THE PLANETARY SOCIETY

THE PLANETARY REPORT

MARCH EQUINOX 2020

VOLUME 40, NUMBER 1

planetary.org

WHAT LIES AHEAD?

PLANETARY SCIENTISTS CHART THE NEXT 10 YEARS OF EXPLORATION

SHOEMAKER GRANT WINNERS ✻ SASHA SAGAN'S COSMIC PERSPECTIVE

Working Remotely

Augmented Reality Helps Far-Flung Partners

HOW DO YOU build a spacecraft when your team is spread all around the country? The Europa Clipper mission, scheduled to launch in the mid 2020s, is led by NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California in partnership with the Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Maryland. Here, team members at APL work in augmented reality (AR) to examine an immersive digital model of the Europa Clipper spacecraft's structure. By wearing special AR headsets and using software developed at JPL called ProtoSpace, team members in different physical locations can examine the spacecraft together as if they were in the same room.

In this issue, we're celebrating the past decade of planetary exploration and looking ahead to what the future holds. Planetary exploration at NASA is driven by the decadal survey, a community-authored report that comes out every 10 years. The past 2 decadal surveys named a Europa mission a high priority, and The Planetary Society advocated for the mission with Congress.

For more information about the mission, visit **planetary.org/europaclipper**.

Johns Hopkins Applied Physics Laboratory/Devin Hahne/Adam Fagan

SNAPSHOTS FROM SPACE

THE GALILEO MISSION'S high-resolution images of Europa revealed a stunning diversity of surface features that have fascinated and puzzled geologists. In this photo, which covers an area of about 250 by 450 kilometers (155 to 280 miles), a variety of sharp fissures and narrow linear ridges crisscross the surface where Europa's thin ice shell cracked due to gravitational stresses from Jupiter and Ganymede. Red spots named lenticulae might identify places where material has welled up from the ocean beneath the icy crust. Europa Clipper hopes to map features like these in detail to determine where best a future landed mission might sample material that originated within Europa's ocean.

–Emily Stewart Lakdawalla

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

SEE MORE EVERY DAY! PLANETARY.ORG/BLOGS

NASA/JPL/Jason Perry/Björn Jónsson/Emily Lakdawalla

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*; *Editors* **DANIELLE GUNN, JASON DAVIS, KATE HOWELLS**; *Art Director* **LOREN A. ROBERTS for HEARKEN CREATIVE**; *Copy Editor* **NICOLE YUGOVICH**; *Technical Editor* **JAMES D. BURKE**; *Science Editor* **BRUCE BETTS**

ON THE COVER: Voyager 1 captured this view of Europa transiting over Jupiter's Great Red Spot on 3 March 1979. The image is composed of a 16-frames mosaic made of 41 individual images. The black spot is Io's shadow on Jupiter's clouds. *Credit: Voyager 1 Imaging Science Subsystem (ISS): NASA/JPL-Caltech/Alexis Tranchandon/Solaris* ⚘ *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.

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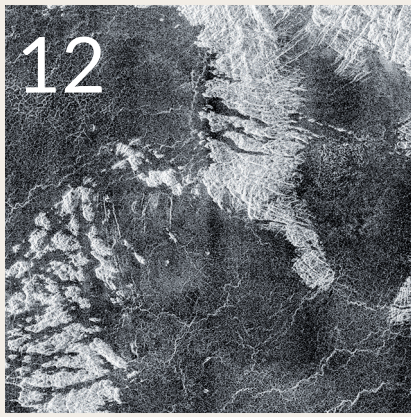


DEPARTMENTS

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

Our Exploration Road Map

Setting the Course for the Next Decade of Advocacy

WE PLANETARY EXPLORATION enthusiasts and professionals all know that getting from one planet to another is not easy. Any mission takes years (Earth years) and millions (of dollars, euros, rubles, rupees, yen, or what have you) to pull off. We have to make careful decisions about where to go, and we have to stick to those plans until we see them through.

With this in mind, scientists who are involved in planetary exploration go through formal processes to chart the course of exploration. In the United States, this is done in what's called the "decadal survey." Under the auspices of the National Academies, the nation's leading planetary scientists come together every 10 years to express their views and debate the scientific priorities for the next period of planetary exploration.

This process is widely respected among policymakers, government agencies, and the science community. NASA's Science Mission Directorate, which initiates and oversees scientific research and missions, follows the decadal survey closely, as does The Planetary Society. Our advocacy priorities don't come out of thin air. We support the priorities made in the decadal survey. When we engage you as a member and advocate, you support these decisions as well, and when we visit with members of the U.S. Congress and their staff, the decadal survey gives our advocacy credibility because our calls for funding are backed by an esteemed community of scientists.

When leading scientists come together to set a course and the public rallies behind them, phenomenal things happen. Among other hits, the decadal survey process gave us the Mars 2020 rover launching in mid 2020, the OSIRIS-REx spacecraft traveling to asteriod Bennu, the New Horizons mission to Pluto, and the upcoming Europa Clipper mission to Jupiter's watery moon.

WHAT'S NEXT?

This issue of *The Planetary Report* gives you a sneak peek at what the scientists working on the frontier of space exploration expect for the next decade.

You'll see how questions become hypotheses. You'll see how ideas become missions. You'll see how what's desired is tempered with what's possible right now and what will be possible with the right investments directed to the right scientists, engineers, and innovators.

As you probably know, for me personally, along with exploring distant exoplanets with ground and space-based telescopes, I hope the next decadal survey directs us to look for life here in our own solar system and beyond. I claim that such a discovery on another world would profoundly change this one.

As you peruse this issue, ask yourself: what do you want to learn about other worlds? What do you want to know next?

Višnjan Observatory

LEFT *A 2019 Planetary Society Shoemaker NEO Grant will help Višnjan Observatory in Croatia measure newly discovered near-Earth objects.*

The 2019 Shoemaker NEO Grant Winners

THE PLANETARY SOCIETY'S Gene Shoemaker Near-Earth Object Grant program helps find, track, and characterize near-Earth objects (NEOs) to determine which objects pose a threat to Earth.

Thanks to your support, over the 22-year history of the program, we have awarded approximately $440,000 in 62 awards to recipients in 19 countries on 6 continents. These award recipients are very advanced, mostly amateur astronomers who are making meaningful contributions to the defense of our planet.

The Planetary Society is excited to announce the newest Shoemaker NEO Grant winners. Because of the support of members like you, these grant recipients will be able to advance their research on potentially hazardous NEOs.

In this round of grants, we awarded a total of $57,906 to 6 groups of astronomers around the world:

LEONARDO SCANFERLA AMARAL of Observatório Campo dos Amarais in Brazil, an important location because of its view of the very southern sky, which is not seen by the current major asteroid-survey telescopes.

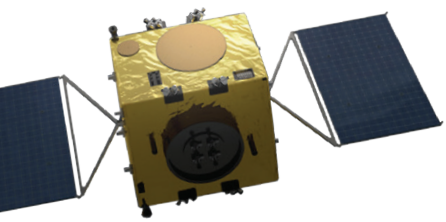
RUSSELL DURKEE of the Shed of Science Observatory in the United States. Durkee studies spin rates and binary asteroids. He is a high school teacher by day and also uses his observatory to mentor young astronomers.

RANDY L. FLYNN of Squirrel Valley Observatory in the United States. Flynn focuses on astrometric-tracking measurements, which help determine the orbit of asteroids, particularly for newly discovered asteroids.

KORADO KORLEVIĆ of Višnjan Observatory in Croatia. The Višnjan Observatory focuses on follow-up astrometric measurements of newly discovered NEOs, including over 1,400 newly discovered NEOs in the last 2 years. The observatory also has educational visits by middle and high school students.

ALESSANDRO NASTASI, **SABRINA MASIERO**, and **MARIO DI MARTINO** of the GAL Hassin Astronomical Center in Italy. Nastasi and his colleagues make astrometric observations of fast-moving, relatively nearby NEOs.

PAOLO BACCI, **LUCIANO TESI**, and **MARTINA MAESTRIPIERI** of the Gruppo Astrofili Montagna Pistoiese at the Osservatorio Astronomico della Montagna Pistoiese in Italy. This group of amateur astronomers focuses on rapid follow-up observations of newly discovered NEOs.



Hera Mission Funded

In November, Planetary Society members joined in an international advocacy movement in support of Hera, a European mission to validate critical asteroid-deflection techniques. The Planetary Society issued a formal statement of support and asked members like you to sign an open petition in support of the mission. ESA's member countries agreed to fund the Hera mission during their latest ministerial meeting, which also produced a record budget for the space agency.

TIME

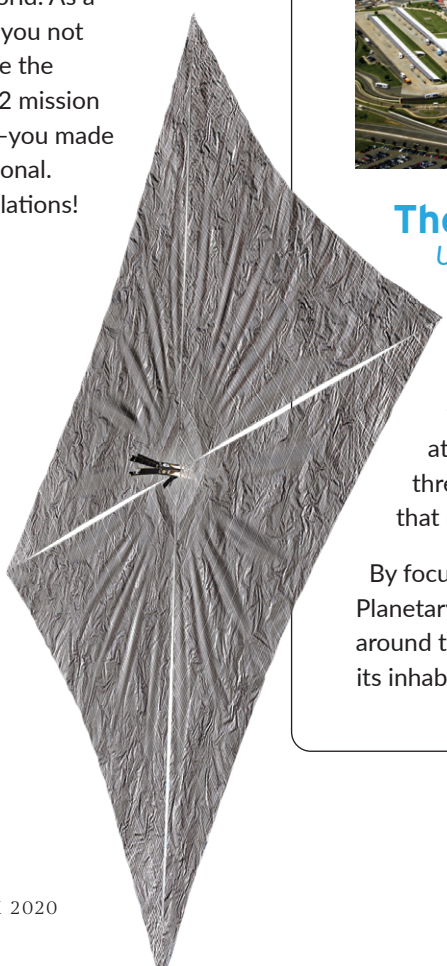
TIME's 100 Best Inventions of the Year

POPULAR SCIENCE

Grand Award Winner for Aerospace in *Popular Science*'s Best of What's New

LightSail 2 Wins Big

In December 2019, the LightSail 2 project won 2 major awards recognizing its ingenuity and impact on the world. As a member, you not only made the LightSail 2 mission possible—you made it exceptional. Congratulations!



Global Advocacy and Education

With your support, The Planetary Society works to advance 3 core enterprises:

- **Explore Worlds**: Increase discoveries about the worlds of our solar system and beyond
- **Find Life**: Elevate the search for life as a space exploration priority
- **Defend Earth**: Decrease the risk of Earth being hit by an asteroid or comet

The Planetary Society continues to take our core enterprises to the global stage, sharing key messages with influential audiences. Recent highlights include:

The Pentagon

U.S. Department of Defense Headquarters

In October, Chief Advocate Casey Dreier gave a special presentation on planetary defense to decision makers at the United States Department of Defense at the Pentagon, highlighting the potential threat of asteroid impacts and the steps that must be taken to protect our planet.

By focusing on specific policy actions, The Planetary Society aims to motivate policymakers around the world to defend our planet and its inhabitants from the asteroid threat.

The Pentagon: Getty Images; Hera: ESA; Lightsail: The Planetary Society

International Astronautical Congress

The World's Largest Space Conference

Every year, the world's leaders in space come together for the International Astronautical Congress (IAC). The discussions range from the highly technical to the philosophical.

This year, as always, The Planetary Society represented our members at IAC and our shared mission to advance space science and exploration.

The Planetary Society's chief scientist, Dr. Bruce Betts, shared the LightSail 2 project with IAC's global audience. LightSail 2's mission continues through outreach like this, showing the groundbreaking developments in space technology that can be made possible through crowdfunded, collaborative projects.

Our CEO, Bill Nye, participated in a plenary discussion of the Europa Clipper program. He also represented Planetary Society members in advocating for global collaboration in the endeavor to find, track, characterize, and deflect potentially dangerous near-Earth objects.

Planetary Society members like you make it possible for us to participate in global meetings like the International Astronautical Congress. Thanks to you, we are able to advance our mission to find life, explore worlds, and defend Earth.

European Space Research and Technology Centre Open Day

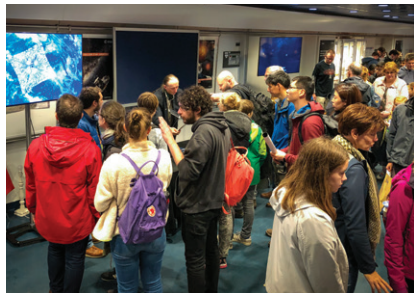
Marquee Public Event for Europe's Largest Space Center

Members across Europe came together in October 2019 to represent The Planetary Society at a public event for ESA's facility in the Netherlands. These members introduced attendees to The Planetary Society, sharing the LightSail 2 story and tying ESA exoplanet research to projects supported by Planetary Society members like you.

When members go above and beyond to advocate for space, they advance our mission to educate, engage, and empower the world's citizens in support of space exploration.

ABOVE LEFT *Planetary Society CEO Bill Nye speaks during a Europa Clipper presentation at the 70th International Astronautical Congress in Washington, D.C.*

ABOVE RIGHT AND BELOW *Planetary Society members in action at the 2019 European Space Research and Technology Centre Open Day.*

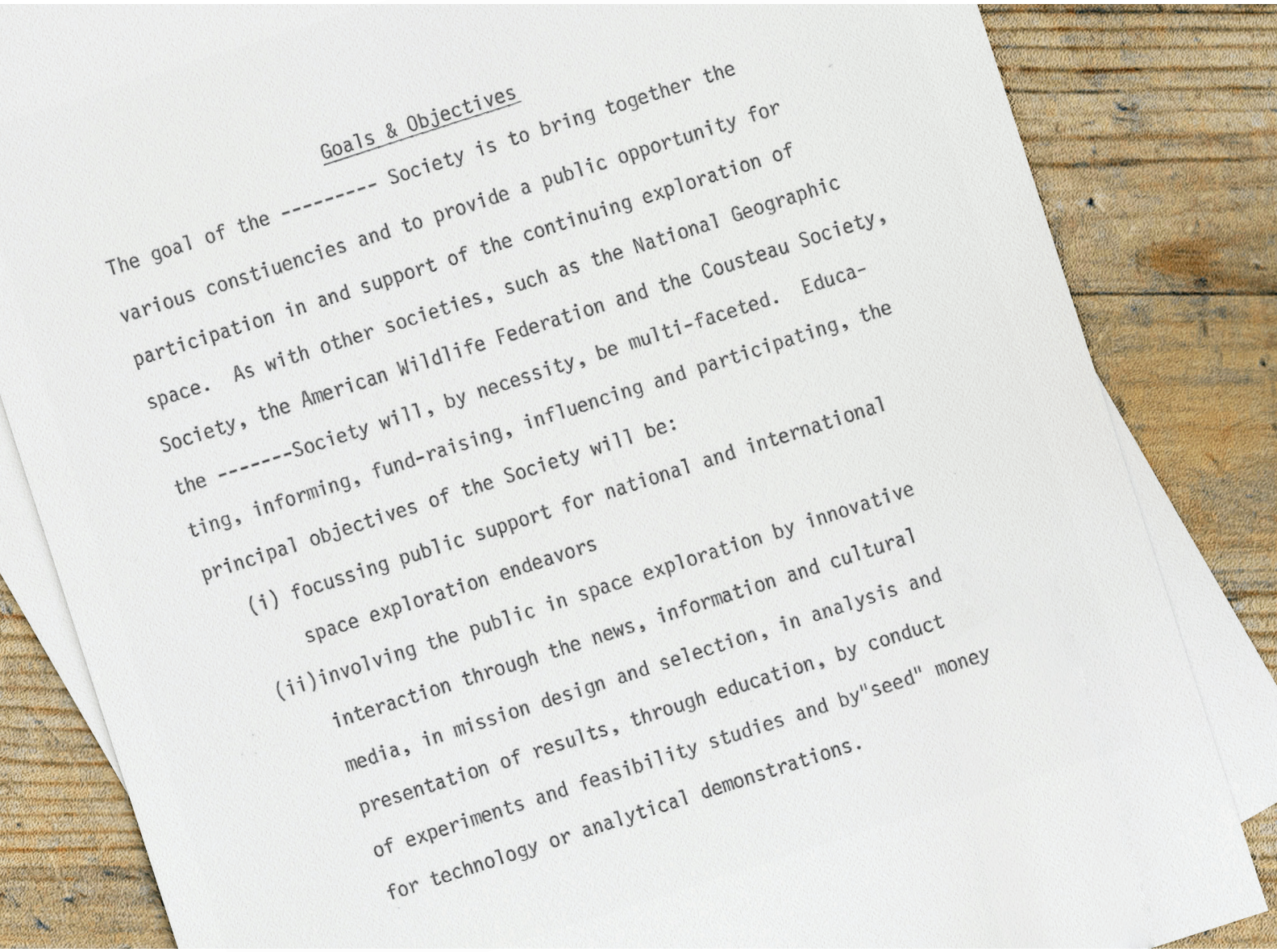


Bill Nye at IAC: Ed Whitman/JHUAPL; ESA ESTEC Open Day photos: Sven Neuhaus

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

THE PLANETARY SOCIETY

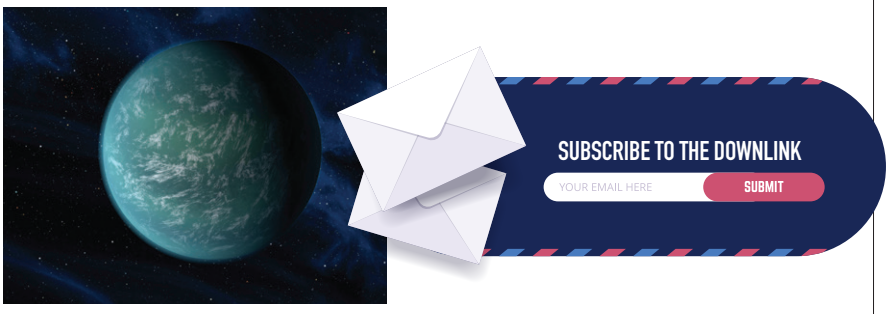
CELEBRATING 40 YEARS



We began as “The --------- Society.” Even before we had a name, our founders, Bruce Murray, Louis Friedman, and Carl Sagan, had a vision for an organization that would unite people in support of space exploration. Forty years later, this vision continues to be realized thanks to you. Throughout 2020, we’ll be celebrating 4 decades of empowering people like you who are passionate about discovery, exploration, and understanding our place in the cosmos. The best is yet to come. Thank you for being with us.

The Planetary Society

ENGAGING YOU As this issue of *The Planetary Report* goes to press, 2 major initiatives are underway to engage you directly in our work.



NASA/Ames/JPL-Caltech

SUPPORT EXOPLANET RESEARCH

Does life exist on worlds orbiting other stars? You can help us find out.

Exoplanet research—the effort to find and study planets around other stars—holds some of the greatest potential in the search for life beyond Earth. That's why The Planetary Society is mobilizing our members to advance this fascinating field of research by supporting Yale University's 100 Earths project.

This follow-on to other successful exoplanet projects funded by The Planetary Society aims to find 100 Earth-sized planets around nearby stars using advanced new technologies. The Society is raising funds to secure a crucial component of an instrument needed to achieve the high precision required to detect stellar movement caused by the gravity of Earth-sized planets.

Exoplanet hunting takes human intelligence, computing power, and, of course, steady funding. You can make a direct contribution to finding Earth-sized worlds beyond our solar system. Go to **planetary.org/100earths** to learn more.

THE DOWNLINK: YOUR WEEKLY SPACE TOOLKIT

Planetary Society members like you are committed to advancing space exploration. That's why you fund special projects and sign petitions, and it's why you tell other people about the exciting things happening in space.

However you choose to act, The Planetary Society is here to give you the tools you need to make an impact. This year, we launched *The Downlink*, a weekly email with everything you need to fuel your love of space and equip you as an advocate.

Here you'll find the latest in space news, shareable images and factoids, ways to get more involved, and much more. Whether you're a new space fan or a seasoned advocate, you'll find tools in this weekly newsletter that can help you share your passion for space and take action to advance exploration.

To get this weekly newsletter, sign up for email updates at **planetary.org/connect**.

Planetary Society Member Adventures

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:

TIBET, 9–23 JUNE 2020
See the eclipse at the "top of the world"

ETHIOPIA, 10–23 JUNE 2020
Including the source of the Blue Nile

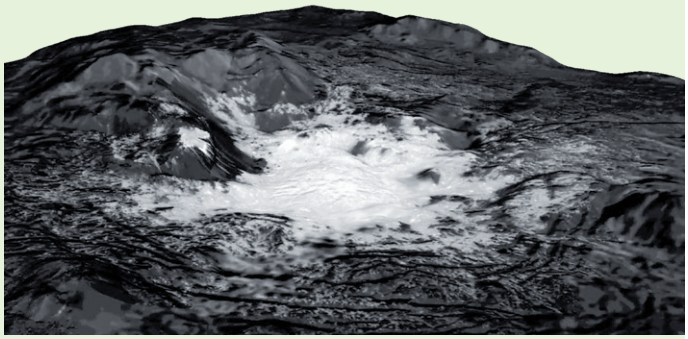
ARGENTINA TOTAL SOLAR ECLIPSE 2020
8–19 DECEMBER 2020
With optional Peru or Easter Island pretrips, 2-8 December 2020

ALASKA AURORA BOREALIS
11–17 MARCH 2021
Come see the aurora dance across the night sky in this perennially favorite expedition!

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.*

WHAT'S UP? *by Bruce Betts*



LEFT *This mosaic of Cerealia Facula on Ceres, an enigmatic bright spot seen by NASA's Dawn mission, combines images obtained from altitudes as low as 35 kilometers (22 miles) above the dwarf planet's surface.*

IN THE SKY

There is a planet party in the predawn East. Look there in late March where very bright Jupiter, bright-reddish Mars, and yellowish Saturn will all be near each other. The Moon will join them on 15 April. Then, Jupiter and Saturn will rapidly get higher in the sky as the weeks pass, with Mars climbing more slowly. Super-bright Venus will emerge low in the predawn East by late June. In the evening sky, Venus dominates the western sky after sunset until June. Bright Mercury is visible low in the evening West after sunset in late May and early June. On 21 May, Venus and Mercury will be very close together in the West after sunset but very low to the horizon. The crescent Moon will join them on 23 May. On 21 June, there will be an annular eclipse whose path crosses central Africa, Saudi Arabia, northern India, and southern China. A partial eclipse will be visible throughout most of eastern Africa, the Middle East, and southern Asia.

RANDOM SPACE FACT

About 2,500 of the dwarf planet (and largest asteroid) Ceres would fit inside Earth (assuming no void space).

TRIVIA CONTEST

Our September equinox contest winner is Mercy Ocasal from Whitestone, New York, USA. Congratulations! The question was: ***As seen from Earth, in what year was the last transit of Mercury across the Sun (at the time the question was asked)?*** The answer: ***2016.***

Try to win a copy of *V.R. Space Explorers: Titan's Black Cat* by Bruce Betts and a *Planetary Radio* T-shirt by answering this question:

Approximately how many of Earth's Moon would fit inside Earth (assuming no void space, i.e., assuming the volume of Moons smooshes into the volume of Earth)?

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 June 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

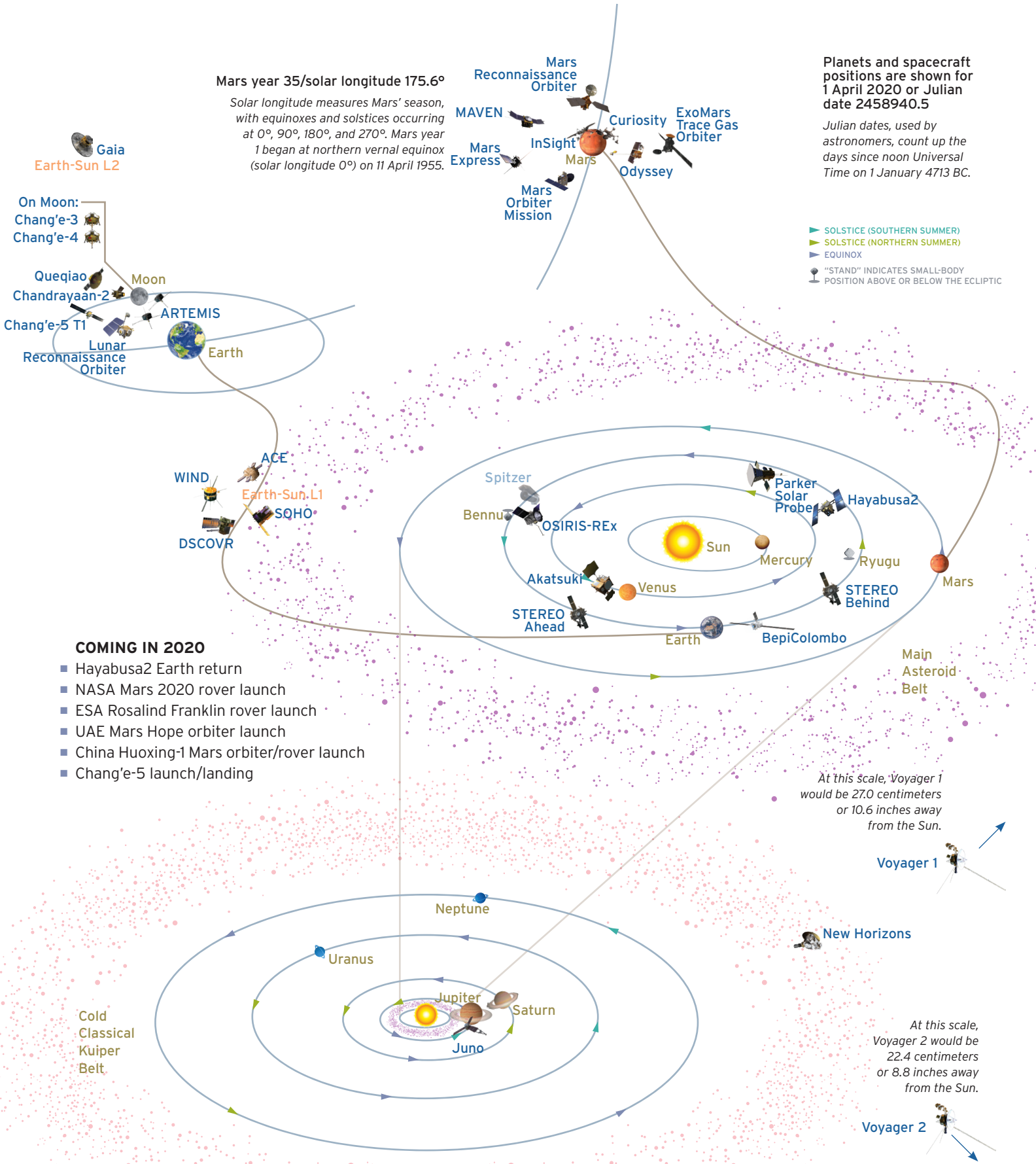
ON 13 APRIL 2020, the European Space Agency's BepiColombo spacecraft will fly past Earth using a nudge from our planet's gravity to drop it into the inner solar system. BepiColombo launched on a mission to Mercury in 2018. It will fly past Venus twice and Mercury 6 times before easing into Mercury orbit in 2025.

The OSIRIS-REx team selected a sampling site on asteroid Bennu in December. It is a subdued hollow filled with fine-grained material, surrounded by large rocks that could present hazards to the mission. The spacecraft is now performing low flybys of the landing site, collecting high-resolution data to prepare for landing rehearsals beginning in June. The first sample attempt is currently planned for August.

Back on Earth, as many as 4 new spacecraft from 4 different space agencies are preparing to launch to Mars. All would launch as early as July 2020 and arrive at Mars in early 2021. Hope, a United Arab Emirates orbiter, is the Arab world's first mission to another planet. It will build a complete picture of Mars' seasonal atmospheric cycles from an orbit that is much higher than NASA's atmospheric mission, MAVEN. NASA's Mars 2020 rover, which appears similar to Curiosity but carries different science instruments, will search for signs of past life and collect samples for future return to Earth. The ESA-led ExoMars 2020 mission includes a rover named Rosalind Franklin that will drill for samples up to 2 meters beneath the surface, searching for signs of past and present life. Finally, China plans to launch an orbiter, lander, and rover mission tentatively called Huoxing-1 that will search for water ice, study Mars' climate, and investigate the planet's habitability.

For mission updates and more, check out *The Downlink*, our weekly email newsletter. Sign up at **planetary.org/connect**.

Ceres: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI; Where We Are: Loren A. Roberts for The Planetary Society after a concept by Olaf Frohn


Mars year 35/solar longitude 175.6°
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 April 2020 or Julian date 2458940.5
Julian dates, used by astronomers, count up the days since noon Universal Time on 1 January 4713 BC.
SOLSTICE (SOUTHERN SUMMER)
SOLSTICE (NORTHERN SUMMER)
EQUINOX
"STAND" INDICATES SMALL-BODY POSITION ABOVE OR BELOW THE ECLIPTIC
Mars Reconnaissance Orbiter
MAVEN
Curiosity
ExoMars Trace Gas Orbiter
InSight
Mars
Mars Express
Odyssey
Mars Orbiter Mission
Gaia
Earth-Sun L2
On Moon:
Chang'e-3
Chang'e-4
Queqiao
Moon
Chandrayaan-2
ARTEMIS
Chang'e-5 T1
Earth
Lunar Reconnaissance Orbiter
ACE
WIND
Earth-Sun L1
SOHO
DSCOVR
Spitzer
Parker Solar Probe
Hayabusa2
Bennu
OSIRIS-REx
Sun
Mercury
Ryugu
Akatsuki
Venus
STEREO Behind
Mars
STEREO Ahead
Earth
BepiColombo
Main Asteroid Belt
COMING IN 2020
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
Chang'e-5 launch/landing
At this scale, Voyager 1 would be 27.0 centimeters or 10.6 inches away from the Sun.
Voyager 1
Neptune
New Horizons
Uranus
Jupiter
Saturn
Juno
Cold Classical Kuiper Belt
At this scale, Voyager 2 would be 22.4 centimeters or 8.8 inches away from the Sun.
Voyager 2

The Next 10 Years

An Introduction to the Decadal Survey

WE SOMETIMES TAKE for granted the bureaucratic processes that turn ideas for space missions into actual flight hardware. For NASA, that process is the decadal survey, a report produced every 10 years by the scientific community for each of NASA's 4 science divisions. The current decadal survey for planetary science was released in 2011 and set priorities for 2013 to 2022. Work on the next iteration, covering 2023 through 2032, formally kicks off this year.

The value of the decadal surveys comes from their open, deliberative process among various planetary science constituencies. Through a process overseen by the National Academy of Sciences, scientists who study specific aspects of the solar system such as the Moon or the outer planets settle on the big science questions for their field and which space missions should answer those questions.

Recommendations made in the decadal reports tend to happen despite the fact that the reports are advisory. Congress, finding the decadal process helpful for evaluating NASA's funding requests, passed legislation making those recommendations an official part of NASA's policy-setting process. As a consequence, the decadal survey serves 2 major purposes: to drive resources into new projects and to defend the cancellation of previously endorsed missions.

In the early 2010s, NASA's Planetary Science Division faced its largest cuts in 30 years. The Planetary Society, working hand in hand with other professional organizations, rallied around the decadal survey to defend existing missions and argue for increased funding for recommended ones. Today, the planetary science budget has rebounded, reaching levels not seen since the days of the Viking missions to Mars in the 1970s. NASA's Mars 2020 and Europa Clipper spacecraft are moving toward launch. The Dragonfly mission to Titan is in development, and the lower-cost InSight, Lucy, and Psyche missions were selected to explore Mars and asteroids.

As work on the next decadal survey kicks off, we've asked scientists representing Mercury, Venus, the Moon, Mars, small bodies, and the outer planets to tell us what we've learned in the past decade and to give us 3 big questions that will drive future missions for the next decade and beyond. The planning, debate, and effort for missions to answer those questions is already in progress. Who knows what marvelous scientific discoveries await as a result?

ABOVE *The Moon holds a rich trove of information about the early history of our solar system that has been largely erased on Earth by weathering and plate tectonics. This image of the lunar horizon and Earth was captured by Japan's Kaguya spacecraft in 2007.*

JAXA/NHK

Mercury

MERCURY, THE FIRST planet from the Sun, is an enigmatic world with important insights for planetary scientists. It has water ice at its poles, which was discovered by the Arecibo Observatory in Puerto Rico and the Goldstone Solar System Radar. This is despite the fact that Mercury's surface can reach 430-degrees Celsius (800-degrees Fahrenheit). The planet has a self-generated magnetic field created by a molten core even though it's only about 3 times the volume of our Moon.

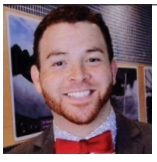
NASA's MESSENGER spacecraft orbited Mercury from 2011 to 2015 and revealed that the planet's core comprises nearly 85 percent of the planet's volume, hinting at a unique formation history. The surface has been heavily modified by volcanoes and tectonics and may still be active today as Mercury contracts. MESSENGER also saw chemically distinct surface features that we still don't fully understand. These findings have led us to fundamental questions about Mercury that, if answered, would help us better understand important planetary processes:

How did Mercury form?

How did Mercury get such a large core?

From where did Mercury's polar ice originate, and how is it distributed in the planet's subsurface?

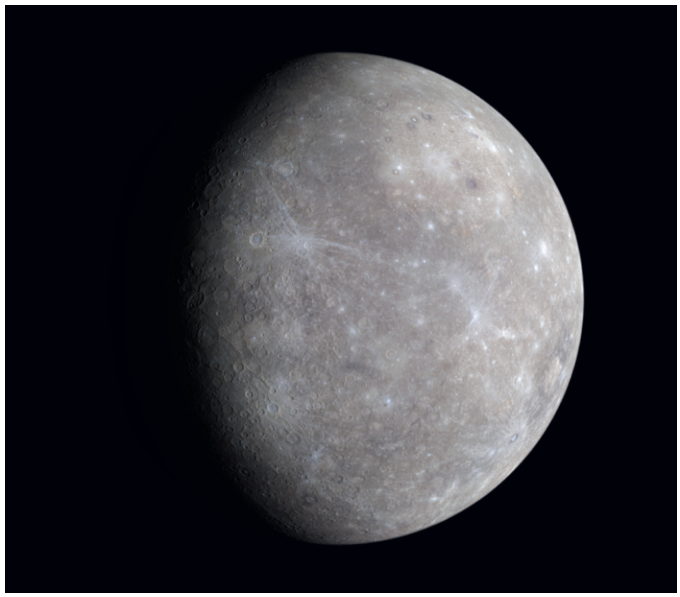
BepiColombo, a joint mission between Europe and Japan, launched to Mercury in 2018 and will arrive in 2025. It will study the planet for at least 2 years. Studying Mercury's interior and unraveling its early history will help us understand how it formed and thus provide insights on the formation of our solar system. We can also learn how Mercury generates a magnetic field, which in turn will help us better understand how planetary magnetic fields form and why some planets have them while others don't. Mercury is also an excellent laboratory to refine our understanding of how stars interact with planetary surfaces via space weathering.

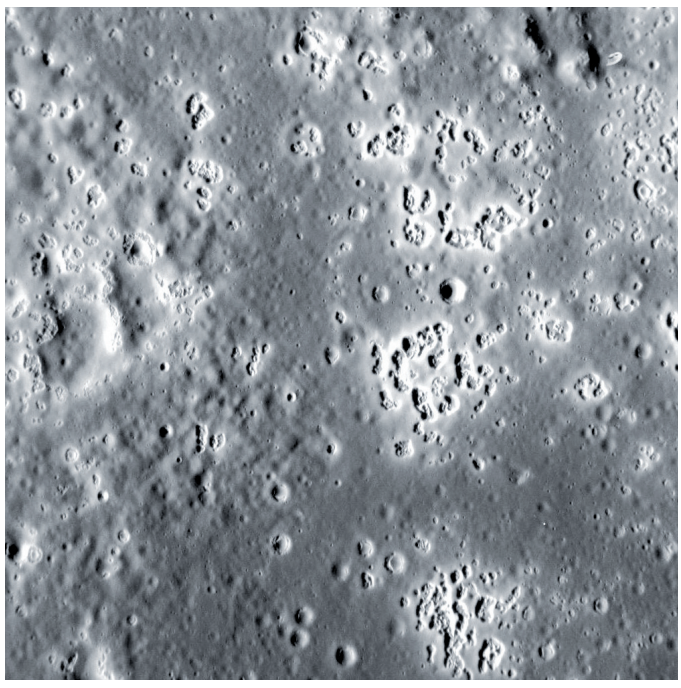


EDGARD G. RIVERA-VALENTÍN *is a staff scientist with Universities Space Research Association at the Lunar and Planetary Institute. Asteroid (389478) 2010 ER87 is named after them.*

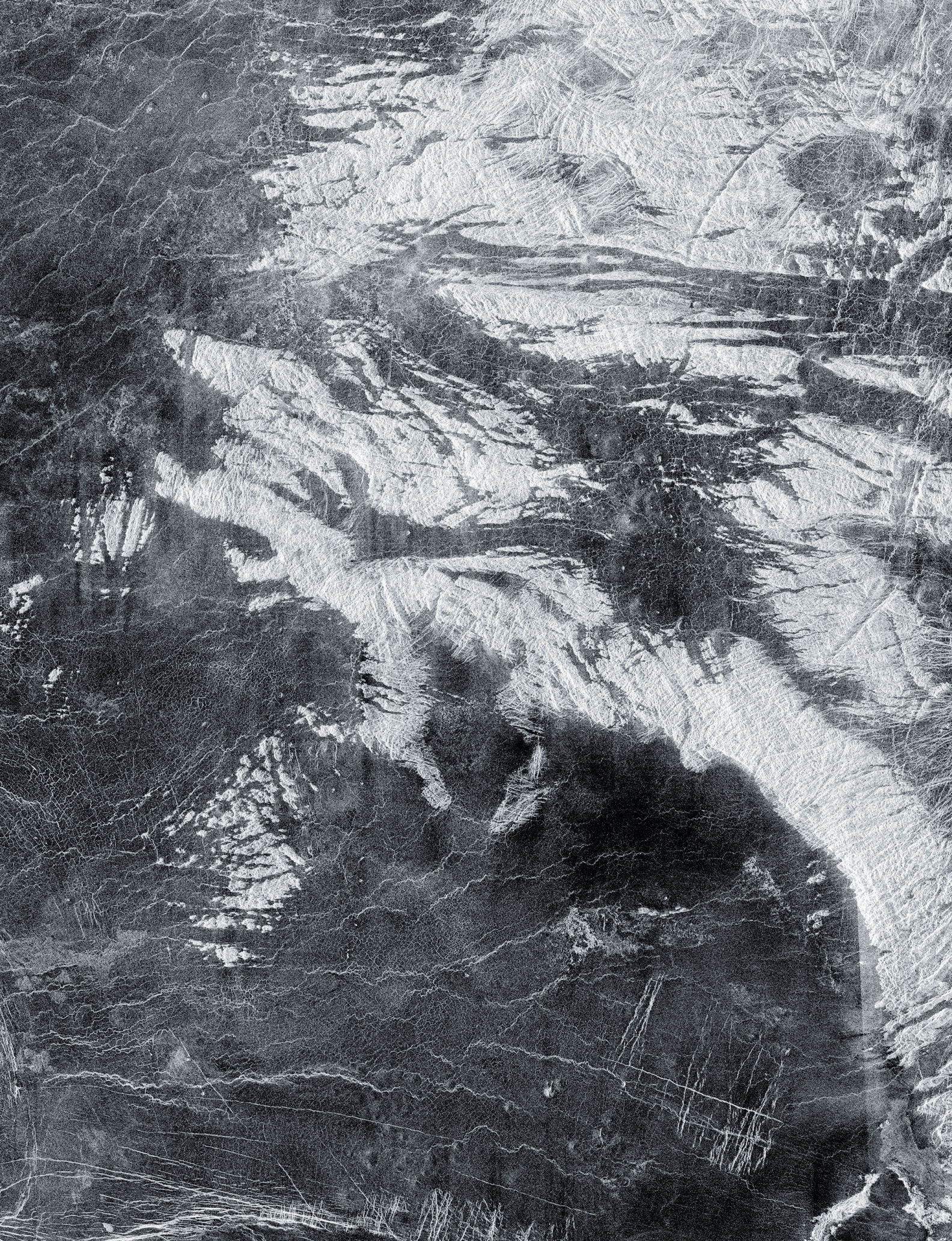
TOP *NASA's MESSENGER spacecraft captured this view of Mercury during its first flyby in 2008.*

BOTTOM *Mercury's hollows are among its most distinctive and unusual surface features. The shallow depressions may be created by the Sun's solar wind striking the surface and turning volatile materials like sulfur from a solid to a gas in a process known as sublimation.*





NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington; NASA/JHUAPL/CIW



Venus

VENUS IS PERHAPS the most Earth-like world in the solar system. However, only 3 space missions have targeted Venus in the past 30 years. They provided tantalizing hints that Venus, though hellish today, maintained temperate surface conditions for billions of years—much longer than Mars! Venus also holds the key to interpreting ongoing observations of Venus- and Earth-sized exoplanets.

Magellan, the last NASA-led mission to Venus, arrived on 10 August 1990. (I was 10 days old.) The spacecraft mapped the surface with radar to see through the thick, visibly opaque atmosphere. Venus is volcanically active today, with an average surface age under 1 billion years.

Missions after Magellan, 2 of which operated in the past decade, focused on atmospheric dynamics. Europe's Venus Express operated from 2006 to 2014, while Japan's Akatsuki failed to enter orbit in 2010 but succeeded in 2015 and survives today. This plucky spacecraft discovered a huge, stationary gravity wave and mapped 3D wind speeds.

The Venus community recently developed a consensus list of scientific goals to inform the next decadal survey. Here are 3 of the many high-priority questions:

Did Venus ever host oceans?

Venus Express discovered that ancient, highly deformed terrain called tesserae may have granite-like compositions, which would imply that they formed near abundant liquid water. The next Venus orbiter could confirm this by measuring the spectral signatures of tesserae with an instrument optimized for the task. Follow-up tesserae landers could characterize their mineralogy in detail.

Can the evolution of Venus help us understand the evolution of exoplanets?

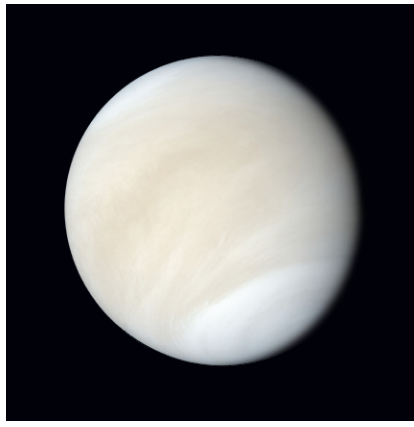
Beyond chasing surface water, we need to narrow down the fundamental properties of Venus that control its evolution as a planetary system over time. In particular, any spacecraft that visits the deep atmosphere should measure the abundances and isotopic ratios of noble gases like krypton and xenon for comparison to well-known values found on Earth and Mars. These measurements will help us learn how Venus got its atmosphere and how certain compounds like water were lost to space over time.

What geologic processes have shaped the surface of Venus?

Whether Venus' crust was resurfaced in a catastrophic event or more gradually has been debated since Magellan. Our existing maps have limited resolution, similar to what we had for Mars in the 1970s. Higher-resolution images would permit basic geologic mapping: identification of different rock types, their distributions on the surface, and how they aged over time. Additionally, better imagery and topography for the entire surface could reveal why Venus lacks plate tectonics.

A mission in NASA's low-cost Discovery flight line, equipped with a modern radar and an infrared camera customized for Venus, would answer most of these high-priority questions while leaving some (including those not listed above) unanswered. Given its potential long-lasting habitability and implications for terrestrial exoplanets, Venus deserves to have a multimission program started in the next decade.

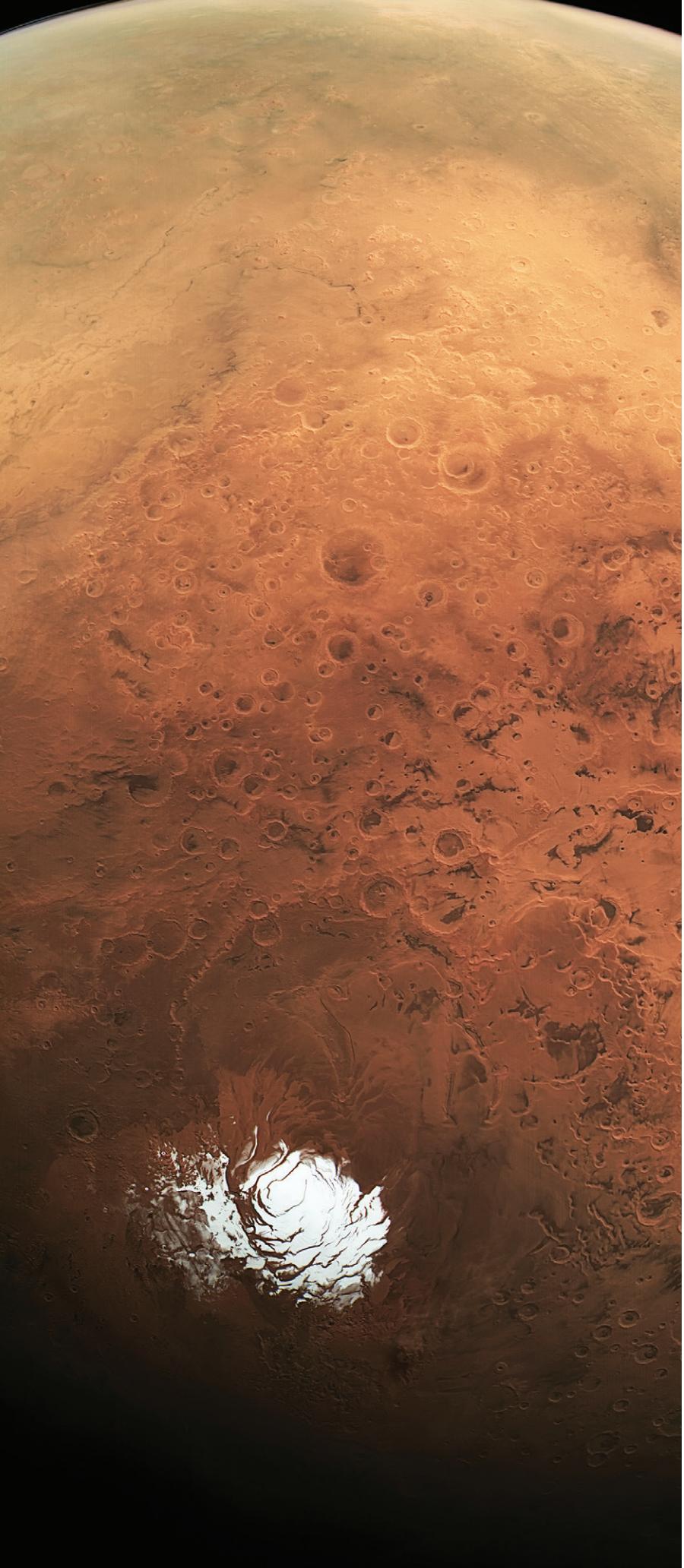
JOSEPH G. O'ROURKE *is an assistant professor in the School of Earth and Space Exploration at Arizona State University and serves on the steering committee of NASA's Venus Exploration Analysis Group.*



ABOVE *Image processor Mattias Malmer created this global color view of Venus using data from NASA's Mariner 10 spacecraft.*

LEFT *The bright, rough terrain in this image of Venus' surface is called tesserae and may have formed in abundant liquid water. NASA's Magellan spacecraft captured this image using radar to peer through Venus' thick clouds.*

NASA/JPL/mapaplanet.org/Emily Lakdawalla; NASA/JPL/Mattias Malmer



ESA/DLR/FU Berlin

Mars

MARS SCIENCE HAS come a long way since Percival Lowell looked through his telescope and saw what he thought were irrigation canals on the Red Planet. To this day, the question of whether life exists or ever existed there remains one of the primary drivers of Mars exploration.

In the past decade, NASA's Curiosity rover discovered organic compounds—the building blocks of life as we know it—on the surface. Curiosity also sniffed out seasonal releases of methane, which could be linked to underground life. The European Space Agency's Mars Express orbiter found evidence for a possible lake underneath the Martian south pole. This is all consistent with new laboratory experiments and fieldwork suggesting that Mars' subsurface may be able to host thriving microbial communities.

We know that ancient Mars had rivers, deltas, and lakes on its surface, supporting the idea of a warmer past climate. Analyses of NASA's MAVEN spacecraft data suggest that the planet likely lost at least 0.5 bar of atmosphere—roughly half of the pressure of Earth's atmosphere at sea level—over the past 4 billion years. (It could be as high as 1 bar or more.) However, we still don't know what Mars was like in its early days. Fortunately, new missions and laboratory work over the next decade could help us figure that out. The answers have implications far beyond Mars: if life emerged independently on 2 planets in our solar system, then it is more likely to be relatively common throughout the cosmos.

What was the atmospheric composition of a warmer early Mars?

One of the great mysteries of Mars' early history is understanding the atmospheric composition that would have supported the once-warmer and once-wetter climate. Because the Sun was much

RAMSES RAMIREZ *is a planetary scientist and astrobiologist from the Earth-Life Science Institute at the Tokyo Institute of Technology and a Space Science Institute affiliate scientist.*

LEFT *The European Space Agency's Mars Express orbiter found evidence for a possible lake underneath the Martian south pole. Mars Express captured this image of the south pole in 2015.*

BELOW *NASA's Curiosity rover, seen here in a 2019 self-portrait, discovered organic compounds—the building blocks of life as we know it—on Mars' surface. Future Mars missions will more directly search for life.*

fainter 4 billion years ago, Mars couldn't have been warmed up by just carbon dioxide and water, the principal greenhouse gases we have here on Earth. Recent models suggest that early Mars could have had a predominantly carbon-dioxide-and-hydrogen-based atmosphere (along with water) instead, which is consistent with our having yet to observe iron bands in Martian rocks that would have likely formed in a more oxygen-rich atmosphere like that on Earth.

We need to run experiments to evaluate whether a predominantly carbon dioxide and hydrogen atmosphere would alter a planet's surface in a way that matches what we see on Mars. Then, future Mars missions, including human crews, could assess rock layers and compare them with our laboratory experiments.

Was early Mars warm and wet or cold and icy with temporary episodes of warmth triggered by events like short-lived volcanism and meteoritic impacts?

NASA's Mars 2020 rover will examine an ancient river delta in Jezero crater. There, it can search for frost wedges—places where rocks fracture due to persistent cold temperatures. The presence of frost wedges would support the cold-and-icy theory. Likewise, Mars 2020 will search Jezero's rock layers for signs of a long-term lake, which would be consistent with a persistently warm and wet climate.

Did life exist—or does life currently exist—on Mars?

A warmer ancient Mars with a thicker atmosphere could have facilitated the emergence of life. If so, fossils may be preserved today. Although the present Martian surface is sterile, life may be safely living in the subsurface. NASA's Mars 2020 rover and the European Space Agency's Rosalind Franklin rover are both scheduled to launch this year. They are equipped with Raman spectrometers that can detect organic compounds and decode their structures. These instruments alone won't confirm the existence of life, but they could point us in the right direction, especially for determining which samples Mars 2020 should store for future return to Earth for more careful analysis.

NASA/JPL/MSSS

Small Bodies

MULTIPLE MISSIONS TO our solar system's smallest worlds ushered in a new era of small-body science during the last decade. Europe's Rosetta spacecraft flew past 2 asteroids before arriving at comet Churyumov-Gerasimenko. China's Chang'e-2 visited asteroid Toutatis in 2012. NASA's Stardust mission, having encountered comet Wild 2 in 2004, was repurposed to fly past comet Tempel 1 in 2011.

There were also 3 sample return missions, 2 of which are still in progress. Japan's Hayabusa spacecraft returned samples from asteroid Itokawa to Earth in 2010. Hayabusa2 is on its way back to Earth with samples from Ryugu, while NASA's OSIRIS-REx is surveying asteroid Bennu in preparation to collect a sample in August 2020.

We have learned that Itokawa, Ryugu, and Bennu are all "rubble-pile" asteroids–essentially, rocks and boulders loosely held together by gravity. The diamond shapes of Bennu and Ryugu indicate there are common processes altering these worlds, including the YORP effect, which alters an asteroid's spin rate due to solar heating and thermal emission. Studies suggest this effect could be responsible for separating some top-shaped asteroids into 2 objects.

Beyond Neptune, NASA's New Horizons spacecraft visited 2 Kuiper Belt objects: Pluto and Arrokoth. The almost-perfectly round lobes of Arrokoth are likely a result of 2 separate spheres of boulders and rocks clumping together and then colliding at slow speeds. This tells us that slow-speed impacts may have been a common occurrence in the early solar system.

Also in the past decade, we discovered additional moons around Jupiter. Many have eccentric, highly inclined orbits–typically opposite from the direction of Jupiter's rotation–which tells us they were probably captured by Jupiter's gravity rather than forming near the planet.

Our myriad discoveries in the last decade have reaffirmed our need to study small bodies in detail. Missions and investigations in the next decade will hopefully answer several of our big-picture questions, which include:

Are asteroids and comets primordial bodies, meaning they are building blocks of planets?

If asteroids and comets are the precursor objects that formed the larger planets by accretion, then it's essential that we keep exploring them for ingredients essential to life, such as water, amino acids, sugars, and ketones. We also need to understand the processes that shaped these worlds into how they appear today. The samples returned by OSIRIS-REx and Hayabusa2 could help immensely. Additionally, their detailed analyses using state-of-the-art laboratory techniques with high accuracy and precision will enable us to answer the big-picture science questions. We also need increased funding for laboratory studies that have specific planetary science goals.

Are there important differences among the different types of small bodies?

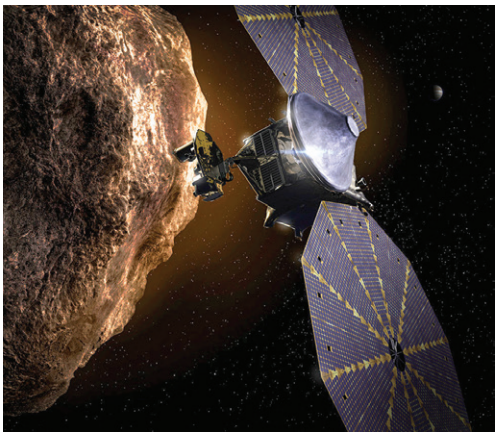
Asteroids receive spectral classifications according to the amount of light they reflect. These classifications usually tell us something about their surfaces, but how important are those differences? Are there common origination processes shared by main-belt asteroids, Trojan asteroids that share Jupiter's orbit, comets, moons of outer planets, and trans-Neptunian objects?

ABOVE *A view of asteroid Bennu from NASA's OSIRIS-REx spacecraft.*

OPPOSITE *NASA's Lucy spacecraft will visit 7 Trojan asteroids from 2027 to 2033.*

NASA/Goddard/University of Arizona; NASA; Deanna Dent/ASUNow

MAITRAYEE BOSE *is a cosmochemist and assistant professor at the Arizona State University School of Earth and Space Exploration. She is on the steering committee of NASA's Small Bodies Assessment group.*



Questions like these will hopefully be answered by the New Horizons extended mission and especially by Lucy, a NASA mission that will visit 7 Trojan asteroids from 2027 to 2033. Did the Trojans form near Jupiter, or did they form in the Kuiper Belt and get flung inward during the migration of the giant planets long ago? Do their surface characteristics indicate a common formation mechanism?

What are the processes that dictate the orbital dynamics of interstellar objects?

ʻOumuamua, which was discovered passing through our solar system in 2017, has an elongated shape, and it is accelerating along its trajectory. However, it does not have a discernible coma nor is it releasing gas and dust tails, which makes this interstellar interloper very mysterious. The path of comet Borisov, discovered in 2019, mimics that of an interstellar object, and it has properties similar to comets in our own solar system. Observations of such objects are possible with ongoing observations by the Pan-STARRS ground-based telescope and are expected to increase after 2022 when the Vera C. Rubin Observatory (originally the Large Synoptic Survey Telescope) becomes operational. Unique interstellar objects could be studied up close in the future with the European Space Agency's rapid-response Comet Interceptor mission.

NASA/JPL-Caltech/Björn Jónsson

The Outer Planets

THE OUTER PLANETS OF Jupiter, Saturn, Uranus, and Neptune as well as their satellites and rings offer a breadth of scientific opportunities for every discipline of planetary science. Whether you're an atmospheric scientist studying storm dynamics, a geologist examining diverse terrains that include active volcanoes and geysers, or an astrobiologist studying the origin and evolution of life, there's something for everyone.

It's no surprise, then, that the fundamental science goals for the outer planets are representative of those of planetary science as a whole. In August 2019, NASA's Outer Planets Assessment Group (OPAG) determined in preparation for the next decadal survey that exploring the outer planets can help answer the following overarching questions:

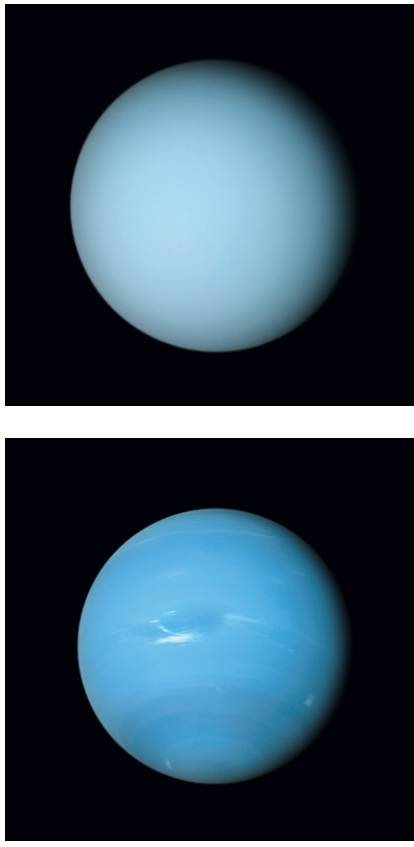
What is the distribution and history of life in our solar system?

How do planetary systems form and evolve?

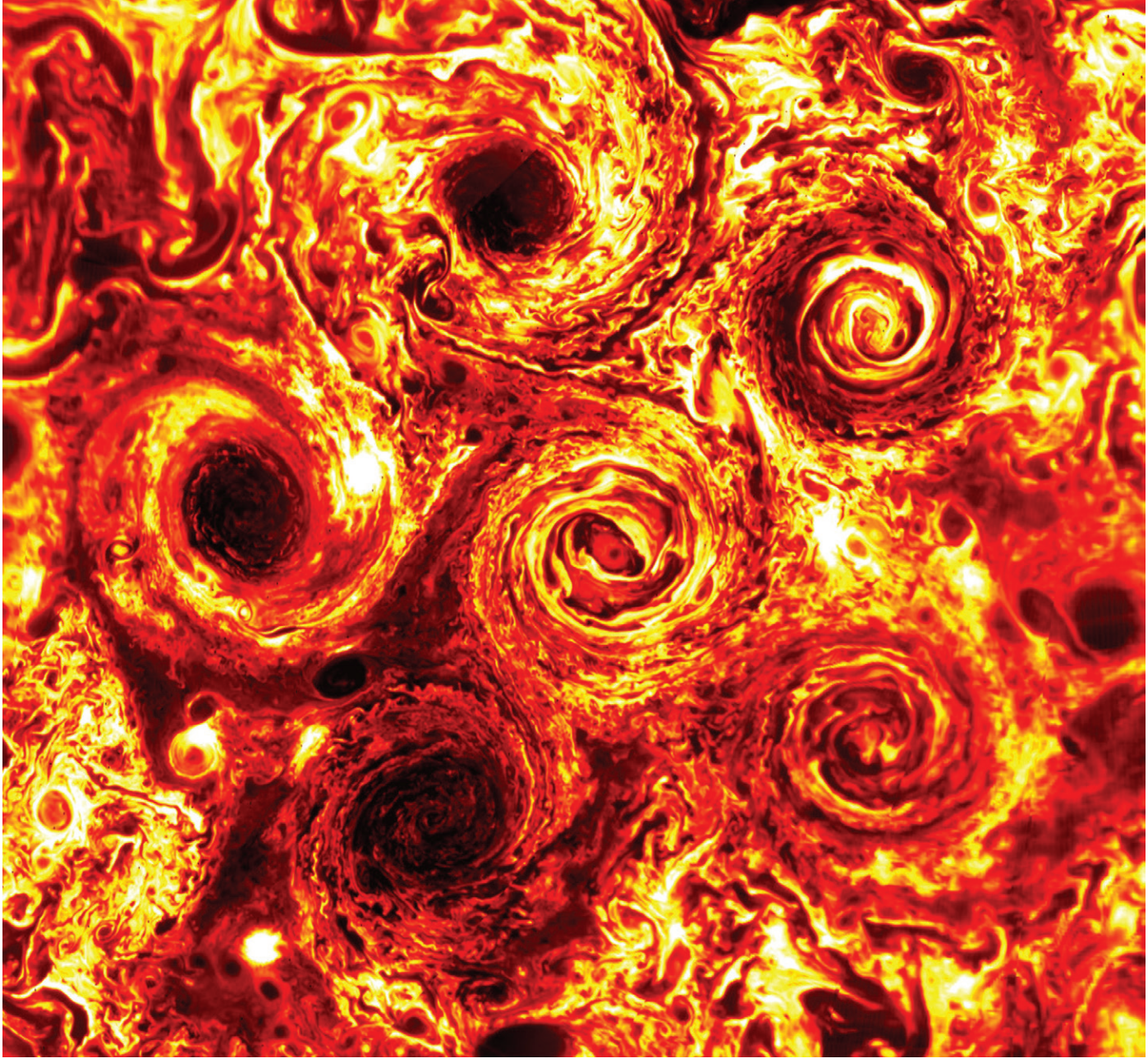
What present-day processes shape planetary systems, and how do we get such diverse worlds?

A version of these questions can be found in the past two decadal surveys, represented as "cross-cutting themes" for all of planetary science. In fact, they also show up in precursor reports dating all the way back to 1965. These long-standing goals show the remarkable consensus that planetary scientists have when it comes to high-level goals for solar system exploration.

Outer-planets research is also relevant to endeavors beyond planetary science. The structure of the outer solar system serves as



ABOVE *Only 1 spacecraft, NASA's Voyager 2, has ever visited Uranus [top] and Neptune [bottom].*



ABOVE *Six cyclones can be seen at Jupiter's south pole in this infrared image taken on 2 February 2017 during the third science pass of NASA's Juno spacecraft. Juno's Jovian Infrared Auroral Mapper (JIRAM) instrument measures heat radiated from the planet at infrared wavelengths.*

NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM

a prototype for exoplanetary systems, and the processes that shape those worlds help us explain similar processes on Earth. As a testament to the diversity of the outer planets, many research topics pursued by scientists studying the outer planets have synergy with other NASA science divisions: astrophysics, Earth science, and heliophysics.

THE PAST 10 YEARS

Outer-planets science during the past decade was led by NASA's Cassini mission at Saturn, which ended in 2017, and Juno, which has been exploring Jupiter since 2016. During Cassini's extended mission, the spacecraft flew in a polar orbit that allowed it to take detailed measurements of Saturn's gravity field. Juno is doing the same at Jupiter, and data from both missions are being analyzed to determine the presence and size of a potential rocky core underneath the gaseous layers we see from space. Learning more about the cores will tell us how those planets formed and grew, capturing hydrogen and helium gas in our solar system's protoplanetary nebula.

Additionally, Cassini and Juno have pointed radio antennas at their planets to measure microwave emissions from Saturn and Jupiter. Cassini used its telecom antenna to measure ammonia in Saturn's upper troposphere, while Juno has dedicated antennas to sense ammonia and water deep in Jupiter's atmosphere. So far, analyzing the Juno data has revealed the distribution of ammonia in

latitude and depth below the colorful cloud tops. These measurements help us understand how the meteorological processes on Saturn and Jupiter work. One eventual goal for both planets is to measure the bulk abundances of volatile molecules such as water and ammonia, which will give us clues on how far from the Sun and how quickly these planets originally formed. We know from studies in the past decade that planets can significantly migrate toward and away from the Sun, which means that the 4 giant planets may not have formed where they are today.

THE NEXT 10 YEARS

During the next decade, NASA will send 2 missions to the outer solar system: Europa Clipper and Dragonfly. Europa Clipper will make repeated flybys of Jupiter's moon Europa, while Dragonfly will land on and then fly around the surface of Titan. The European Space Agency's JUICE (JUpiter ICy moons Explorer) mission will investigate Ganymede, Callisto, and Europa. All 3 of these missions have a focus on determining whether life could have arisen beyond Earth.

Other missions to the outer planets have also been proposed. The main job of the decadal survey will be to prioritize specific science goals and evaluate which missions will best address these goals. The future mission concepts fall into 4 broad themes.

Surveys of Uranus and Neptune: Each of the ice giants has only been visited once—by Voyager 2. A spacecraft in a polar orbit of either world would allow us to examine the planet's interior, and diverse moons and complex ring systems promise new discoveries like those made by the Cassini mission at Saturn. The current decadal survey recommended starting work on a Uranus mission after a Europa mission was greenlit.

Astrobiology: Following the Europa Clipper mission, a Europa lander would examine the surface for signs of life. A dedicated Enceladus mission could directly sample plume material spewing into space.

Atmospheric probes: Probes at Saturn, Uranus, and Neptune are needed to complete the noble-gas and volatile-species survey started by the Galileo Probe at Jupiter in 1995. A second Jupiter probe would also be helpful since the Galileo Probe entered an anomalously dry location, its measurements of volatiles were inconclusive, and Juno's measurements can benefit from an in-situ validation.

Long-duration surveys of active worlds: We need long-term data on the active phenomena that shape worlds in the outer solar system, including up-close looks at the surfaces of Enceladus, Triton, and Io, the dynamic atmospheres of the giant planets and Titan, and the rings of each of the 4 giant planets. In addition to missions that visit these destinations, a space telescope dedicated to solar system targets would ensure that active worlds like these are observed regularly without large gaps.

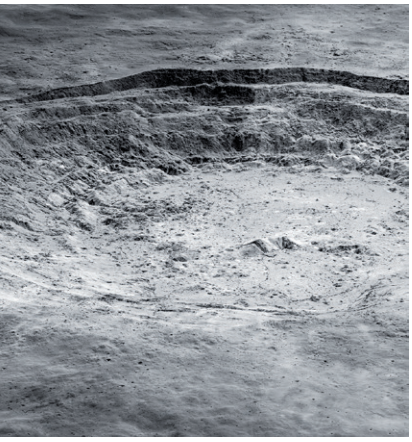
The decadal survey is a truly major undertaking and a good occasion to remind ourselves that even with a diversity of destinations with many mission possibilities, we are all unified under common long-standing goals, and the heart of the survey's task is to recommend the best strategy to answer those fundamental goals. Some of the outer-planet missions will last decades and span multiple generations of scientists, so such strategic planning is also important in shaping the careers of the next generation of scientists. No matter what the recommendations become, the outer planets offer something for everyone, and the decadal survey is sure to illuminate a path toward our next big discoveries.

KUNIO M. SAYANAGI *is an associate professor at the Hampton University Department of Atmospheric and Planetary Sciences.*

ABOVE *Saturn's moon Enceladus hosts jets of water that spray from a subsurface ocean into space, where they could be sampled by a future spacecraft.*

NASA/JPL/SSI/Color composite by Gordan Ugarkovic

Moon



TOP *Aristarchus crater, surrounded by Oceanus Procellarum on the lunar nearside, exposes diverse volcanic materials of unusual composition.*

BOTTOM *This is Shackleton crater at the Moon's south pole; the exact south pole is located at the upper-right corner of this image. The interior is permanently shadowed and is thought to contain water ice.*

FOR THE MOON, our partner in a billions-year-long dance, the 2010s were a decade of profound revelations. Discoveries from our robotic spacecraft and a closer look at soil and rock samples collected by astronauts during the Apollo missions have led lunar scientists to a new understanding of the Moon.

Starting in 2009, NASA launched 4 missions to the Moon: Lunar Reconnaissance Orbiter and its crater-creating partner, LCROSS; GRAIL, which gave us new maps of the Moon's gravity field; and the dust-detecting LADEE. China placed the Chang'e-3 and -4 landers and rovers on the surface, while India launched Chandrayaan-2 into lunar orbit.

We confirmed the existence of water ice in the Moon's permanently shadowed polar regions. We found water locked in Apollo moon rocks in abundances that were surprising given the Moon's violent and fiery origin. Enormous dikes, visible only in gravity data, may have provided pathways to the surface for the floods of lavas that covered much of the nearside. The Moon's volcanism, while mostly ancient, may have continued up to less than 100 million years ago, meaning our small Moon retained enough heat to sustain eruptions through essentially the present day, geologically speaking.

With new discoveries comes the ability to ask new questions or find new ways to think about old ones. Fortunately, the lunar community is ready, armed with a wealth of data and an enthusiastic, vibrant group of scientists. Our high-priority questions for the coming decade include:

What does the Moon's history tell us about the time period for the late heavy bombardment, when the inner solar system was battered with asteroids and comets?

What is the structure and composition of the Moon's interior?

What is the nature and origin of water and other volatiles at the Moon's poles, and what is the history of magmatism during more than 4 billion years of lunar evolution?

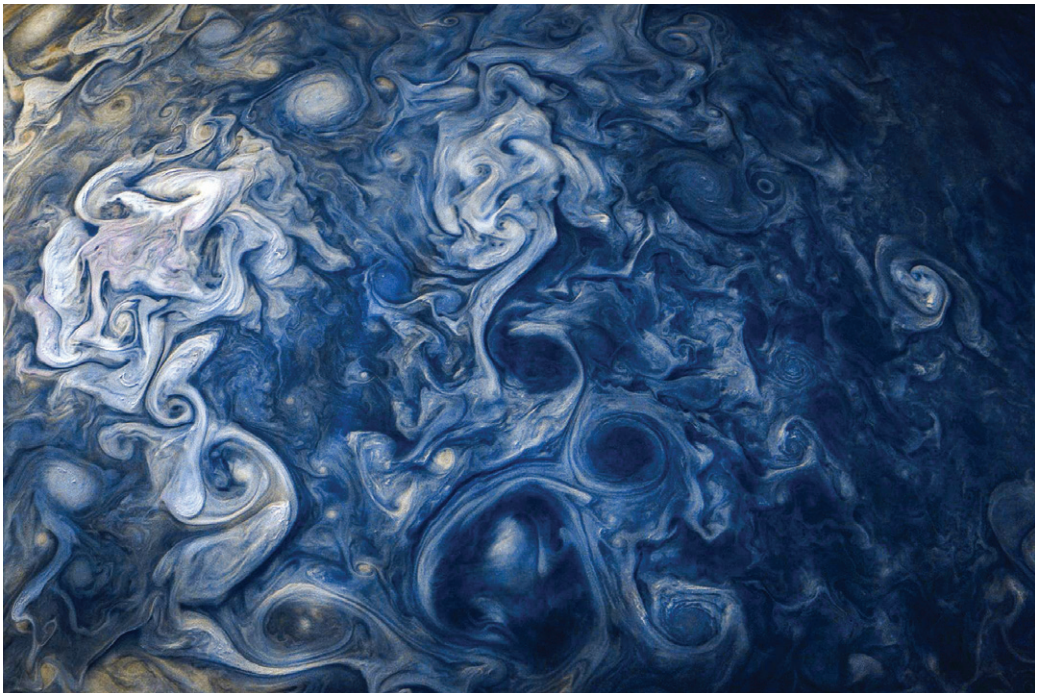
The South Pole-Aitken Basin Sample Return mission, which appeared in both the 2003-to-2012 and 2013-to-2022 decadal surveys, would bring rocks and regolith from an unexplored region of the Moon back to Earth. By dating the formation of the largest basin on the Moon, we would gain vital information to constrain the period of late heavy bombardment–a period when Earth and the Moon were slammed with comets and asteroids, the end of which may coincide with the emergence of life on Earth.

The Lunar Geophysical Network, which appeared in the current decadal survey, would see several landers widely distributed across the lunar surface acquire simultaneous seismic and heat-flow measurements. This network would tell us about the structure of the Moon's mantle and core as well as its thermal state and evolution and inform our understanding of all rocky, differentiated worlds that are separated into distinct layers beneath the surface.

Rovers that could travel long distances and operate through the lunar night or in the extreme cold of permanent shadows would allow us to answer a multitude of key planetary science questions. A rover measuring the composition and abundance of the Moon's water and other volatiles at its poles would provide a window to how and when water was delivered to the Earth-Moon system billions of years in the past. A rover exploring Oceanus Procellarum, the largest dark region you can see on the Moon's nearside from Earth, would give us access to 4 billion years of lunar volcanism and a huge diversity of landforms, compositions, and eruption styles.

BRETT DENEVI *is a planetary geologist at the Johns Hopkins University Applied Physics Laboratory. She is currently serving as the deputy principal investigator for the Lunar Reconnaissance Orbiter camera. Asteroid 9026 is named Denevi in her honor.*

NASA/GSFC/Arizona State University



LEFT *This image of Jupiter's paint-like swirls is among Sasha's favorite images of space. This image was taken by NASA's Juno spacecraft in 2017.*

The Cosmic Perspective

I DON'T THINK it'll come as much of a surprise to anyone how I became interested in space exploration. My dad was the astronomer, educator, and Planetary Society cofounder Carl Sagan. Growing up, understanding our place in the cosmos as revealed by science was a source of deep meaning and thrilling awe, something akin to spirituality. From an early age, my dad, together with my mom, writer/producer Ann Druyan, taught me the importance of knowing our coordinates in space and time—not just the city or town we happen to inhabit, not just the nation or planet, and not just the day or year but in the grandest sense we are able to grasp: our solar system, our galaxy, and our moment on the scale of the entire universe. It was a way of understanding who we are—our identity as humans and as Earthlings in the sometimes-overwhelming enormity.

Each new image from deep space is like a new revelation. Unlike a religious revelation that is perceived by just one person or a few, telescopic images of other worlds, stars, nebulae, and galaxies can be seen by everyone on Earth. We can all have these revelations together. With each one, we glean how much breathtaking beauty there is in the vastness and how much is out there that puts our own existence in perspective. The tinier we realize we are, the more vulnerable we understand ourselves to be and the more precious each and every moment is here on our little world. In this way, I feel we can begin to understand how lucky we really are to have one another, no matter our differences, on this pale blue dot.

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

SASHA SAGAN *is a writer and the daughter of Ann Druyan and Planetary Society cofounder Carl Sagan, who together created the* Cosmos *television series. Her first book,* For Small Creatures Such as We: Rituals for Finding Meaning in Our Unlikely World, *came out in 2019. It's part memoir about growing up with amazing parents and partially an exploration of rituals and celebrations, their histories, and how those of us who see science as the pathway to understanding might create our own. She loves to travel, another kind of exploration.*

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

astronomical art

Peter Thorpe, *Rocket #70*

Rockets have always been at the core of humanity's exploration of the cosmos. Every spacecraft, every astronaut, and every experiment has relied on a rocket to reach outer space. These vehicles were initially designed as missiles and in the 1950s were adapted to launch the first satellites into orbit. Humanity's first excursions into space, carried by powerful rockets, were infused with geopolitical conflict and competition. Over the decades, though, the exploration of space has grown far beyond its bellicose origins. With the help of rockets, we have come to understand our cosmos, our origins within it, and the fact that we are all inhabitants of the same pale blue dot. By exploring further, we may bring ourselves closer together.

Peter Thorpe is an American illustrator and astronomical artist. See more of his rocket artwork at **peterthorpe.net/rockets**.