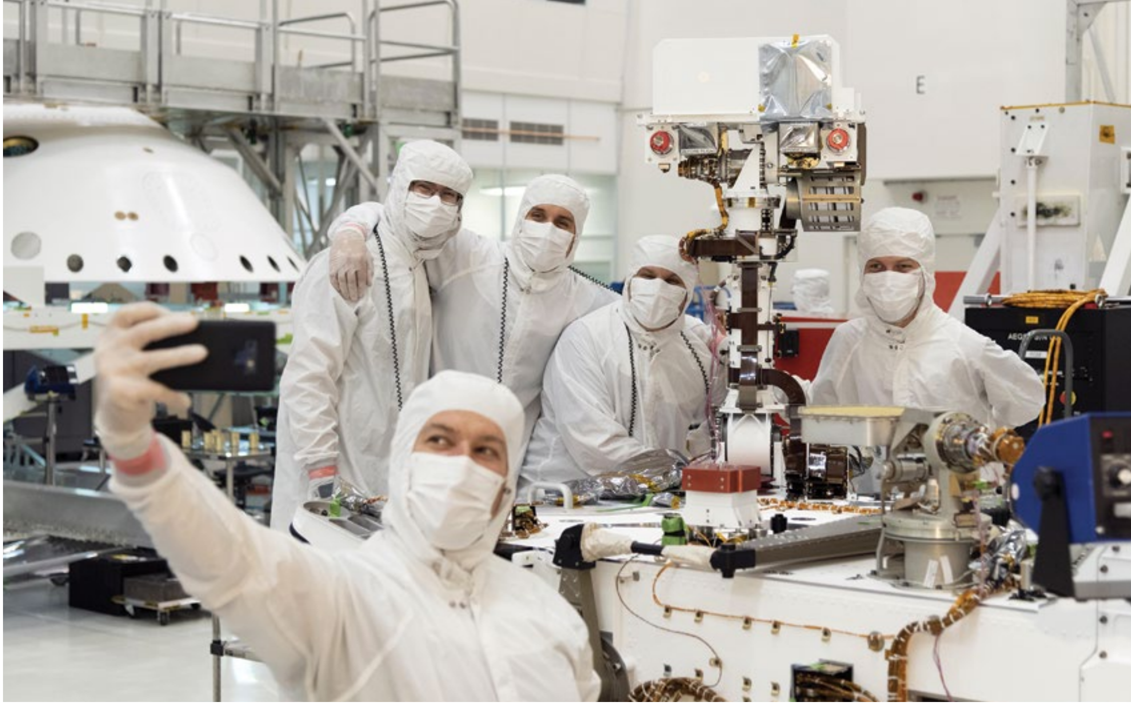
The orbiters Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, MAVEN, Mars Orbiter Mission, and now ExoMars Trace Gas Orbiter have sent to Earth thousands of terabits of information about the surface and atmosphere of Mars. Landed missions Mars Pathfinder, the Mars Exploration Rovers, Phoenix, Curiosity, and Insight have ground-truthed these measurements at landing sites characterized from orbit.

We now have a continuous weather record dating back to 1997. We know Mars' atmosphere very well–its composition, pressure, temperature, and how these vary with the seasons. We know the motion of Mars' winds and how their flow conforms to Mars' topography. We are beginning to understand how Mars lost its atmosphere over time. There are open questions, like how dust storms become global and how the atmosphere evolved to its present state, but we have made great advances in characterizing the climate of Mars.

We have located volcanoes, impact craters, lava flows, deep channels, depositional deltas, and vast plains, and we understand by analogy to Earth how many of these formed. We have mapped the distribution of chemical elements and minerals like clays, sulfates, and carbonates. However, we only know the planet's surface. To understand Earth's evolution, geologists explore its interior. We look for places where its inner layers have been exposed by tectonic movements and employ seismographs to see hidden layering. A deep drill is usually our best option to see into Earth's geology. It is the same on Mars. In some places, erosion has exposed inner layers, but much is hidden. We can say that we have characterized the surface geology of Mars but not its interior.

We have not advanced much in determining whether life ever arose on Mars, but we have found that the necessary conditions for life existed in Mars' past. These conditions include

LEFT *While liquid water may not have been exposed at the surface of Mars for much of its 4.5-billion-year history, evidence from orbiters and rovers suggests it has been available underground for much longer. The channels of the Hephaestus Fossae region within Utopia Planitia (top) likely formed when impacts released subsurface water in massive floods. Data from the Mars Express orbiter provides the basis for this elevation map. Cool colors represent depressions; warmer colors are higher areas. The image is about 55 kilometers (35 miles) wide.*



ABOVE RIGHT *NASA is preparing the Mars 2020 rover for a July 2020 launch as well. In this 5 June 2019 photo, engineers take a selfie after attaching the remote sensing mast. Like its predecessor Curiosity and its contemporary Rosalind Franklin, the Mars 2020 rover (which will receive a more colloquial name before launch) is able to drill to acquire samples. Unlike the other missions, Mars 2020 plans to package and drop those samples for future retrieval and return to Earth. The work it does on the surface with cameras and spectrometers will document the geologic context of the samples, making them a rich prize for future science in Earth laboratories if Earth can successfully retrieve them.*

NASA/JPL

liquid water, some key elements (carbon, nitrogen, phosphorus, and sulfur), chemical gradients (to provide energy for metabolism), and adequate environment (in terms of radiation, temperature, chemical conditions, and so on). However, we have detected no biosignatures. We have found some carbon-containing molecules, but they could all have an abiotic origin. (Meteoritic falls deliver 100 tons of material to Mars each day, a portion of which is carbonaceous.) Complex, carbon-rich molecules are quite prone to degradation by radiation. Therefore, they can only be found below the surface. Similarly, for present life, all evidence suggests that if Mars has stable liquid water, it resides below the surface. The Mars community consensus is that we need to go beneath the surface in order to progress in the search for life.

Robotic missions have taken some steps to help prepare for future human exploration by studying the radiation environment on the way to Mars and at the surface. NASA's Mars 2020 rover will perform a first demonstration experiment for in-situ resource utilization, generating oxygen from the Martian atmosphere. The biggest contribution to future human exploration has involved terrain mapping and climate characterization.

LIFE DETECTION AT MARS SURFACE

Several missions plan to launch toward Mars in summer 2020. Two in particular seek to advance the search for life by exploring beneath the surface: Mars 2020 and ESA's Rosalind Franklin rover. The design of Mars 2020 is based on the Curiosity rover, but it has different instruments and an improved capacity to detect organic molecules thanks to its Raman spectrometers. Its goal is to drill and collect samples for future Mars sample return. The Rosalind Franklin rover is also equipped with a Raman spectrometer and has a drill that can collect a sample up to 2-meters deep for onboard analysis.

Raman spectrometers are widely used in Earth laboratories but have never before flown to Mars. They can identify the presence of carbon-containing compounds and the kinds of chemical bonds they contain. Mars 2020 has 2: SHERLOC, which is at the end of the robotic arm, and SuperCam, which is in the rover mast with the cameras. They will be able to operate on hundreds of different targets. In Rosalind Franklin, the spectrometer is called RLS and is in the rover's internal sample analysis laboratory.

Raman spectroscopy alone cannot prove life existed on Mars. It is possible that one

JAVIER GÓMEZ-ELVIRA *is director of the Payload and Space Science Department at Spain's Instituto Nacional de Técnica Aeroespacial (INTA) and former director of its Centro de Astrobiología (CSIC-INTA). He is the principal investigator of the REMS weather sensor instrument on the Curiosity rover and coinvestigator of the similar MEDA instrument on the Mars 2020 rover.*

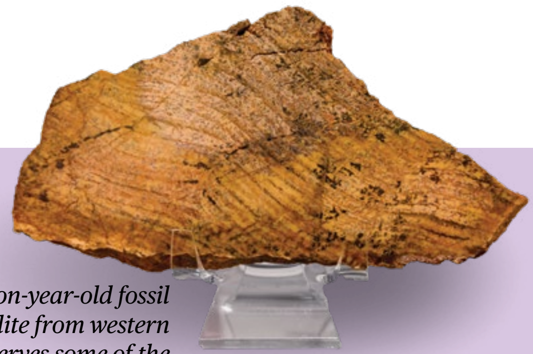
of the rovers could spot a carbon-containing molecule that is a perfect match for a known compound of biological interest. More likely, they will find evidence that some carbon-containing compounds are present. In all cases, additional analyses are required to determine the origin of the material. Some rover-based experiments can help to narrow this down, like the isotopic and chirality (molecule shape) analyses that Rosalind Franklin could perform.

Neither of the rovers can produce definitive evidence for life on Mars. We will need to do more detailed analyses that the rovers cannot perform, employing more powerful spectrometers or bringing new techniques like immunoassay detection and sample processing to extract and concentrate organics. Raman spectroscopy is a very good technique for selecting samples for further analysis. We will either need to bring samples back to Earth or bring a more powerful laboratory to the site, perhaps operated by human explorers.

NASA and ESA are now discussing plans for the return of the Mars 2020 rover samples. A surface-retrieval lander would deploy a sample fetch rover that would spend 6 months collecting the samples and loading them into a basketball-sized sample canister launched by a rocket from the lander deck. A sample-return orbiter would rendezvous with the canister in Mars orbit and return it to Earth. Each of these 2 missions would have components built by both NASA and ESA. As currently envisioned, the spacecraft would launch in 2026, and the samples would return in 2031.

DIGGING DEEPER

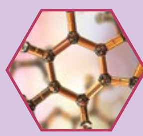
Many organizations besides NASA and ESA are planning future Mars missions launching in 2020, 2022, and 2024. We are now in a period of discussion and planning for the following decade's missions. ESA is currently developing a new, long-term plan of



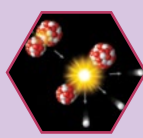
A 3.7-billion-year-old fossil stromatolite from western Australia preserves some of the oldest evidence for life on Earth.

Signs of Life on Mars

When we talk about searching for signs of ancient life on Mars, what we are actually looking for is a biosignature: an object, substance, or pattern that could only have been made by life. There are 6 specific kinds of biosignatures that we might encounter on Mars:

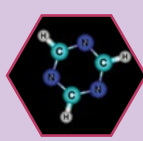


ORGANICS Organic compounds contain carbon and hydrogen and other light elements. All life on Earth is made of organic compounds, but organic compounds also form in the absence of life. Systematic patterns in the types of organic matter could be a biosignature.



ISOTOPES Atoms of one chemical element always contain the same number of protons but can have differing numbers of neutrons. On Earth, biological processes sometimes prefer one isotope over another, and that preference can be preserved in rocks.

MINERALS On Earth, some minerals are uniquely associated with life. Discovery of a mineral that requires life to form would be a biosignature.



CHEMICALS Earth-life metabolic activity often has a chemical signature. Signs of varying pH or oxidation state over very small scales might be the signature of microbial metabolism in an ancient environment.

SMALL-SCALE STRUCTURES At the microscopic level, it's possible to spot signs of individual microscopic life forms: fossilized cells, or molds of cells, or casts of cells.

LARGE-SCALE STRUCTURES At the macroscopic level, microbes on Earth build mats, stromatolites, reefs, and other structures.

On Earth, geologists look for biosignatures in ancient rocks to learn when life originated. The record for oldest evidence for Earth life is from stromatolites in the Pilbara region of Australia. They show mineral, chemical, and structural evidence for the presence of life on Earth 3.5 billion years ago. The more different kinds of biosignatures observed, the more confident we can be in the conclusion that life was present.

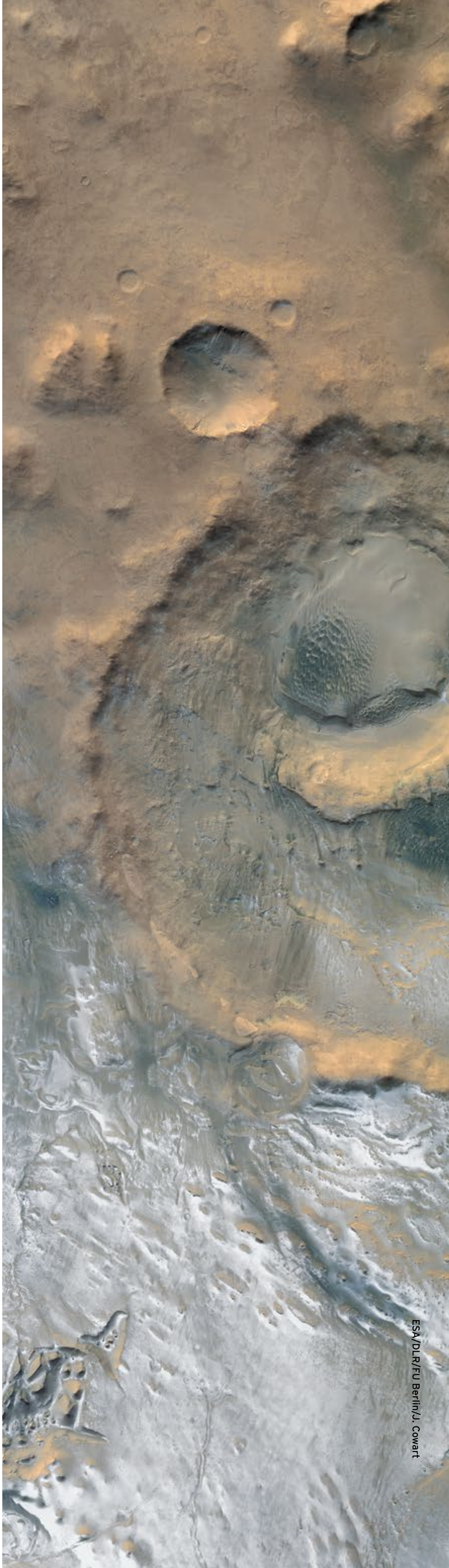
Getty Images

its scientific priorities, called Voyage 2050. In the United States, the National Research Council is soliciting community input for the next Planetary Science Decadal Survey, which will state NASA's scientific priorities for 2023 to 2032.

If our goal is to search for extant life, drilling deep enough to encounter subsurface liquid water looks like the best option. It will take a heavy lander to drill deep enough–tens to hundreds of meters beneath the surface–to encounter stable, habitable environments and to carry a powerful-enough scientific payload to analyze them. This in turn will require new landing systems. The same kinds of heavy landing systems will eventually be required for human missions to Mars.

Even if we had the technology, we could not yet drill to water on Mars. Current international agreements on planetary protection prohibit contact with liquid water on other worlds in order to avoid any type of contamination from Earth. There is an active discussion in the community about relaxing these restrictions. We believe that the highest level of sterilization must be used with the components in contact with water, developing new techniques and protocols if needed. If we wish to find current life, we must be able to interact with liquid water.

Exploration is in the DNA of humankind, but the immense cost of sending humans to Mars requires a motivating reason developed through the consensus of international space agencies and the scientific community. A win-win option for searching for life on Mars and advancing human presence in the solar system looks like a combination of robots and astronauts. With robotic reconnaissance, we can select promising sites where subsurface life could be present. I imagine a scenario in which humans can select drill sites, highly sterilized robots can drill for and retrieve samples, and humans can perform core analysis in Mars-based laboratories. Soon, we will find out how Earth plans to carry on the search for life on Mars.



RIGHT *Heavy frost deposits coat the ground in and around the 139-kilometer diameter (86-mile diameter) Hooke crater in this Mars Express image. The frost serves as a reminder that Mars still possesses water that moves dynamically between the atmosphere and the surface, mostly in the form of ice and vapor. At present, Mars has thick water-ice polar caps and icy clouds. In many locations, temperatures get low enough overnight for the relative humidity to reach 100 percent, and frost forms on the ground as water vapor condenses. As water has moved around with Mars' shifting climate over its long history, there may have been many periods of wetting and drying all over the planet.*

A Life of Learning

PEOPLE OFTEN ASK me why I became an astronomer. I think it started with the science-fiction books I collected when I was young. They were more than a library. They became an obsession when I was a teenager—a way to escape the harsh reality of life as a person of color in France and in a world that I thought was on the verge of destruction.

In books, I could imagine a world that mastered faster-than-light propulsion, explored new planets, started conflicts, created egalitarian societies, found weird life, and communicated with extraterrestrials. I explored within my mind first and then joined the space exploration community. Luckily, I lived in Toulouse, France, the European capital of aerospace, where I met astronomers and astronauts who told me their stories and explained why they explored.

Shortly after the discovery of an exoplanet orbiting 51 Peg, I heard about adaptive optics (AO) and how it could help astronomers tap the full potential of ground-based telescopes. I quickly decided to dedicate my career to AO. Today, AO has lowered the cost of space exploration and has enabled new discoveries, including moons around asteroids and the first picture of a Jupiter-like exoplanet.

Astronomy is far more than a research field. It also has a huge impact on our civilization. My generation was motivated by the iconic picture of our pale blue dot taken by Voyager 1 in 1990. It made us realize that the solar system is our backyard, and Earth is not the limit. The recent flyby of Pluto, once called the ninth planet, is just one consequence of this image.

Today, AO is everywhere, including on every large telescope, but we have only begun to tap its huge potential. We are building another generation of extremely large telescopes that use AO, and we are even considering bringing AO to space with Project Blue and ambitious concepts like HabEx and LUVOIR. Someday, one of these telescopes will take an image of another pale blue dot, which will tell that

somewhere around a nearby star, there is a world like ours—a planet with a liquid ocean, a biosphere, and perhaps intelligent life. We will learn a lot from studying this planet—about the past and future of our Earth, about life, and about intelligence. We might find out that indeed, we are not alone.

What a feast this will be for astronomers, anthropologists, sociologists, and others! If these extraterrestrials confronted and overcame the same issues we face today, we may find an answer to our problems by learning from these older siblings. We may also realize that we are not a plague in the universe but an inevitable evolution of intelligence. If and when this happens, it will take me back to stories I read in my science-fiction books and my earliest drive to explore.

FRANCK MARCHIS *(above left) is a senior planetary astronomer and science outreach manager of the Carl Sagan Center of the SETI Institute and chief scientific officer and cofounder at Unistellar. His hobbies include CrossFit, biking, video games, and reading. His favorite quote is from Nelson Mandela: "It always seems impossible until it's done." His favorite space image is an artwork of the binary asteroid Patroclus and Menoetius. "In a few years, when the Lucy mission visits the binary system, we will have a real picture of this binary asteroid. I named Menoetius, the smaller component, after publishing their orbits. I can't wait to see real pictures of it."*

Photo courtesy of the author

WHY I EXPLORE *Planetary Society members are explorers. We share this common passion, although we have different stories that drive our passion. We're curious to know your story. If you'd like to share, we've set up a form at* **planetary.org/whyexplore***, where you will also be able to read other "Why I Explore" stories. We'll also continue to share stories in future issues of* The Planetary Report.

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

astronomical art

Adrianna Allen,
Life on Mars: Cave Colonies

The surface of Mars is an extremely hostile environment for life. It experiences radiation by high-energy particles from the Sun and space and is drier than the most arid Earth desert. If life exists on Mars today, it would be better off below ground, sheltered from radiation, where there may be liquid water. Human astronauts may one day look for both shelter and water underground.

Adrianna Allen, a scientific illustrator, envisions future astronauts encountering Mars life. About this digital painting, she writes: "As she descended farther into the cave, what was detected in the initial scans suddenly became obvious to her eyes. There indeed had been water trapped here once. The Red Planet was about to reveal its most wondrous secret." See more of her work at photonillustration.com.