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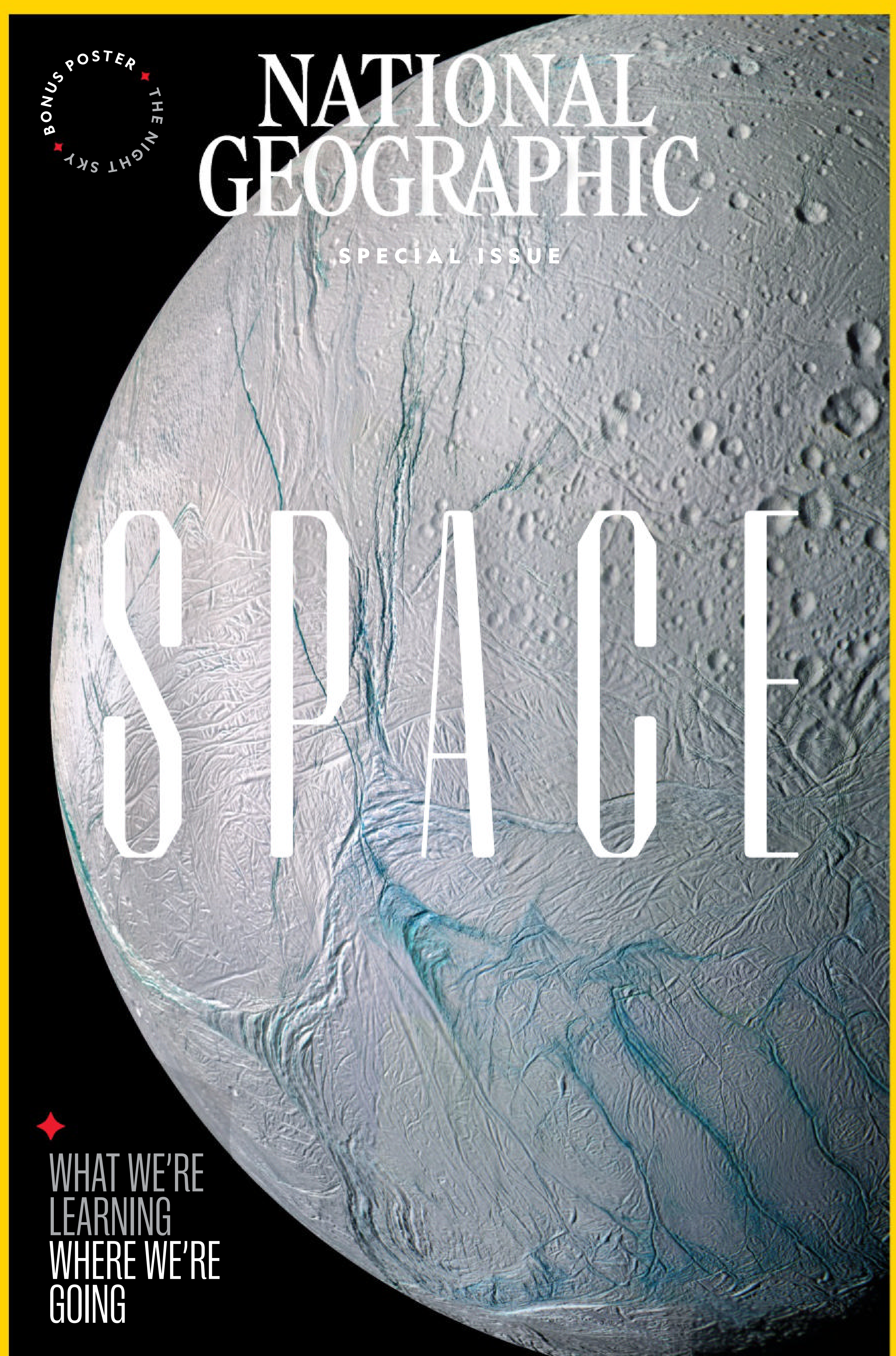


NATIONAL GEOGRAPHIC

SPECIAL ISSUE

BONUS POSTER ✦ THE NIGHT SKY ✦

SPACE

WHAT WE'RE LEARNING
WHERE WE'RE GOING

NATIONAL GEOGRAPHIC

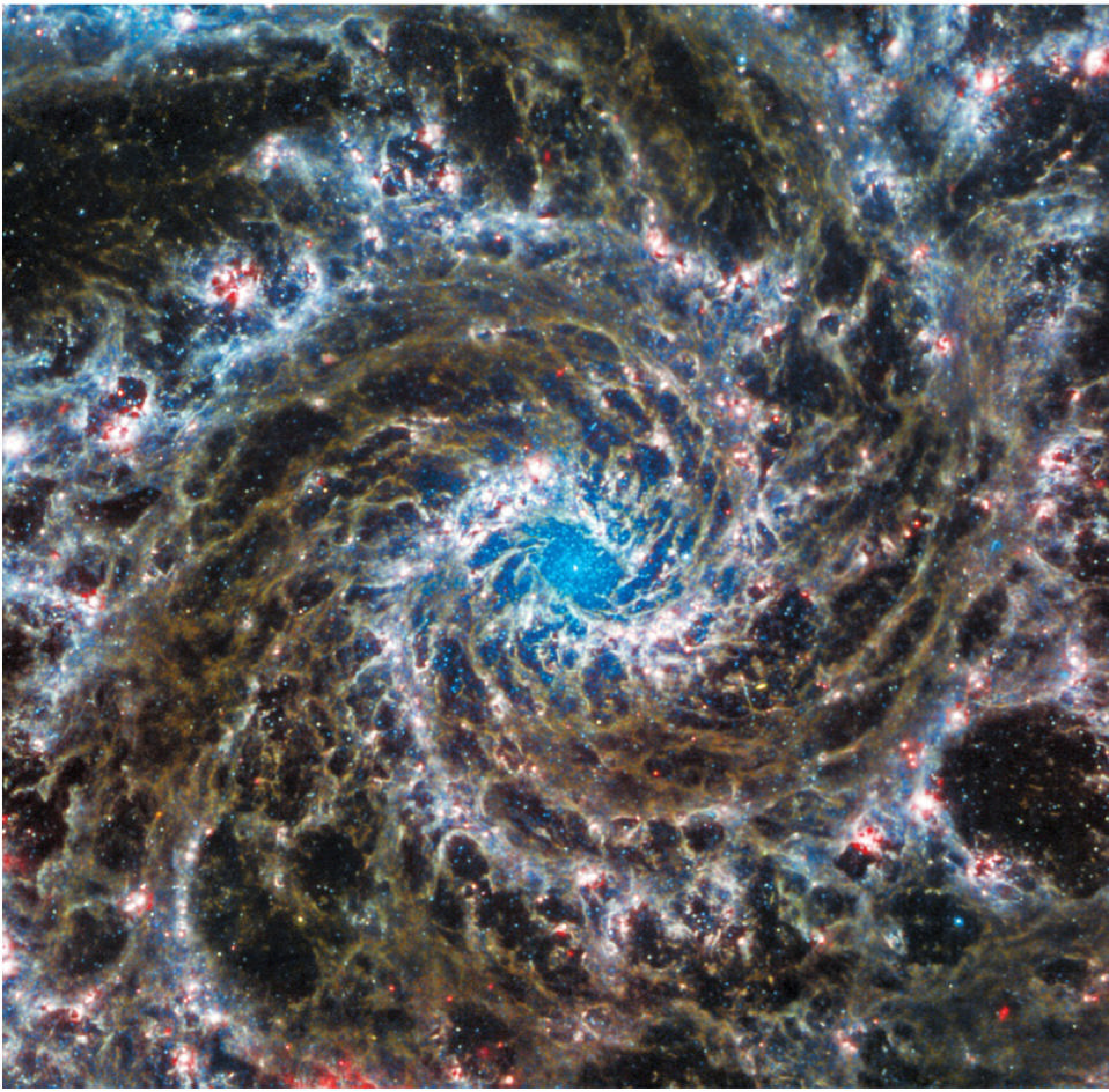
SPACE ✦ ISSUE

CONTENTS

On the Cover
Surface fractures (shown in blue) vent water from the vast interior ocean of Enceladus, Saturn's ice-covered moon, which contains key ingredients for life.

FALSE-COLOR MOSAIC OF 21 IMAGES BY NASA/JPL/SPACE SCIENCE INSTITUTE

NATIONAL GEOGRAPHIC



FEATURES

ABOVE: Gas and dust form the spiral arms of the Phantom galaxy, official name Messier 74. Although the galaxy is 32 million light-years away, the Webb telescope captured it clearly.

PHOTO: ESA/WEBB, NASA & CSA, J. LEE AND THE PHANGS-JWST TEAM

BY **NATHAN LUMP** PHOTOGRAPH BY **DAN WINTERS**

IN A SERIES of articles from the mid-1960s into the early '70s, *National Geographic* covered the findings, the adventures, and the significance of NASA's Apollo missions to the moon. As Editor Gilbert M. Grosvenor wrote in our September 1973 issue, the moon was the "first port of call on man's greatest voyage of discovery." He also noted that the Apollo program's value went far beyond what we were learning about space: Apollo sparked hope that we could, with a similar commitment, find "an answer to the energy crisis, the environmental crisis, and to every other major problem of humanity."

Half a century later, we're in a new era of exploration and discovery in space while facing acute problems on our own planet. And, perhaps fittingly, we are once again setting our sights on the moon. In this issue, we share the first installment from our ongoing partnership with NASA to document the Artemis missions that will land people—women as well as men—on the moon for the first time since Apollo. We also have terrific stories about how the James Webb Space Telescope is shaping our knowledge of the universe, how Earth's extreme environments hold clues to possible life on Jupiter's and Saturn's moons, and much more.

Technology continues to advance our ability to understand the cosmos. Just as in Apollo's day, though, there are some who question spending time and money on that instead of on our planet's urgent problems. But, like my predecessor, I appreciate what bold demonstrations of human ingenuity can do for our collective spirit.

Personally, I'm not hoping we find a new planetary home somewhere out there. I'm hoping that space exploration serves to reinforce how special Earth is and reminds us that, when we put our minds to it, we can beat the odds.

We hope you enjoy the issue.

The Artemis II mission will be the second voyage into space for astronaut Christina Koch, seen here in Building 9 at the Johnson Space Center in Houston. Koch previously set a record for the longest single spaceflight by a woman, with a total of 328 days in space, and participated in the first all-female space walks.

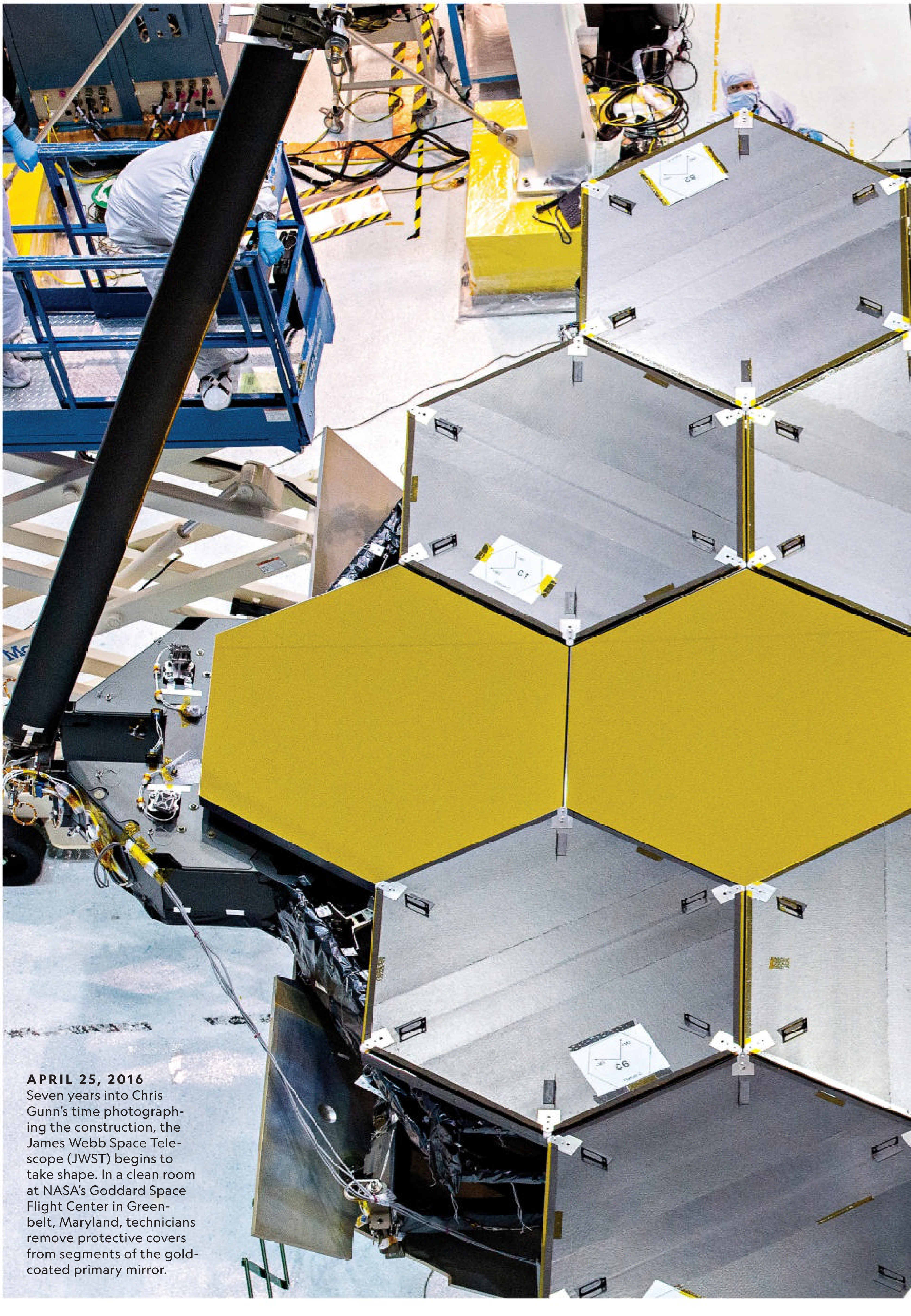
JULY 10, 2014
Engineers at Northrop Grumman in Redondo Beach, California, prepare to unfurl a test version of the five-layer sun shield, designed to keep the new observatory cool.

LOOKING AT THE EARTH FROM EVERY POSSIBLE ANGLE

PHOTOGRAPHS BY **CHRIS GUNN**

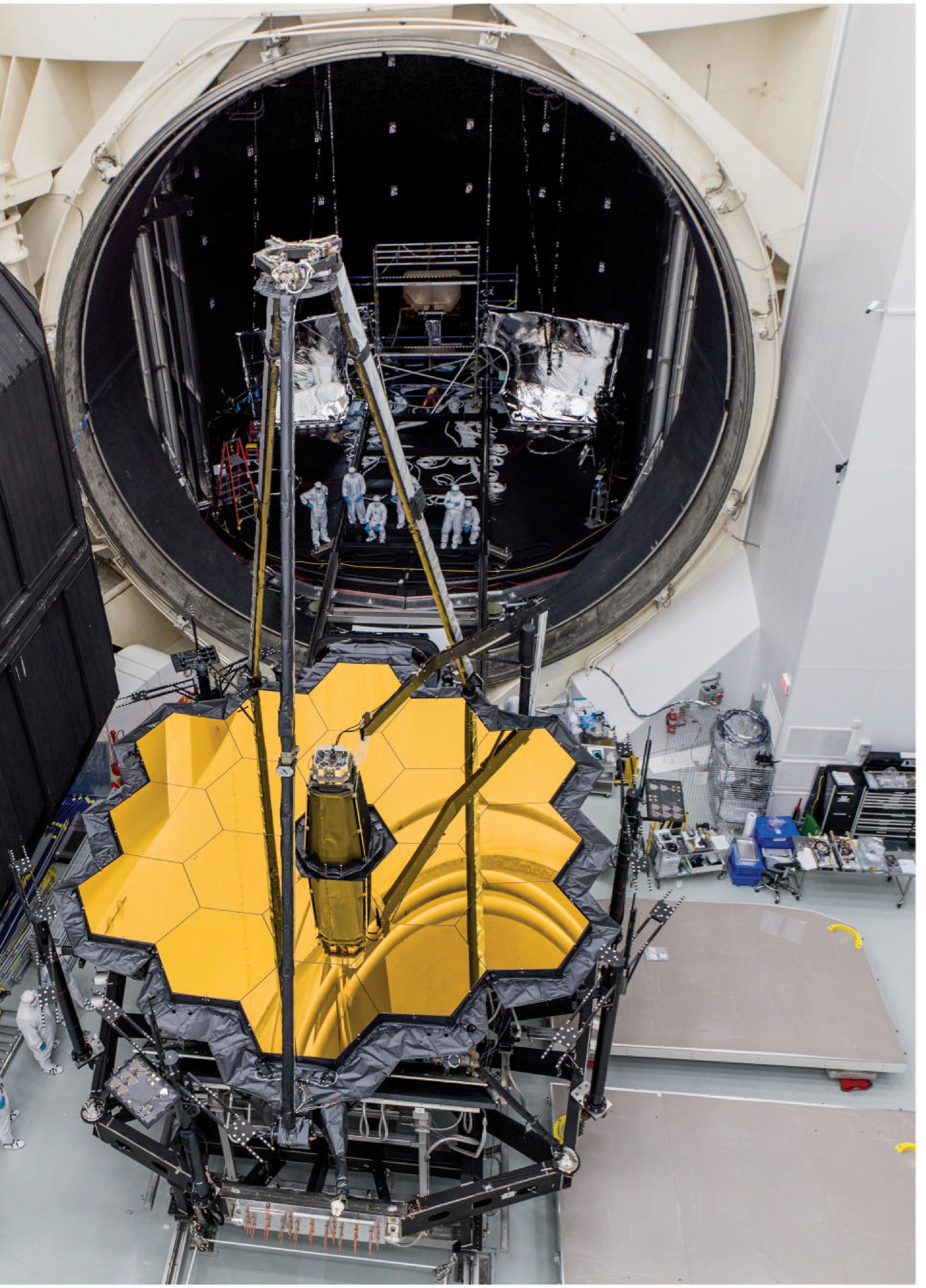
A photographer documents the construction of NASA's James Webb Space Telescope—a project that spanned 12 years.


PROOF
NATIONAL GEOGRAPHIC
VOL. 244 NO. 4
MAKING OF A MASTERPIECE



APRIL 25, 2016
Seven years into Chris Gunn's time photographing the construction, the James Webb Space Telescope (JWST) begins to take shape. In a clean room at NASA's Goddard Space Flight Center in Greenbelt, Maryland, technicians remove protective covers from segments of the gold-coated primary mirror.

DECEMBER 1, 2017
From a lift eight stories high, Gunn captures the JWST as it is moved out of the thermal vacuum chamber where it had undergone cryogenic testing for about a hundred days at NASA's Johnson Space Center in Houston. After the successful test, the workers' excitement was palpable, Gunn says: "That much closer to launch."



THE BACKSTORY

A PHOTOGRAPHER CHRONICLES 'SOMETHING SPECIAL': THE COMPLEX EFFORT THAT BUILT A NEW SPACE OBSERVATORY.

IF YOU SEE ANY photographs of the James Webb Space Telescope being built, it's a good bet that Chris Gunn made them.

In 2009 NASA selected Gunn as the full-time scientific and technical photographer to embed with the engineering team at the Goddard Space Flight Center in Greenbelt, Maryland. He spent 12 years documenting the observatory's construction, from the arrival of the first "chassis" to its launch into space. Did Gunn capture every nut, bolt, and mirror? "In a generic sense, yes, but I'm sure there are some nuts and bolts that I didn't photograph," he replies with a chuckle.

"For me, the magic comes when the big pieces start to get assembled and you can start to call it a telescope," he says. "When some of the more exotic parts, like the mirror, started to show up, you really knew that this was something special. Indeed it was."

According to Gunn, some NASA managers consider the JWST "to be on par with the Apollo missions from the standpoint of it being something that hadn't been done before." The largest instrument of its kind, the observatory is now a million miles from Earth.

When Gunn witnessed the launch of the JWST in Kourou, French Guiana, on December 25, 2021, he felt a mixture of joy, anxiety, and hope. "There weren't any tears, but I was definitely choked up," he says. "I mean, I was speechless. The only other thing I've done for that length of time was stay married and raise my kid, but that's a long time to work on a project. It was very, very rewarding." —KURT MUTCHLER

SEPTEMBER 16, 2021: Technicians watch as the bulky yet fragile JWST is laid on its side for the first time during preparation for shipping to its launch site in Kourou, French Guiana.

ILLUMINATING THE MYSTERIES—AND WONDERS—ALL AROUND US EVERY DAY
NATIONAL GEOGRAPHIC | VOL. 244 NO. 4

Interview With a Rock Star Scientist

BRIAN MAY—CO-FOUNDER OF THE BAND QUEEN, CONSULTANT TO NASA—BLENDS ASTROPHYSICS AND ROCK MUSIC TO CREATE COSMIC HARMONY.

BY **NADIA DRAKE**

A

AS A WORKING-CLASS YOUTH in London, Brian May first built his own telescope. Then he built his own electric guitar. Two days after earning a bachelor's degree in physics, he was onstage with his band, opening for Pink Floyd. It was 1968.

Today May, 76, is known as one of the greatest guitarists in rock history. This month he's back on the road with the latest incarnation of Queen, the legendary band he co-founded with Roger Taylor and the late Freddie Mercury. Also this month: publication day for May's latest book, an atlas of the asteroid Bennu, featuring May's stereoscopic photography.

I met May in 2015 when he was working with NASA's New Horizons mission. He's now a friend; we share a fascination with the stars (he earned a Ph.D. in astrophysics in 2007), as well as a deep and abiding love of animals (he's an activist for animal welfare). I've been to more than a few of his concerts, often running into others backstage who

'I BASICALLY TRAWL THE DATA FROM EVERY SPACE MISSION WITH A COLLEAGUE OF MINE IN ITALY, AND WE FIND DATA TO MAKE 3D PICTURES'—INCLUDING THE FIRST 3D IMAGE OF PLUTO.

are both Queen fans and space nerds (including a NASA official who once showed up with a copy of May's doctoral thesis).

Even a special Space Issue lacks the space for all the space interests Brian and I discussed—so this interview has been edited and condensed for clarity.

NADIA DRAKE: I'm betting that many people who know you as a musician have no idea you're Dr. May—that you earned a Ph.D. studying zodiacal dust, a cloud of rocky grains that fills interplanetary space in our solar system. Why did you choose that topic?

BRIAN MAY: I knew you were going to ask. I was doing my graduate work in infrared astronomy at Imperial College in the 1970s, and one of the professors had been doing spectroscopic studies of zodiacal dust. It had come to a standstill because most of the equipment didn't work anymore. So they said, Would you like to take this over? Once I looked at it, I thought, This is fascinating. It was something few people had done.

What did you want to know about the dust?

Very simply, where it comes from and where it's going. Everybody else was studying the light reflected by the zodiacal cloud, but we were looking at how that cloud moved, by tracking an absorption line in the sun's spectrum, which is Doppler shifted because of the motions of the dust relative to Earth. We thought that a component of the dust ought to be the debris shed by comets, and a certain amount of it might be from asteroids. I had this crazy idea that a small component might be interstellar because the solar system is moving through space. But I was kind of dismissed as a crank, and my supervisor said, "Don't put that in the thesis, because everyone's gonna laugh at you."

But you were right?

The funny thing is, I thought I could see an interstellar element that was flowing through the solar system. But I never published that part of the data—after all, there were big error bars on my measurements. Looking back on it, I kind of wish I had because we now know that interstellar stuff is coming through all the time. Notably 'Oumuamua, the interstellar object that zipped through in 2017. Now there's a big lump of dust that sure didn't come from inside our solar system—and there's no knowing what we're going to encounter next, is there?

You've moved on from dust and are now working a lot with asteroids and other small bodies in the solar system. Where does that interest come from?

That's a passion, really. It connects to my interest in stereoscopic photography. All of the objects visited by uncrewed spacecraft lend themselves to 3D stereo images—for those, you need two different views of an object to make a stereo pair. And it is a

very basic fact that everything in the solar system rotates. Which is fortunate, because rotation gives you the pair of views from slightly different angles that you need. I basically trawl the data from every space mission with a colleague of mine in Italy, and we find data to make 3D pictures.

We started to get friendly with some of the teams from NASA, the European Space Agency, and the Japan Aerospace Exploration Agency, and once they saw what we were doing, the word spread to other missions. Our first great opportunity was New Horizons, which made history with its flyby of Pluto.

Guitarist Brian May is such a fan of blending art and science that many of Queen's concerts feature space-themed special effects—for example, to make it look as if he's riding an asteroid among planets. In March 2023, Britain's King Charles knighted May to honor his service to music and charity.

PHOTOS: STUFISH ENTERTAINMENT ARCHITECTS (CONCERT); DENIS PELLERIN (PORTRAIT)

I remember running into you during the flyby in 2015. Such a fun time!
Watching that data come in was one of the greatest experiences of my life. We saw what Pluto looked like for the first time, and we got two different views: one just before the flyby and one that came in as the spacecraft was going by. I put a couple of those together and made the first 3D picture of Pluto.

I've done a lot of good stuff in my life—I've been very lucky—but that was one of the most thrilling moments I can remember: to suddenly see Pluto, which in my childhood was a white dot, in all its glorious detail in three dimensions. It was just a thrill beyond measure.

Now you're working with the OSIRIS-REx team, which sent a spacecraft to the asteroid Bennu.
That mission proved that stereo imagery isn't just for fun; it can be useful too. Stereo can give you such an instinctive feel for terrain that it can help you choose a landing site. This was crucial at Bennu: The mission was to take a sample of the asteroid, so we were put to work making stereo pictures of every potential landing site. I think there were 24 of them. And we did it—we helped to choose the final site, and the samples were safely gathered.

What will we learn by studying this asteroid?
Asteroids are like time capsules from the early solar system. We can learn a lot about what this place was like 4.5 billion years ago by studying primordial material from Bennu.

They're also a whole lot more important than people realized until recently. They've long been recognized as potential hazards. They're also possible sources of minerals—people are talking about mining them. But what's become more and more apparent is the role that asteroids must have played in setting up the Earth for us to be on it, for the biosphere to be here, by delivering water and organic molecules.

You suddenly realize that asteroids, as well as being the harbingers of death and destruction, must have played a crucial role in the creation of life on Earth. Then you develop a lot more respect for them.

What are the unanswered questions in astronomy, astrophysics, or planetary science that are the most compelling to you now?
A lot of things. I'm excited about this multiverse idea. It's funny how these concepts start off as something which is crazy, and then everybody is talking about them as a very normal thing.

One of my favorite memories from your concerts is when special effects had you standing on an asteroid, surrounded by planets, riffing on Dvořák's *New World Symphony* [previous page].
I'm planning a new variation of that for the coming U.S. tour. I will be going further down that road. I love it. And those little planetoids around me are real objects; they're not projections.

You're at the center of your own planetary system! That's typical of your approach to art and science: You mash up these fields. Why? And are they really so different from one another?
This is central to my life and my beliefs. I was told that I couldn't do art and science as I progressed through school. And I was very resentful about that because I love them both. I feel like the rest of my life has been trying to prove them wrong. More and more and more, I've discovered that artistic thinking and scientific thinking are just different parts of the same thing. It's a continuum. They're inextricably linked. You have to have both sides to function at your full potential.

Creativity seems like another shared element there. To succeed in both fields, you must be willing to break the rules, to test new ideas, and ultimately to help people see the world in a different way.
Yeah, that's right. I actually don't think I had that talent as a Ph.D. student, or maybe I didn't have enough confidence to apply it. When Queen started to move, when it looked like we could actually go out as a rock group, I was quite relieved to give up the Ph.D. I'd already written it up, I'd submitted it to my supervisor, and he'd rejected it and told me I had to go away and do more research.

I always thought science benefited from me going off and playing music for 30 years; I hope it's also benefited from me coming back.

Are you excited about going back on tour?
I'm excited, but I'm also nervous. It's a long time to be away from home, and these days I don't find that so easy. But apart from that, it ought to be good to get out and do what we do one more time, right? ▫

Flyby Music

Brian May not only collaborated with NASA on its New Horizons mission to Pluto but also created a rock anthem and video to honor the spacecraft (right), which in 2019 logged the most distant flyby in history—and is still going. Watch May's video at ***natgeo.com/NewHorizons.***

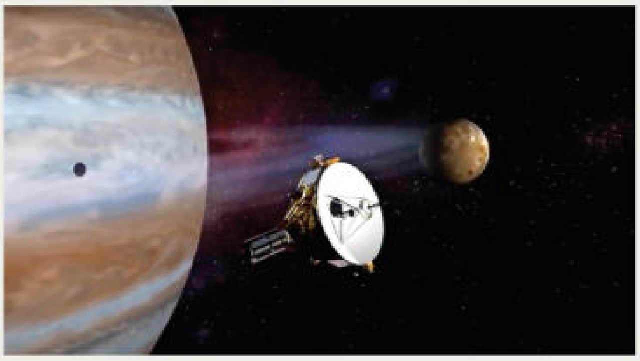


PHOTO: BRIAN MAY, NEW HORIZONS (ULTIMA THULE MIX)

DESIGNING WOMAN

Sabrina Thompson is on a mission to empower women, starting with a flight suit that fits.

SINCE 1963, WHEN Soviet cosmonaut Valentina Tereshkova became the first woman to slip the bonds of Earth, dozens have followed in her contrails. Despite this, flight suits haven't exactly been designed with women in mind. Sabrina Thompson, founder of the brand Girl in Space Club and a NASA engineer, has created a suit for female fliers that, she says, is not only functional but also fashionable.

"I listened to the women who would wear it," Thompson says, "and I'm still listening." Her suit, meant for a variety of environments, including the International Space Station, is "a blend of STEM, art, and fashion." Thompson is also developing a pressurized version that could be worn during launch and reentry. She hopes to start a movement that results in women exploring space in chic comfort—and inspires them to create what they need to succeed, whether on Earth or off. –ANNIE ROTH

Thompson (right) has incorporated these elements into her design.

1. Flattering custom fit
Each suit can be tailored to accommodate various sizes and shapes. The form-hugging garment follows body contours while allowing the wearer to maintain a full range of motion.

2. Adjustable belt
The user can tighten or loosen the waistline according to her preference. The belt, which has a quick-release buckle, also prevents any excess fabric from hanging loose and getting caught on equipment.

3. Convenience flap
With this patent-pending feature, the back of the suit can unzip and snap onto the front, allowing its wearer to take bathroom breaks without having to remove the entire suit.

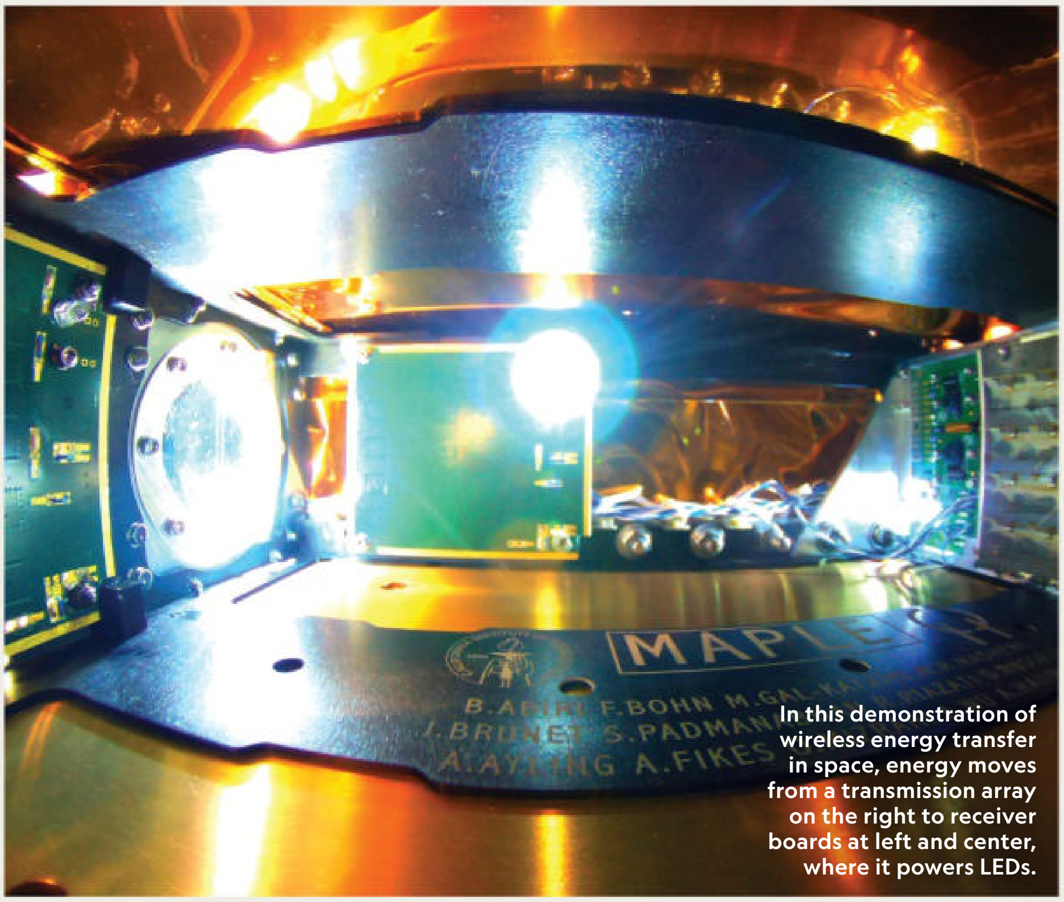
4. A bit of flair
Patches and accent fabrics on areas such as the chest and shoulder "add a touch of elegance and style to the women's flight suit" without sacrificing functionality, Thompson says.

PHOTO: REBECCA HALE, NGM STAFF

DISPATCHES FROM THE FRONT LINES OF SCIENCE AND INNOVATION

Farming produce, darkly

On future Mars missions, NASA foresees crews growing food—a challenge, as the red planet receives less than half of Earth's sunlight. So scientists are developing a plant that will thrive in little to no light, fed instead by a carbon-rich solution that astronauts can generate. —ANNIE ROTH



In this demonstration of wireless energy transfer in space, energy moves from a transmission array on the right to receiver boards at left and center, where it powers LEDs.

SUSTAINABLE ENERGY

SOLAR POWER FROM SPACE

SCIENTISTS ARE HONING TOOLS THAT WOULD SEND THE SUN'S ENERGY TO EARTH AS RADIO SIGNALS.

Though it was fantasy just a few decades ago, space-based solar power may soon be reality—and a renewable energy breakthrough: accessible anytime, unlike ground-based solar panels limited by darkness, and available anywhere on Earth, even if infrastructure is lacking.

How would it work? Enormous space-based structures would support photovoltaic panels that collect sunlight and convert it into radio signals for transmission to Earth. This type of space mission is "one of the most complex engineering problems that we have in front of us," says Mamatha Maheshwarappa, a payload systems lead at the UK Space Agency, which is helping fund project research and development. The mission also will be pricey, projected to cost tens of billions of dollars.

And at Caltech, researchers recently reported significant progress with their Space Solar Power Demonstrator. The craft has been in orbit since January 2023, testing materials and electronics, and has successfully transmitted wireless energy in space for the first time. "This is a step in a long journey," says the Caltech team's co-director, Ali Hajimiri. And like any good story, he says, "it will probably have many turns and twists." —LIZ KRUESI

TECHNOLOGY

Star creation, in miniature

Imagine holding the cosmos in your hand. Drawing on knowledge of the physics occurring in stellar nurseries—dynamic regions of space where dense dust and gas clouds give rise to stars—astronomers Nia Imara (below) and John C. Forbes and 3D-printing expert James C. Weaver made stellar nursery simulations. The softball-size spheres let the earthbound glimpse the complex patterns that make these parts of space so special. —AR

PHOTOS (FROM TOP): ANNIE SHELTON; CALTECH MAPLE TEAM; REFA ONE

A SOARING LIFE'S LEGACY

ARTIFACTS FROM SALLY RIDE'S CAREER AND PERSONAL LIFE BEAR WITNESS TO HER ROLE AS A PATHFINDER—IN SPACE AND BEYOND.

BY **ERIN BLAKEMORE**
PHOTOGRAPHS BY **MACKENZIE CALLE**

PHOTO (OPPOSITE): COURTESY NASA, AS PHOTOGRAPHED BY MACKENZIE CALLE

WHEN PIONEERING FEMALE astronaut Sally Ride died of pancreatic cancer in 2012, a single line in her official obituary disclosed what a lifetime of press coverage had not: her 27-year partnership with another woman, Tam O'Shaughnessy.

The acknowledgment that Ride was a member of the LGBTQ community added another first to her lengthy list of historic accomplishments. She was not just the first American woman to go to space—more than 40 years ago, on June 18, 1983—but the first known queer astronaut. The revelation added a poignant, personal dimension to Ride's public image as the intense and brilliant physicist, the loyal crew member, the passionate science education advocate.

It also led some to question what Ride's life might have been like in a less homophobic, sexist world.

Though Ride and O'Shaughnessy were open with their friends and family, they hid their relationship in public—especially after co-founding their science education company, Sally Ride Science, because they feared blowback from their corporate sponsors.

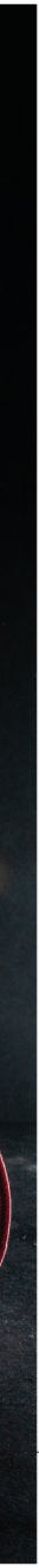
Only after Ride's death did the public learn the true nature of the partnership, as the couple had intended. In November 2013, O'Shaughnessy accepted the Presidential Medal of Freedom in Ride's honor.

Many of the astronaut's most prized possessions, from her personal telescope and academic papers to her NASA uniform, are now housed at the Smithsonian's National Air and Space Museum. O'Shaughnessy, who entrusted the artifacts to the Smithsonian, gave photographer Mackenzie Calle special permission to photograph them. Calle has spent years documenting what it means to be an LGBTQ astronaut through her project, the Gay Space Agency.

Among the artifacts is the in-flight suit Ride wore on her first trip to space. Her assignment to NASA's STS-7 space shuttle mission came with a heaping dose of sexism: After the agency announced she'd be its first female astronaut, Ride faced interviewers' intrusive questions about her looks, emotional temperament, reproductive organs, and family plans.

NASA engineers even created a spaceflight-ready makeup kit for her journey. Ride didn't use it, and reporters often commented on her fresh-faced appearance. Despite intense interest about her gender—and the modifications NASA made to its spacecraft to accommodate female astronauts—Ride attempted to keep the focus on space exploration.

Ride's career interests didn't start, or end, in space: If she hadn't been an astronaut, she might have had a professional tennis career. Though she briefly pursued that possibility, her love of science pushed her toward the space program instead.



Memorabilia that Calle photographed include an image of O'Shaughnessy and Ride during a trip to Australia in 2004, standing by the Sydney Harbour Bridge. The two met as junior tennis competitors, but it took years for their friendship to blossom into love.

Ride smiles in this photo from June 1983 aboard the *Challenger* during a six-day mission that covered 2.5 million miles.

She earned a doctorate in physics, then was one of six women selected for NASA's first class to include female astronauts. After training, she helped the agency develop the space shuttle's robotic arm and also served as capcom—NASA's capsule communicator, who maintains contact from Earth with in-flight astronauts—for the shuttle's second and third flights, in 1981 and 1982.

Then it was her turn. Ride completed two spaceflights; on her second mission, in 1984, the crew included Kathryn D. Sullivan—the first time two women had flown in space simultaneously.

Once out of orbit, Ride made more history. She was the only person on the investigating committees for both space shuttle losses, *Challenger* in 1986 and *Columbia* in 2003. Critical of what came to be called the "faster, better, cheaper" culture of NASA, Ride pushed the agency to make spaceflight safer.

She also steered a comprehensive 1987 planning document—now called the Ride Report—in which she underscored the importance of observing Earth from space, urged NASA to explore more planets, and considered the logistics of human outposts on Mars.

After NASA, Ride focused on science education, becoming a physics professor and developing Sally Ride Science with O'Shaughnessy, now its executive director. The organization publishes books promoting science, technology, and math literacy; operates academies for school-age children; and provides enrichment for educators. It all helps keep Ride's memory—and her inquisitive, daring scientific spirit—alive for the boundary breakers of tomorrow.

Spaceflight enthusiasts gather for the May 2010 launch of the space shuttle *Atlantis* from Florida's Kennedy Space Center.

GAWKING AT ROCKETS

FROM COAST TO COAST, LIFTOFF FANS IN THE U.S. ARE MAKING PILGRIMAGES TO A HISTORIC NUMBER OF NEW ROCKET LAUNCHES.

BY **JOE PAPPALARDO**

"YOU'RE HERE FOR THE LAUNCH?" Ted Ebbers asked me the night of April 19, 2023, when we met on the beach of South Padre Island, Texas. The answer was obvious: We both were killing time before the next day's scheduled flight of the world's most powerful rocket. A recently retired Canadian federal employee, Ebbers, 58, drove from his home in Toronto to SpaceX's spaceport in Boca Chica to watch his first rocket launch. He made the 1,900-mile trip alone, sleeping overnight at rest stops inside his Tesla Model Y.

At dawn, Ebbers and I were among the thousands who had gathered to see the first test flight of the 33-engine Super Heavy booster as it carried its Starship upper stage, built by SpaceX to deliver payload and passengers to the moon and Mars. The crowd at Isla Blanca Park, on the island's southern tip with the best view of the launchpad, was festive and diverse: college students in "Occupy Mars" T-shirts, snowbirds in Hawaiian shirts.

It's the best time in U.S. history for the public to watch a space launch. There's a steady stream of rockets rising from spaceports in Florida, California, and Virginia, and at each you'll find gawkers.

They're enjoying firsthand what might be called a golden age of American spaceflight. During the George W. Bush administration, NASA started to shift from designing rockets and spacecraft to renting

PHOTO: LSP1982/ISTOCK UNRELEASED

rides in ones created by private companies. This commercialization trend gained speed under the Obama, Trump, and Biden administrations.

Ebbers watched his first launch as dozens of engines on Starship's booster ignited at 8:33 a.m. on April 20. "We saw the rocket beginning to lift," he says. But the booster exhaust blasted huge chunks of concrete from the launchpad, suspected of damaging some engines (and three others failed to ignite at liftoff). The 394-foot-tall rocket staggered through the sky as it climbed above 120,000 feet. After nearly four minutes of flight, Starship and its booster self-destructed, never even having had the chance to separate stages.

"It didn't matter," Ebbers said of the untimely end. "The spacecraft flew, and we all got to see it." He may be a first-timer, but no launch tourist could state their creed any better. □

WHAT TO KNOW

ROCKET LAUNCH TOURISM

WALLOPS ISLAND, VA

ROCKETS BOUND FOR THE SPACE STATION

Watching 139-foot-tall Antares rockets rise from the **Mid-Atlantic Regional Spaceport** (yes, MARS) to bring cargo to the International Space Station has become a periodic bonus of beach vacations here. This spaceport is near quaint Chincoteague Island, known for its national seashore, local saltwater taffy, and island-hopping wild horses.

'WE SAW THE ROCKET BEGINNING TO LIFT. THE NOISE SEEMED TO REVERBERATE THROUGH MY WHOLE BODY. BUT THE CHEERS WERE SO LOUD, IT COULD BARELY BE HEARD.'

—TED EBBERS, SPACE-LAUNCH TOURIST

LAUNCH SITES THAT SELL TICKETS CAN RUN OUT, SO PLAN A BACKUP.

Research and scout alternative viewing locations before launch day; be sure they're open to the public, and arrive early with all the water, sunscreen, and snacks you'll need.

100K

VISITORS

That's the number of people who thronged to the area around Florida's **Kennedy Space Center** last year for the launch of an Orion capsule that circled the moon—with no passengers on board. KSC's big events will be the moon-bound Artemis crew launches; the first is scheduled for November 2024.

BEST FOR SEASONED ROCKET CHASERS

At **Vandenberg Space Force Base,** in California, Space Launch Delta 30 (logo above) manages operations for United Launch Alliance send-offs of secret government payloads, Air Force intercontinental ballistic missile tests, and SpaceX commercial flights.

Launch site most likely to experience a scrub

Compared with other spaceports, there's a higher chance of a scrub—a launch cancellation due to weather or technical glitches—at SpaceX's **Starbase** in Boca Chica, Texas. Its purpose is the construction and testing of new hardware. The trial and error brings uncertainties. Prudent space-launch tourists pad their itineraries to account for scrubs. Plan to be away for extra days, and fill downtime with activities that are flexible enough to shift dates.

PHOTOS: UNITED STATES SPACE FORCE (LOGO); DAN WINTERS (LAUNCH). NGM MAPS

Welcome to the Cosmic Odyssey

WHEN TODAY'S EXPLORERS LOOK TO THE HEAVENS, THEY BECOME PART OF 'A THRILLING, HUMBLING, AND THOROUGHLY ENTERTAINING JOURNEY OF DISCOVERY.'

BY **NEIL DEGRASSE TYSON** AND **LINDSEY NYX WALKER**

ONCE UPON A TIME, before humans understood what lay above the clouds, the realm of sky and stars was inhabited only by gods and explained only by myths and fables. But a series of discoveries, intermingled with fits and starts, wrong ways and dead ends, ultimately shattered those primal beliefs, empowering humankind with the knowledge to unveil strange and humbling truths.

The odyssey of cosmic discovery had begun—and it has continued on ever since. Slowly but surely, a new universe emerged—one roiling with molecules, lurking with monstrous black holes, snaking with voids and galaxies of every size and shape, and hinting at untold mysteries.

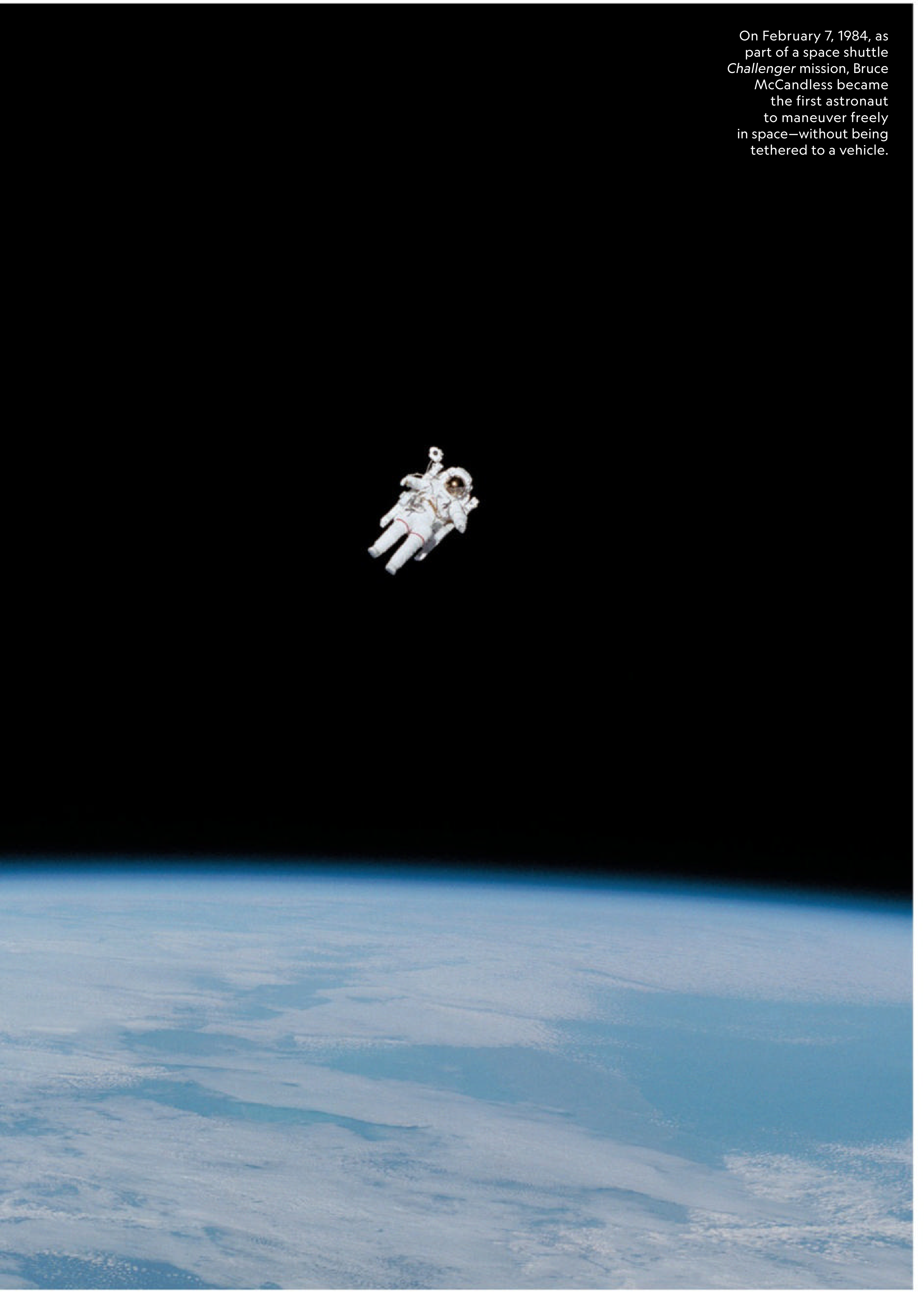
What empowered humans to escape our home, physically and intellectually, and soar into the unknown? What insights, what courage, what technological failures and successes carried us to the knowledge we have today? And what mind-blowing realizations at the edge of our understanding provide glimpses of a vast cosmos yet to be explored?

Vastness, emptiness, darkness, coldness: concepts ill fathomed by a comfortably warm-bodied, recently evolved, carbonaceous creature in a suburban solar neighborhood of the Milky Way galaxy. If you did not already know that Earth orbits the sun, and not the other way around, you would have a hard time discovering that truth for yourself. If you did not know our solar system includes eight planets, hundreds of thousands of asteroids, and millions of comets, you might understandably assume that only Earth and the five planets visible to the unaided eye make up our little corner of the cosmos. To reach these milestones of knowledge, we had to leave the nest.

The force that keeps Earth whole, that tethers our moon to Earth and Earth to our sun, has also kept humans stuck beneath the clouds for nearly all our existence. We cannot easily escape Earth's gravity, which may be why the Wright brothers' first powered flight, in 1903, and the Apollo 11 moon landing, in 1969, appear near the top of everyone's list of the greatest human achievements. Since then, thousands of satellites, hundreds of space probes, rovers, and even a helicopter have launched from Earth, turning our solar system into an explorer's backyard.

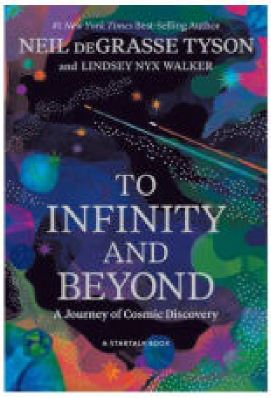
And that backyard continues to expand. In 2012 the Voyager 1 space probe went interstellar, escaping our solar system entirely—but not before transforming the mysterious planets and their moons into worlds of wonder. Voyager's final mission is not done: The tiny craft carries a golden record, an audio recording of songs and sounds of Earth and its species, bidding hello to anyone or anything that might intercept our greeting. Voyager carries forward the unending quest passed down from the first humans who wondered what more awaits our outstretched hands and upturned eyes.

Beginning in 2022, the James Webb Space Telescope extends the odyssey ever outward, sending us images of the most ancient light ever seen and



On February 7, 1984, as part of a space shuttle *Challenger* mission, Bruce McCandless became the first astronaut to maneuver freely in space—without being tethered to a vehicle.

PHOTO: NASA



Tyson and Walker drew this essay from *To Infinity and Beyond: A Journey of Cosmic Discovery,* available where books are sold.

reminding us just how expansive our universe really is. Webb's First Deep Field image unveiled thousands of faint and distant galaxies, including several that formed 13.7 billion years ago, bringing us as close to the big bang as we've ever been able to reach.

Try to imagine explaining that composite image to Newton or Galileo, whose radical new understanding of the universe upended all Christendom and shook the worlds of knowledge and belief. Imagine telling them that we are but one of trillions of planets in a universe with no tangible end. Imagine sharing with them how quantum physics and general relativity hint that not one, but countless, universes may exist beyond our own.

Welcome to the cosmic odyssey—a thrilling, humbling, and thoroughly entertaining journey of discovery through space-time to infinity and beyond.

Astrophysicist and best-selling author **Neil deGrasse Tyson** is a recipient of National Geographic's highest honor, the Hubbard Medal, recognizing lifetime achievement in research, discovery, and exploration. **Lindsey Nyx Walker,** senior producer and head writer of the acclaimed *StarTalk* podcast that Tyson hosts, is his co-author on the new National Geographic book *To Infinity and Beyond.*

When Innovation Is Extraterrestrial

THESE NATIONAL GEOGRAPHIC EXPLORERS ARE LOOKING INTO THE LIMITLESS FUTURE OF SPACE.

SAMANTHA CRISTOFORETTI

Astronaut

"Humanity's outpost in space"—that's what Samantha Cristoforetti calls the International Space Station. It's her outpost, for sure. Across two missions since 2014, Cristoforetti has spent more than a year on the ISS. An astronaut with the European Space Agency and a former fighter pilot in the Italian Air Force, she broke barriers as the first European woman to conduct a space walk and the first to serve as ISS commander. Now safely back on Earth, Cristoforetti is working on an initiative called the Human Inspirator, which aims to build excitement among her fellow Europeans for future spaceflights. If her past work is any indication, she'll likely find an audience: Her videos from space have been viewed millions of times on TikTok.

MORIBA JAH

Space environmentalist

From his base at the University of Texas at Austin, Moriba Jah talks a lot about space trash: the tens of millions of objects now orbiting Earth, most not functioning but still taking up, well, space. This debris threatens communications, financial systems, space travel—and the sunlight it reflects toward Earth interferes with astronomers' observations, limiting "our ability to push our scientific frontiers," Jah says. This year, he was awarded a National Geographic grant to develop Glint Evader, a data-based online application that will help astronomers predict and avoid the disruptive reflections.

BETHANY EHLMANN

Planetary geologist

Water in the solar system: That's what Bethany Ehlmann is hunting. For more than a decade, this professor of planetary science at Caltech has played a key role in research that the rovers Curiosity and Perseverance are conducting on Mars to learn the red planet's environmental history. Lately, Ehlmann's focus has shifted closer: She's preparing for the upcoming launch of the Lunar Trailblazer mission to map forms of water on the moon's surface. Now is "a new era of lunar science and exploration," she says. "It's going to be a really exciting decade."

PHOTOS: ESA/NASA, CC BY-SA 3.0 IGO (CRISTOFORETTI); MARK THIESSEN (JAH); LANCE HAYASHIDA, CALTECH (EHLMANN)

A NEW ERA OF DISCOVERY

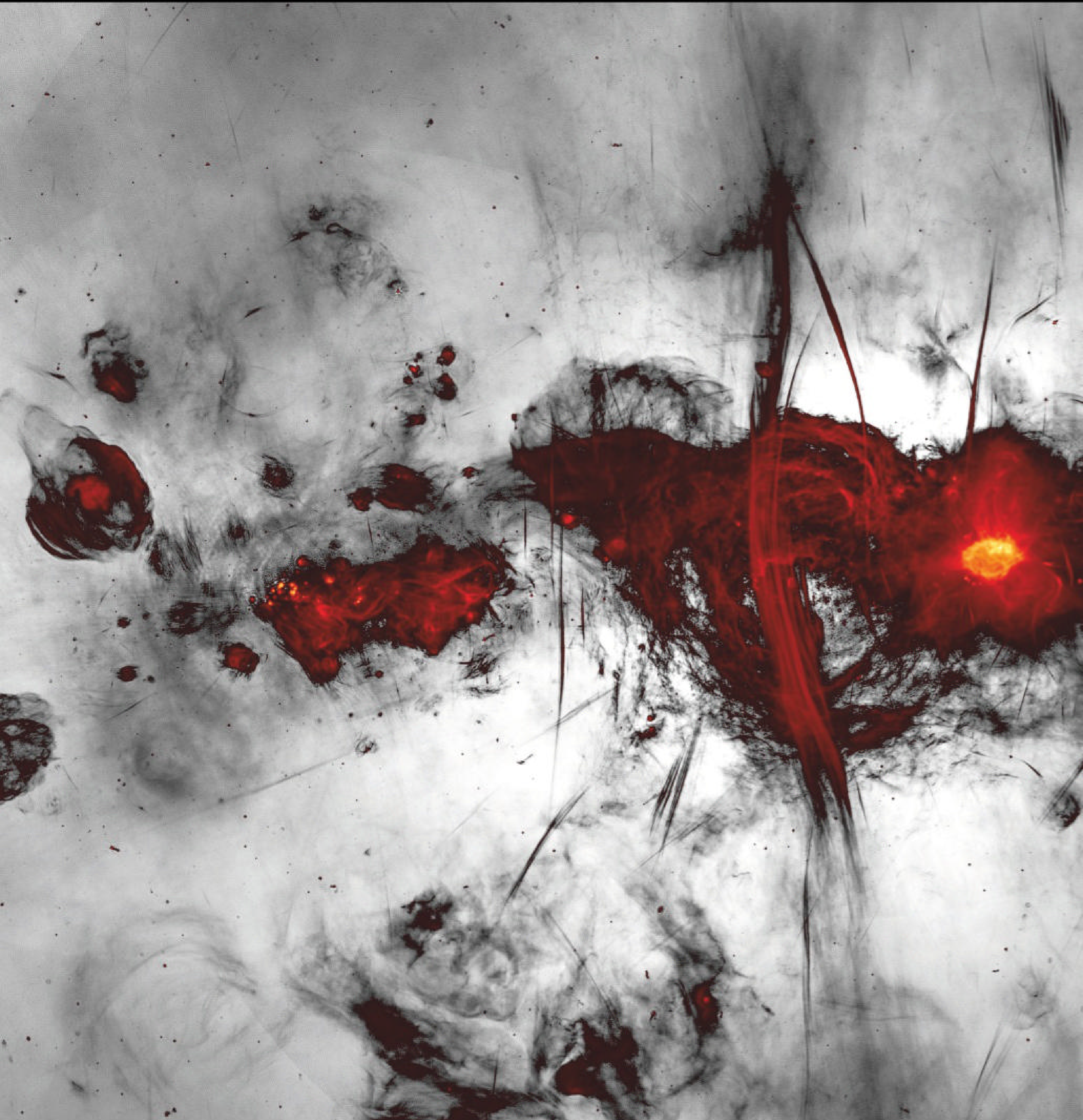
SPAC

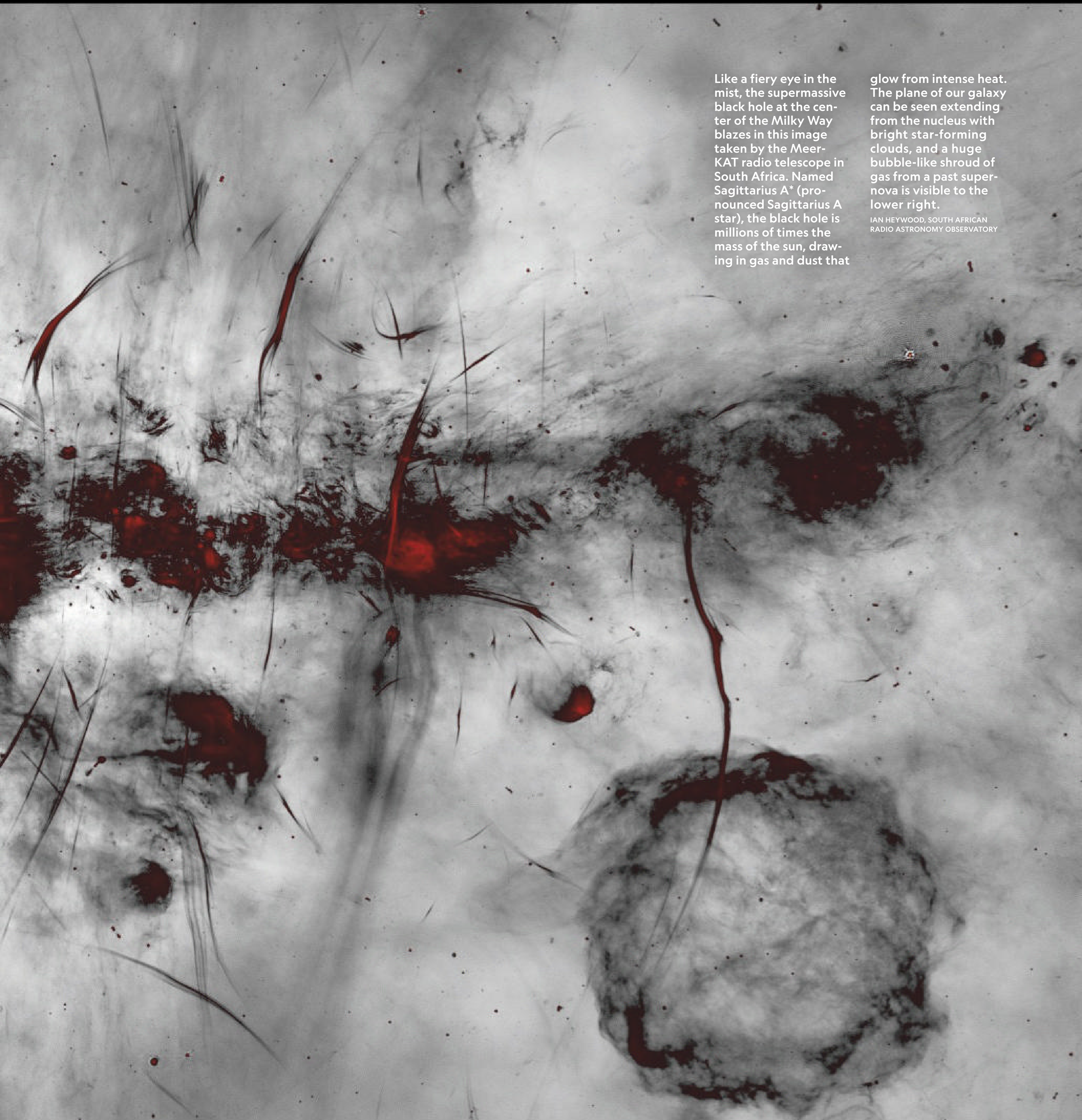
The James Webb Space Telescope penetrated the Tarantula Nebula's clouds to capture thousands of stars, including never-before-seen young ones enveloped in cosmic dust.

NASA, ESA, CSA, STSCI, WEBB ERO PRODUCTION TEAM

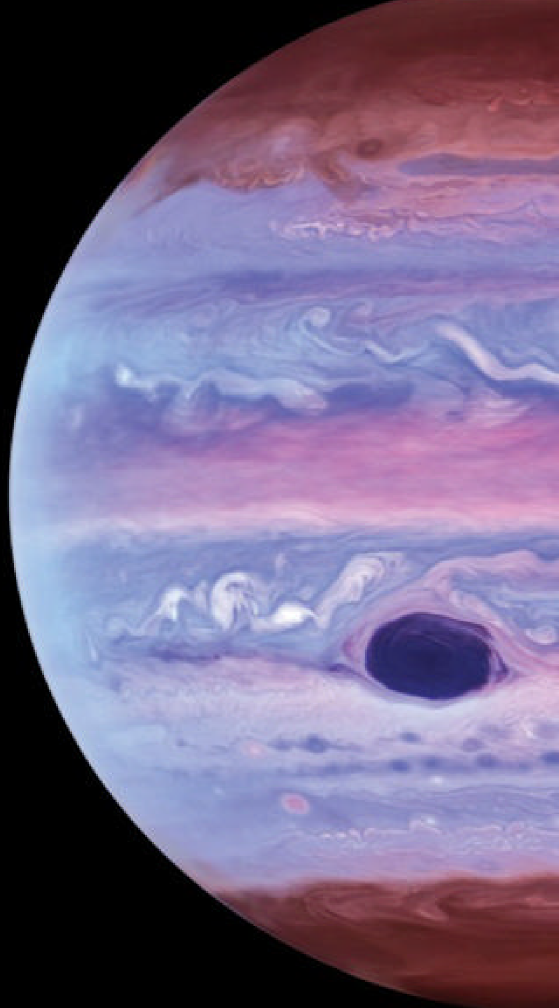
NATIONAL GEOGRAPHIC

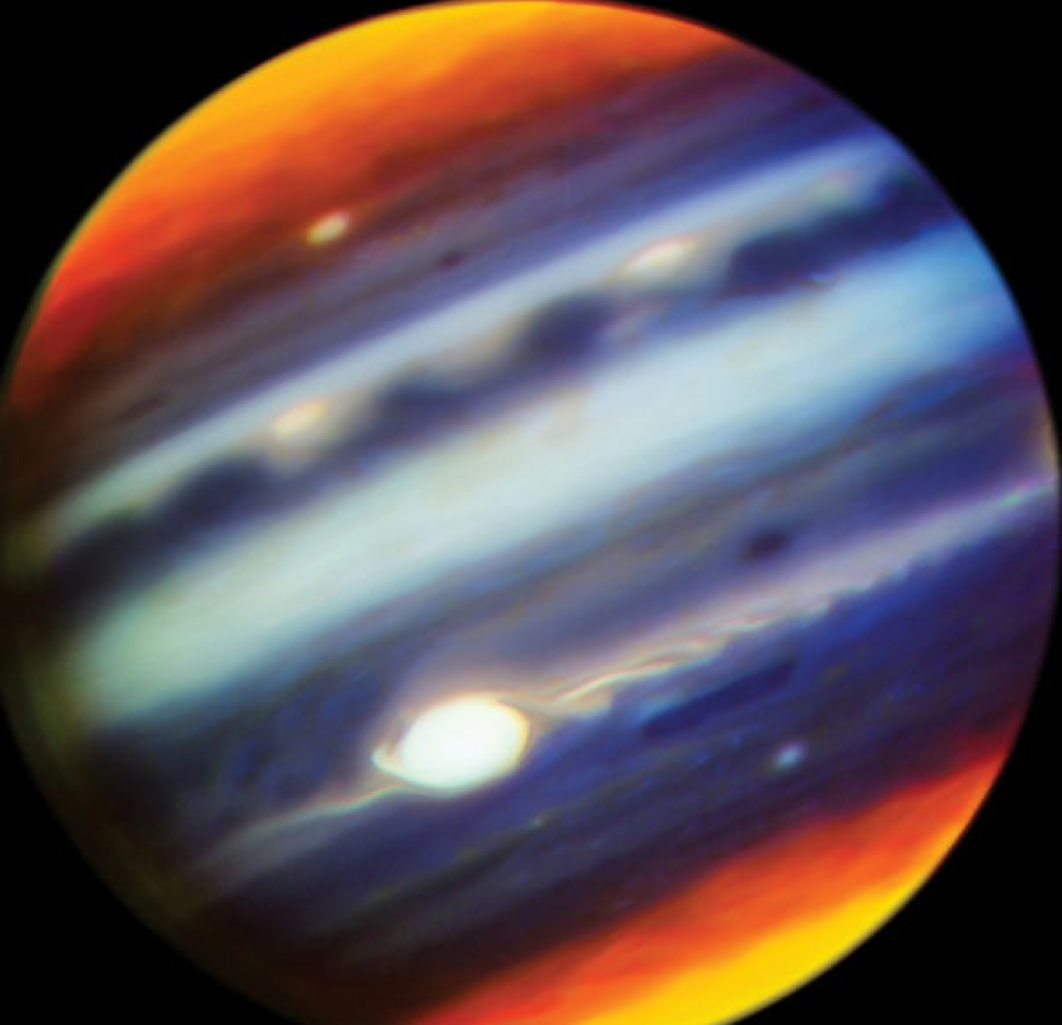
SPACE ✦ ISSUE



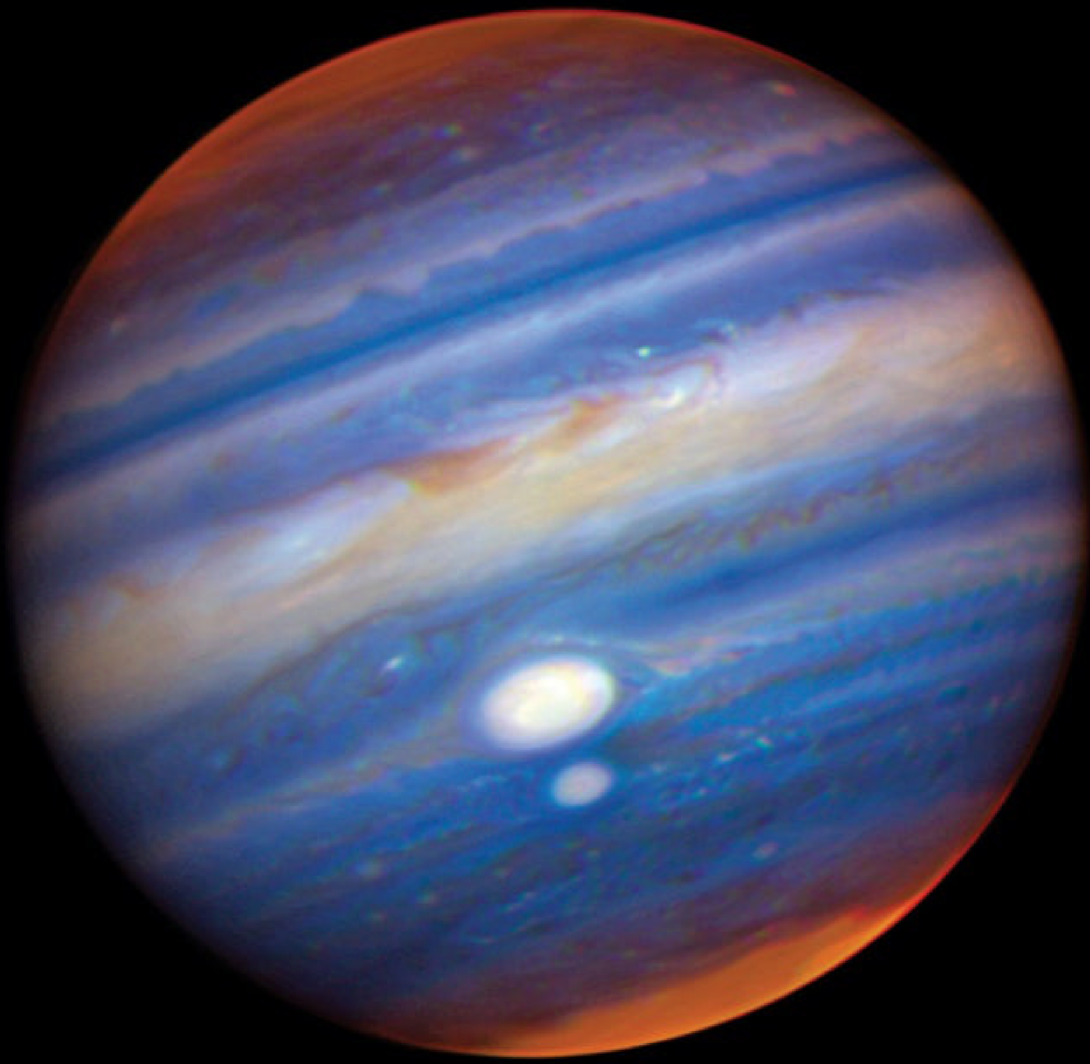


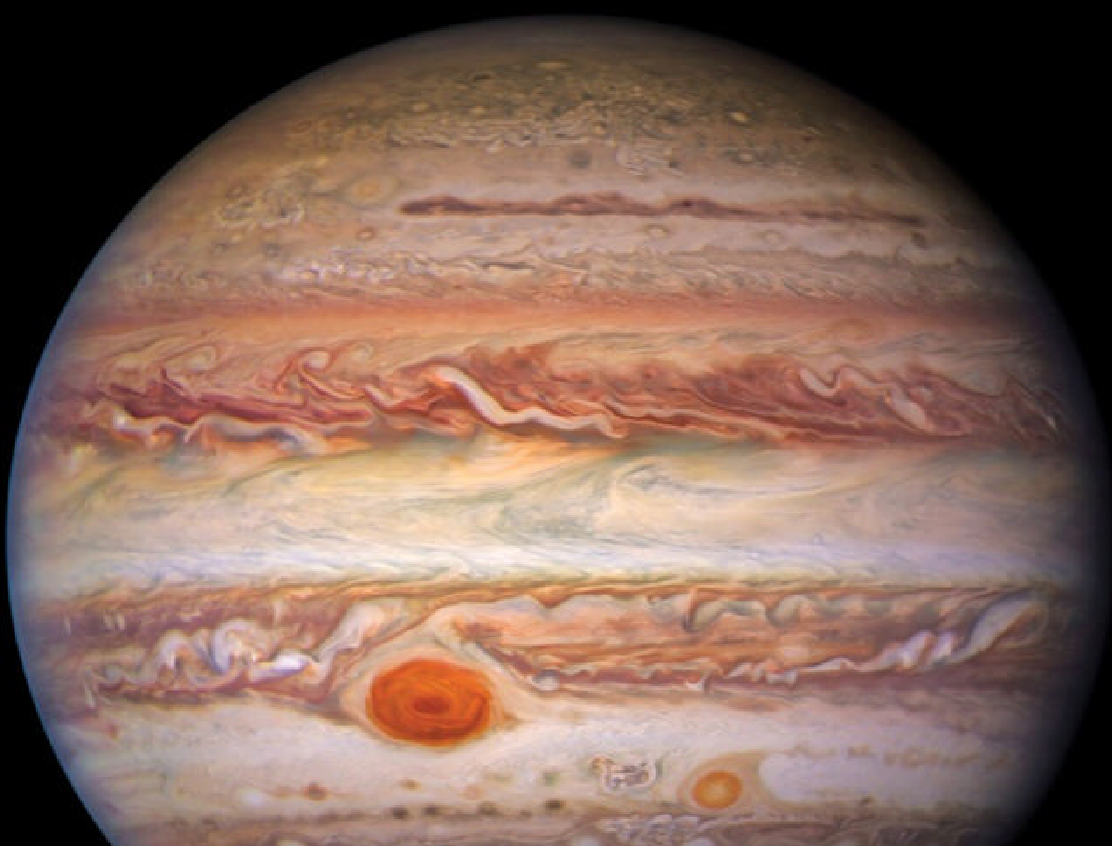
Like a fiery eye in the mist, the supermassive black hole at the center of the Milky Way blazes in this image taken by the MeerKAT radio telescope in South Africa. Named Sagittarius A* (pronounced Sagittarius A star), the black hole is millions of times the mass of the sun, drawing in gas and dust that glow from intense heat. The plane of our galaxy can be seen extending from the nucleus with bright star-forming clouds, and a huge bubble-like shroud of gas from a past supernova is visible to the lower right.
IAN HEYWOOD, SOUTH AFRICAN RADIO ASTRONOMY OBSERVATORY



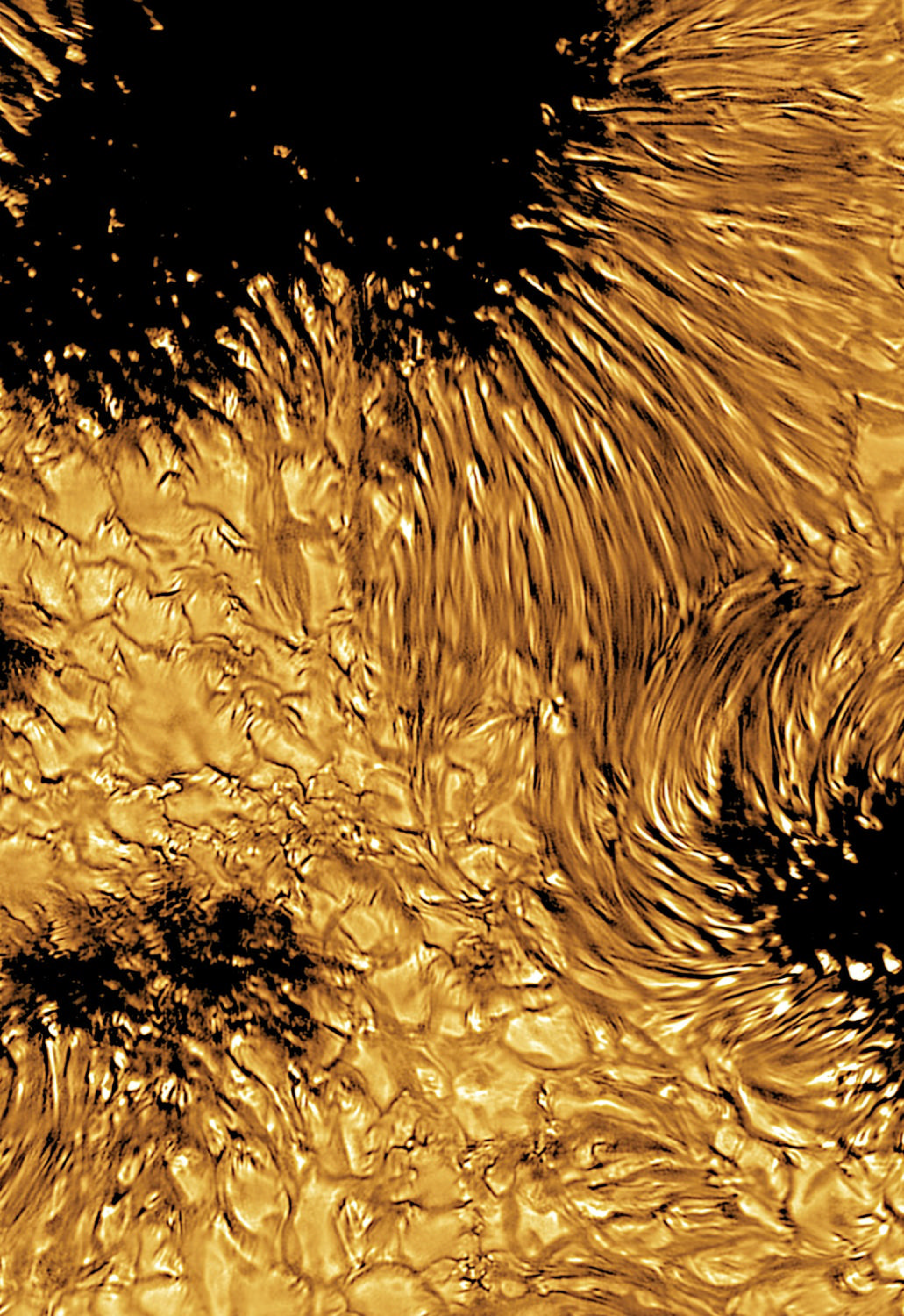


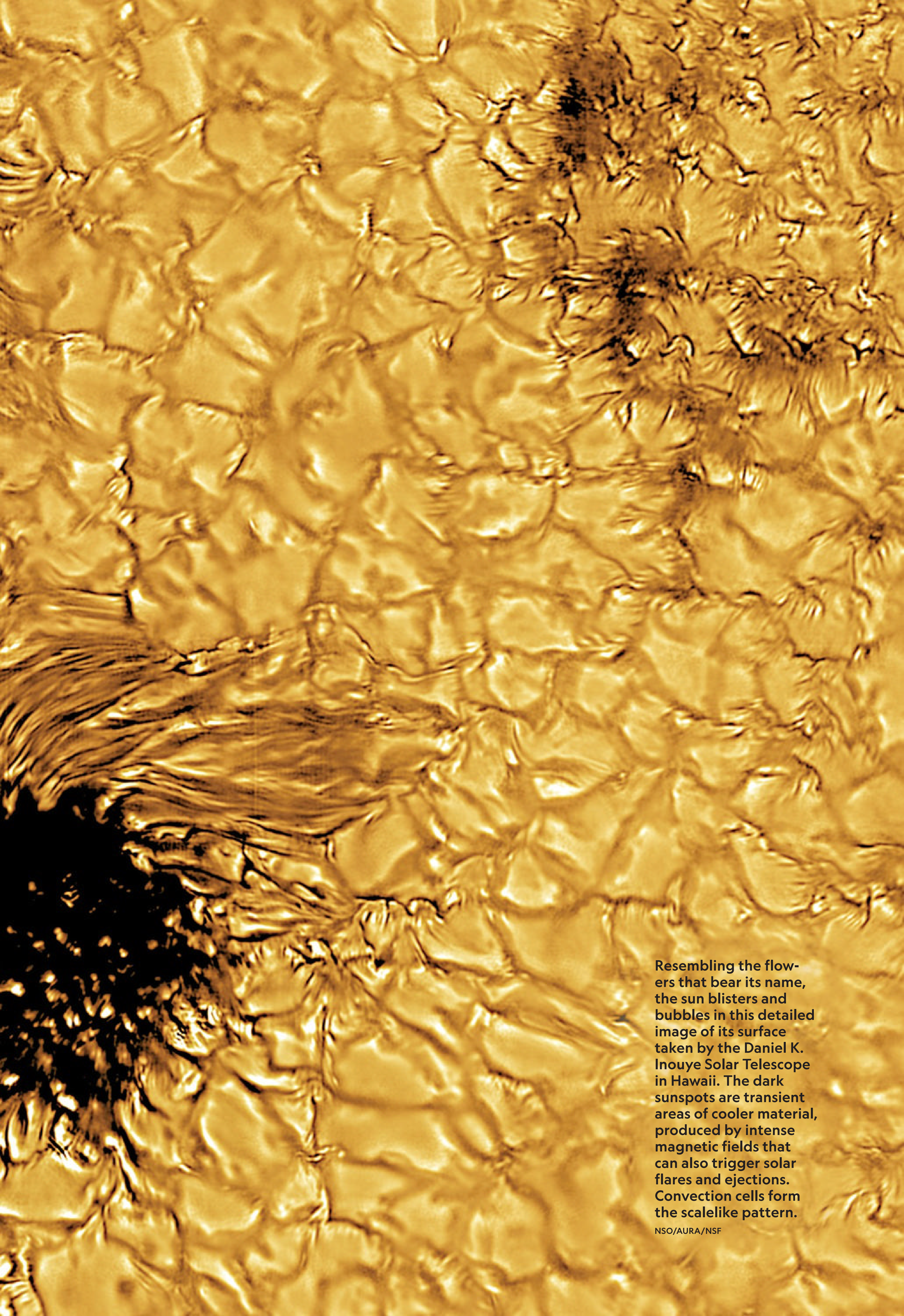
NASA, ESA, CSA, JUPITER ERS TEAM, IMAGE PROCESSING BY JUDY SCHMIDT; NASA/ESA/NOIRLAB/NSF/AURA/M.H. WONG AND I. DE PATER (UC BERKELEY) AND OTHERS; INTERNATIONAL GEMINI OBSERVATORY/NOIRLAB/NSF/AURA; INTERNATIONAL GEMINI OBSERVATORY/AURA/NSF/JPL-CALTECH/NASA; MOSAIC OF 38 IMAGES BY THE INTERNATIONAL GEMINI OBSERVATORY/NOIRLAB/NSF/AURA, M.H. WONG (UC BERKELEY) AND TEAM; NASA/ESA/NOIRLAB/NSF/AURA/M.H. WONG AND I. DE PATER (UC BERKELEY) AND OTHERS





The banded clouds and swirling cyclones of Jupiter are revealed in different wavelengths of light in these six images. By row, from top left, the planet is seen in infrared light by Webb, ultraviolet by the Hubble Space Telescope, and three different infrared views from the Gemini North telescope in Hawaii. The final image of Jupiter was captured in visible light by Hubble.





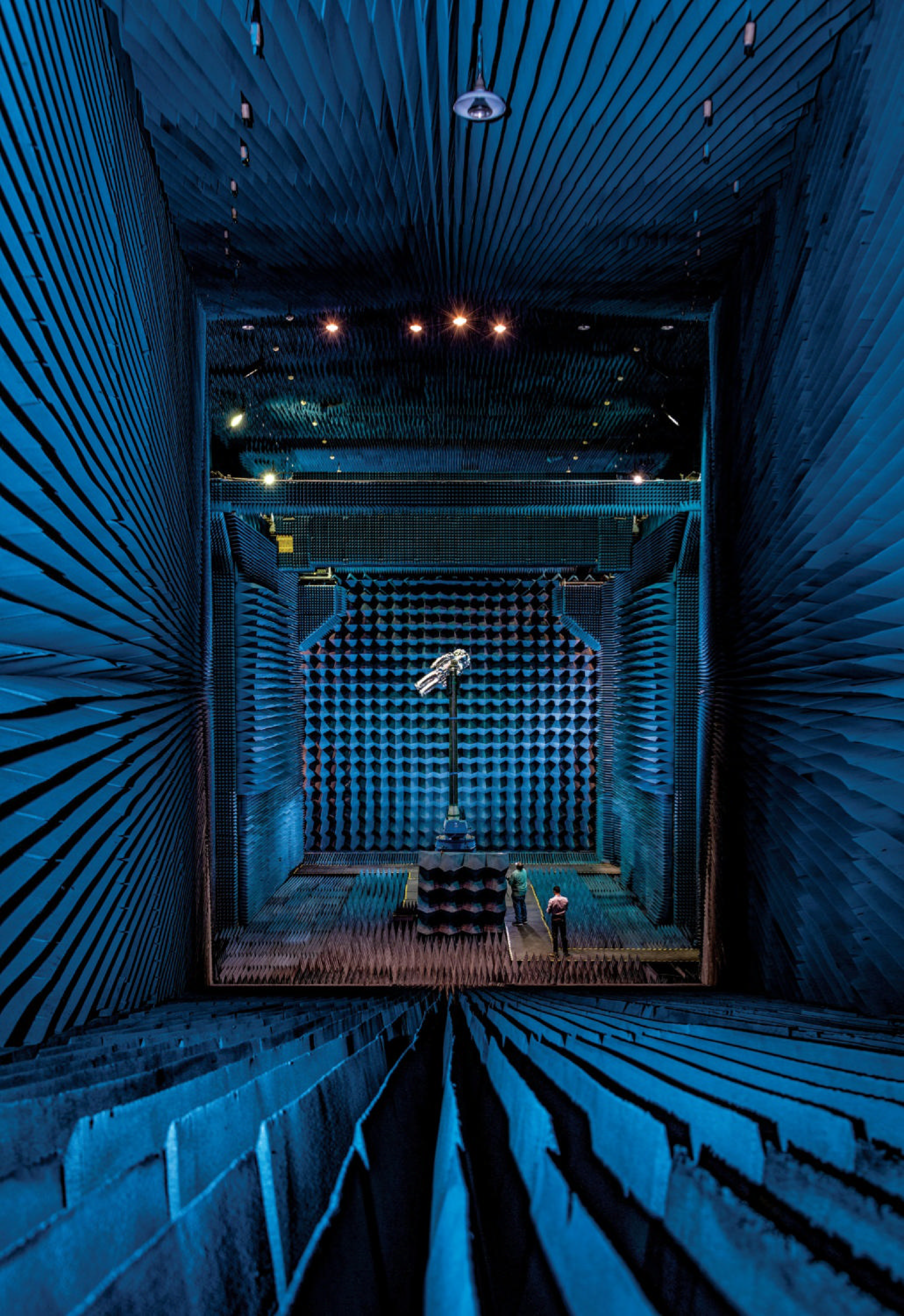
Resembling the flowers that bear its name, the sun blisters and bubbles in this detailed image of its surface taken by the Daniel K. Inouye Solar Telescope in Hawaii. The dark sunspots are transient areas of cooler material, produced by intense magnetic fields that can also trigger solar flares and ejections. Convection cells form the scalelike pattern.
NSO/AURA/NSF

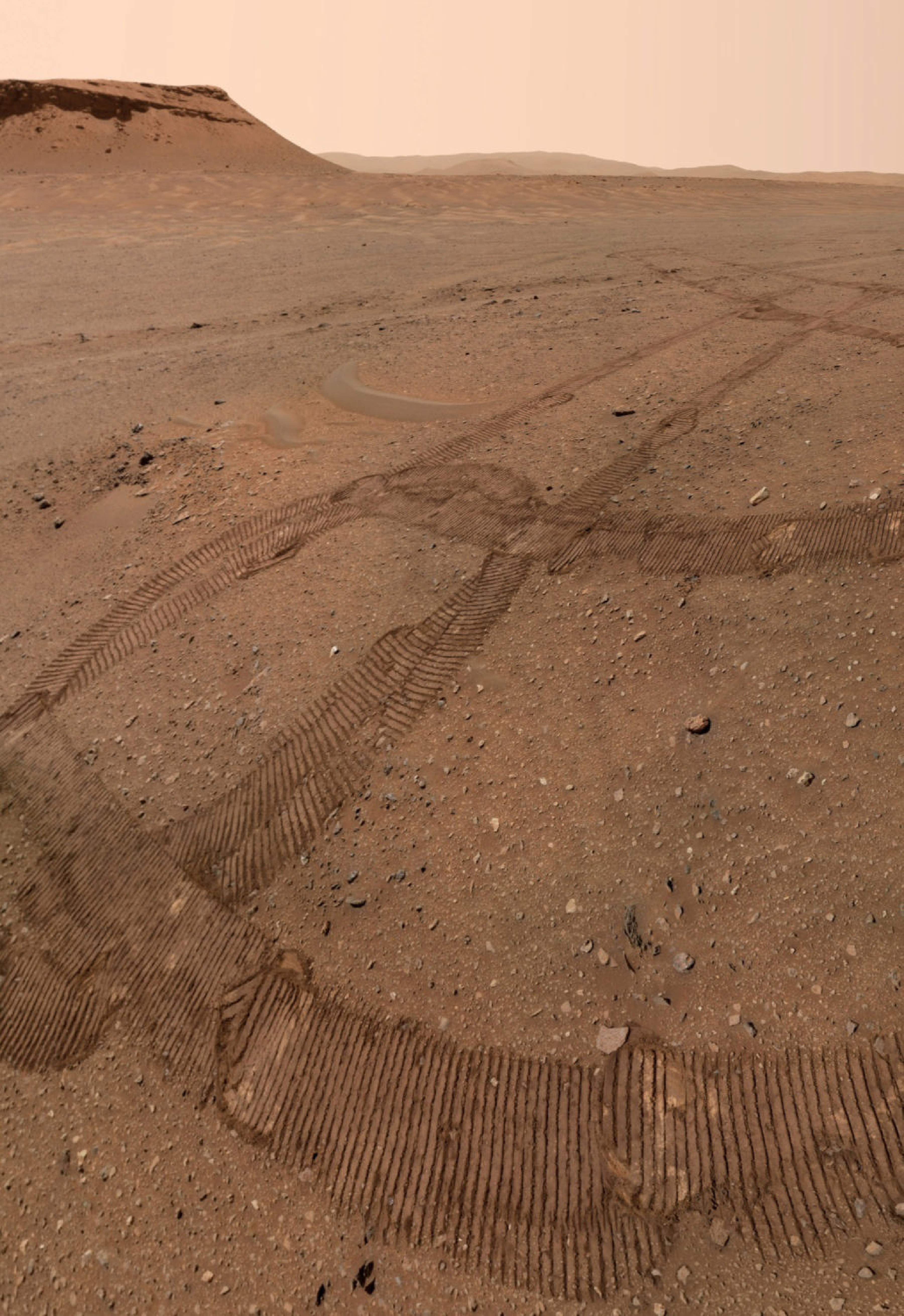
Bright asteroids within the solar system streak across this image captured by Hubble of thousands of galaxies scattered throughout the universe. Rather than leaving a continuous trail, the asteroids are seen in multiple exposures by Hubble, appearing to arc across the sky as the space telescope orbits Earth.

NASA, ESA, AND J. LOTZ (STSCI) AND THE HFF TEAM

NASA tests the next generation of space suits (right) at the Johnson Space Center in Houston, Texas, within a chamber that limits electromagnetic radiation. The exploration extravehicular mobility unit (xEMU) is being designed for astronauts to return to the surface of the moon.

NORAH MORAN, JOHNSON SPACE CENTER/NASA





Like a dog with a bone, NASA's Perseverance rover looks down at a sample tube filled with Martian rock that it deposited on the surface for a future mission to collect. By studying the rocks of Mars in laboratories on Earth, scientists may learn if the red planet ever supported life.

MOSAIC OF 59 IMAGES BY NASA/JPL-CALTECH/MSSS

Up

BY **MICHAEL GRESHKO**

PHOTOGRAPHS BY **DAN WINTERS**

GRAPHICS BY **ALBERTO LUCAS LÓPEZ**

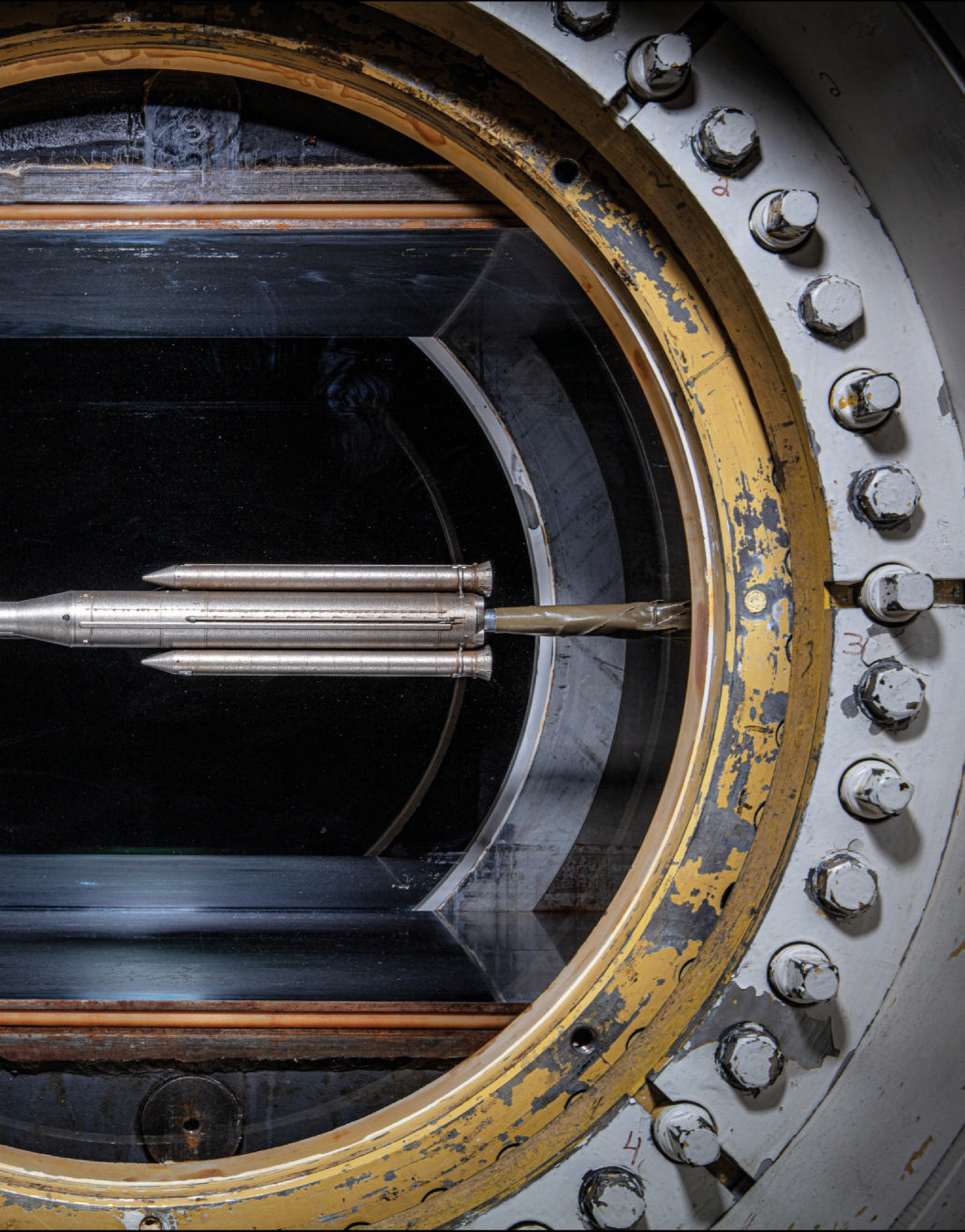
AWAY

NASA'S ARTEMIS PROGRAM BRINGS US ONE GIANT LEAP CLOSER TO THE MOON, MARS, AND BEYOND.

The Artemis moon program will fly its crews atop a rocket called the Space Launch System. NASA ran early aerodynamic tests for the SLS with this 1:250 scale model, inside a 14-inch-wide wind tunnel at the Marshall Space Flight Center in Huntsville, Alabama. This tunnel was also used to design Apollo's Saturn V rocket and the space shuttle.

PREVIOUS PHOTO

Before Artemis ever sends humans to the lunar surface, NASA will run high-fidelity tests on Earth. When astronauts Drew Feustel (at left) and Zena Cardman conducted mock moonwalks last October, they each wore a training suit weighing more than 80 pounds to simulate a real suit's range of motion and weight in lunar gravity.



To get the astronauts moon bound, SLS relies on a pair of 177-foot-tall side boosters filled with solid polymer fuel. When ignited, as seen here during a July 2022 test firing in Utah, just one of these boosters chews through about six tons of propellant a second and gives off 3.6 million pounds of thrust. The boosters are the biggest of their kind ever built.

For Artemis missions, SLS launches a habitable spacecraft called Orion into lunar orbit. The two vehicles are built separately, so before any launch, NASA must join them within the world's largest single-story structure: the Vehicle Assembly Building, at the agency's Kennedy Space Center in Florida. The VAB is seen here holding the "full stack" for the uncrewed Artemis I test in March 2022.

I

'I LOVE IT WHEN IT JUST TURNS INTO A STAR!'

Christina Koch exclaimed. The NASA astronaut and three colleagues, dressed in blue flight apparel, were standing on a knoll at the Kennedy Space Center in Florida peering into the night sky as the most powerful rocket that had ever launched turned into a pinprick of light.

Minutes earlier, at 1:47 a.m. on November 16, 2022, the 32-story flying machine known rather prosaically as the Space Launch System (SLS) had lifted off. Through my binoculars, the rocket's orange pillar of exhaust was nearly blinding. Every crackle of its 8.8 million pounds of thrust—equivalent to 31 jumbo jets—rattled my lungs.

That colossal rocket, hurtling downrange at more than 17,500 miles an hour, hoisted aloft the Orion spacecraft, designed to carry astronauts farther into space than they have ever ventured. To measure how deep space will affect astronauts, the gumdrop-shaped crew module carried a mannequin named Campos and two female "phantoms," or artificial torsos. Over the subsequent 25 days, 10 hours, and 53 minutes, the test dummies would soar to more than a quarter million miles from Earth before plunging back through the atmosphere at nearly 25,000 miles an hour. The next Orion will have four people on board as it voyages around the moon. Koch (whose name is pronounced Cook) hoped to be among them.

The launch of this 2022 mission, named Artemis I, marked a milestone for NASA, which aims to put humans back on the moon for the first time in more than 50 years. If all goes as planned, Artemis II could send a crew on a lunar flyby as soon as November 2024. Then comes Artemis III—a crewed landing—as soon as late 2025, followed by more missions to establish a lunar presence.

Why go back to the moon? For one, the lunar surface remains a scientific wonderland. Its rock and dust chronicle the sun's changing activity over 4.5 billion years. Its craters could reveal secrets from the ancient bombardments that also hit Earth. The icy schmutz around the lunar north and south poles might offer insights into how water finds its way through the solar system. Artemis plans to land crews near the south pole to study these suspected frozen water deposits, a step toward possibly harvesting ice for water, oxygen, and rocket fuel.

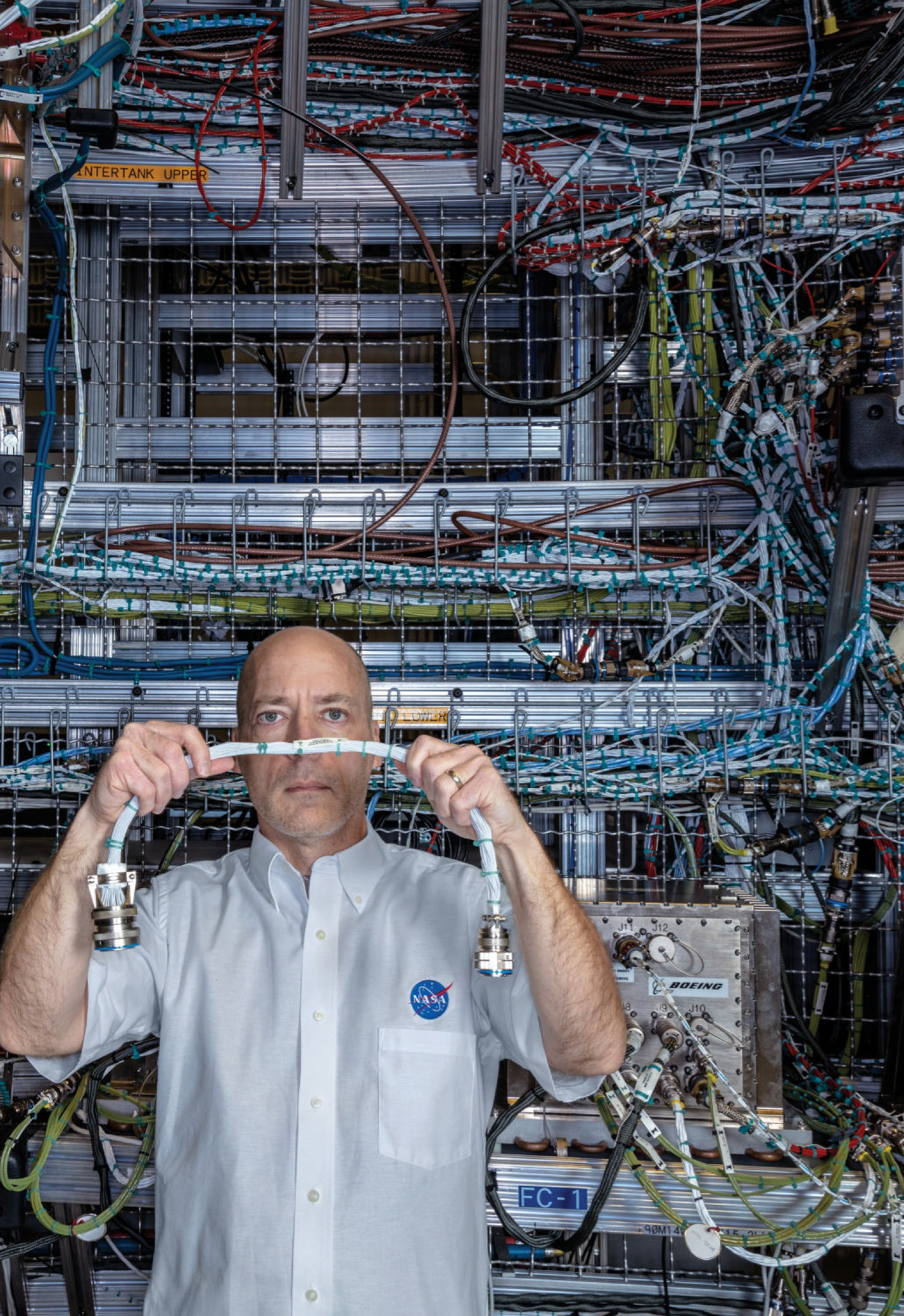
There are political calculations too: international cooperation, aerospace contracts, skilled jobs.

Beyond that, the moon is preparation for a crewed journey to Mars, perhaps in the 2030s, as part of the agency's push to find out whether the red planet ever harbored life. The moon and Mars differ, but both are forbidding realms where humans need technologies such as pressurized habitats and advanced space suits to survive. And the moon is only a few days away. With the engines we have today, it could take seven to nine months to reach Mars.

Artemis has faced challenges. Years of delays. Billions in cost overages. Skepticism that humans are even needed for space exploration. But if Artemis succeeds, it won't just return astronauts to the lunar surface. It could also begin an era of vast possibility and humbling responsibility: one where humankind regularly lives and works on worlds beyond our own. "This is turning the first page on a brand-new chapter of space exploration," said Jacob Bleacher, NASA's chief exploration scientist.

ONE CLEAR NIGHT LAST OCTOBER, astronaut Zena Cardman clambered through a field of lava rock in a mock-up space suit, her eyes locked on the moonlike landscape. Cardman, a geobiologist, and fellow astronaut Drew Feustel, a geophysicist, were on a mission to collect rock samples near Arizona's S P Crater, an 820-foot-tall cinder cone that formed during an ancient volcanic eruption.

Long shadows slithered across the craggy landscape. At a distance, a scientist in a baseball cap wheeled a spotlight


INTERTANK UPPER
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J11
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FC-1

Though Artemis I's Orion was uncrewed during its November 2022 launch, a humanoid figure sat in the commander's seat: the "moonikin" Campos. Named for a NASA engineer who helped save the lives of the Apollo 13 crew, Campos recorded what astronauts would have experienced during Artemis I, including vibrations, radiation dosage, and acceleration.

PREVIOUS PHOTO

Virtual missions have flown many times thanks to the Systems Integration Lab at NASA's Marshall Space Flight Center. Engineers such as NASA contractor Don Biggs run launch simulations for SLS's intricate flight software on real avionics hardware, which is mounted on a curved stand to mimic its layout inside the rocket.

> ‘NOTHING OF THIS SCALE HAS EVER LAUNCHED DURING MY LIFETIME … WE’RE BRINGING THE SPIRIT OF THE ENTIRE PLANET WITH US.’
>
> JESSICA MEIR, ASTRONAUT

around on a small cart, keeping it trained on the two astronauts. When Cardman and Feustel dipped out of the glare—meant to replicate the harsh sunlight at the lunar south pole—they couldn’t see more than 30 feet. The duo tried orienting themselves with low-resolution maps, meant to simulate working off satellite images. No GPS or compass bearings were allowed: Neither would be much use on the moon missions. “It was actually remarkably difficult to pinpoint where we were,” Cardman said. “Mission Control is telling us, ‘We’re pretty sure you should see a hill in front of you’ … and we’re like: ‘Maybe!’ ”

The main goal of this simulated moonwalk and other analog missions isn’t to train astronauts. Instead, they’re meant to test everything else, from the chisels that moonwalkers will wield to the procedures that Mission Control will follow back on Earth. And then, after years of careful rehearsal, it will be time for liftoff.

“It’s starting to sink in that it’s real,” said Jessica Meir, a member of the astronaut corps since 2013. “Nothing of this scale has ever launched during my lifetime.”

Meir has prepared for this moment since she was five years old. When her first-grade teacher asked her class to draw what they wanted to be when they grew up, she didn’t just draw an astronaut—she drew one on the moon. A biologist by training, Meir once focused her research on how penguins and geese respond physiologically to extreme environments. Now she works in one. From September 2019 to April 2020 she lived aboard the International Space Station (ISS), and performed nearly 22 hours of space walks outside the station with crewmate Koch—the first space walks ever conducted by an all-woman team.

In its early days, NASA had a narrow view of the “right stuff” for astronauts: all male, mostly military test pilots. Today they might be submariners or seismologists, programmers or physicians—women and men from an eclectic array of backgrounds. One of the Artemis program’s stated goals is to put the first woman and person of color on the moon.

“We’re bringing the spirit of the entire planet with us,” Meir told me.

BILL

NELSON RECALLS EXACTLY where he was when Apollo 11 commander Neil Armstrong took his first steps on the moon: in a hotel room in London, just before 4 a.m., enraptured by the grainy broadcast on a black-and-white TV. He grew up in Melbourne, Florida, as scientists and rocketeers were turning nearby Cape Canaveral—Apollo’s eventual home port—into a missile test site. Later, in his career as a congressman and senator from Florida, he established himself as a legislative leader on space policy. In 1986 he even flew on a six-day space shuttle mission. Now 80 and NASA administrator, he is overseeing Artemis’s first missions.

Artemis as we know it today grew out of a Trump-era push to put humans on the moon as a stepping stone to Mars. The Biden administration has embraced it with minor tweaks. But arguably, the Artemis era began on February 1, 2003, when the space shuttle *Columbia* broke apart during reentry and killed its seven crew members. The disaster, precipitated by mid-launch damage to the shuttle’s fragile heat shield, hastened the fleet’s retirement—and raised the question of what would follow.

In 2004, the George W. Bush administration unveiled a moon-to-Mars strategy to replace the shuttle, enshrined into law as the Constellation program. The initiative, which included Orion, soon blew its budget and fell behind schedule, and in 2010 the Obama administration proposed canceling it. But lawmakers, co-led by Nelson, voted to keep Orion going and backed two new rocket strategies: the Commercial Crew program, which contracts with SpaceX and Boeing to ferry astronauts to the ISS; and the SLS, whose design borrowed as much technology as possible from the 1970s-era space shuttle.

All of this represents a substantial national commitment. The NASA Office of Inspector General estimates Artemis's total cost through September 2025 will hit $93 billion. Still, total spending on Apollo exceeded $280 billion in today's dollars, and after adjusting for inflation, Apollo's peak annual cost was roughly 60 percent more than NASA's entire budget today.

FOR ALL THE SUPERFICIAL similarities to Apollo—the big rocket, the gumdrop capsule—Artemis has modern ambitions. The missions it will fly will be longer: Orion was designed to keep a crew of four alive for up to 21 days. And the electronics on board SLS and Orion are more sophisticated. But NASA's newest vehicles still rely on Apollo's manufacturing network.

Both are born in New Orleans 15 miles east of downtown at NASA's Michoud Assembly Facility. For decades the 43-acre plant has played a key role in the agency's rocket manufacturing. Once a French sugar plantation, the facility was taken over in 1961 by NASA, eager for a site with a deepwater port to build Apollo's Saturn V rocket. The first stage was made here. So was the space shuttle's fuel tank. "Until recently, you didn't get out of Earth orbit unless you went through Michoud," said Amanda Gertjejansen, an engineer with Boeing, an SLS prime contractor.

The construction of SLS core stages moves across Michoud from east to west. Curved aluminum panels, which arrive in gigantic wooden crates, are welded into cylindrical segments that get stacked and then welded together. After welds are checked, insulation is added, and avionics systems are installed, finished core stages are floated by barge to Florida. Orion also makes its way to the Sunshine State: Following construction of its main metallic skeleton, led by Lockheed Martin, it's shipped to Kennedy Space Center for assembly.

Before that barge ride, the core stage sits in a cavernous room on its side for final assembly. Safety glasses on, Gertjejansen led me around the rocket. At 27.6 feet in diameter and 212 feet long when fully assembled, it felt preposterously big: a pharaonic monument awaiting a final lift into place. Silvery piping ran along the outside to feed fuel to the engines. When we poked our heads into the engine section—the part of the rocket she manages—the plumbing-stuffed cavity had the feel of a cramped jungle gym.

As sophisticated as this behemoth is, artisans contribute its finishing touches. Some of the foam insulation is hand-sprayed. Chessboard-like markers along the rocket's sides—used to track its orientation and speed from afar—are hand-painted. "When you think of building a rocket, you think of rocket scientists," Gertjejansen told me. "Those are only a very small part."

AT NASA'S MARSHALL SPACE Flight Center in Huntsville, Alabama, a wall of TV monitors features live video feeds, from every conceivable angle, of Launch Complex 39B, the Artemis launchpad. During tests and launch attempts, this room holds a team of experienced SLS engineers, ready to troubleshoot a problem. "You put plans in place to deal with the things that you don't plan on, so when they happen, you're not reacting—you're responding," said David Beaman, who manages this team and hundreds of other engineers.

Beaman's father was one of the engineers for the Saturn V rocket, and eventually Beaman found himself in his father's line of work. He started with the shuttle program and took over its booster team. Then Beaman helped establish the structure of NASA's SLS team,

In April 2023, SpaceX conducted the first full test flight (left) of the silvery rocket known as Starship. The reusable vehicle has more thrust than SLS, and a variant of its upper stage will act as Artemis III's lunar lander. Many tests await Starship: Four minutes into flight, SpaceX blew up this rocket for safety after it began to flip uncontrollably.

Unlike NASA, SpaceX rapidly builds and tests many prototypes of its rockets, speeding up the design process and increasing the risk of "rapid unscheduled disassembly." This fireball (below), one such "disassembly," occurred in December 2020 during a landing attempt for a Starship upper stage. In May 2021, an updated vehicle landed successfully.

NASA has long sought moonscapes here on Earth to prepare for lunar missions. Among them is Arizona's lava-encrusted San Francisco Volcanic Field, which is peppered with hundreds of extinct volcanoes. Last October, astronauts Cardman (at left) and Feustel trekked for miles across this terrain to test how well Artemis crews will be able to navigate in harsh lunar lighting with only maps.

painfully aware of the failures that the shuttle had endured—not just the technical ones but the organizational ones too.

He considers NASA's current safety approach to be less susceptible to human error: a strategy based on taking the extra time to make sure every nagging concern is resolved. "If it means making a few hard decisions, and waiting a few more days, and getting a little more data, we're gonna do that," he told me.

NASA scrubbed Artemis I's first launch attempt in August 2022—attended by VIPs including Vice President Kamala Harris—amid concerns over weather, a misbehaving temperature sensor, and a hydrogen fuel leak. The following month another attempt was called off because of more leaking. Next came Hurricane Ian, and then in November, Hurricane Nicole, which buffeted the rocket on the launchpad with hundred-mile-an-hour gusts. Then another leak appeared, hours before its scheduled November 16 launch. With the rocket almost fully fueled—and dangerous to approach—NASA sent a "red crew" out to hand-tighten nuts on a valve. "The rocket, it's alive. It's creaking. It's making venting noises. It's pretty scary," said Trenton Annis, who helped make the repair.

Finally, after meeting the 489 criteria necessary for launch, Artemis I was on its way. On November 28, Orion flew beyond the moon to more than 268,500 miles away—nearly 20,000 miles farther than any other "human rated" round-trip mission—and then on December 11 plunked into the ocean off Mexico's Baja California peninsula. "This is what mission success looks like," a relieved Mike Sarafin, Artemis I's mission manager, said after splashdown.

ARTEMIS II

IS A GO, a 10-day sojourn around the moon that will come within 6,500 miles of the lunar surface. Koch, who watched alongside me as Artemis I launched, received the historic assignment in March. Agency officials had tried to surprise her and her NASA crewmates with a clandestine in-person meeting. Two of them ran late; the third dialed in while coming from a doctor's appointment. Mild embarrassment soon gave way to elation.

Koch, an electrical engineer and one of Artemis II's mission specialists, has spent her career chasing the allure of the remote, from working at a South Pole research station to helping build a science instrument that's aboard Juno, a spacecraft now orbiting Jupiter. Three military pilots will be joining her: NASA's Reid Wiseman and Victor Glover, and the Canadian Space Agency's Jeremy Hansen.

Wiseman, Artemis II's commander, served as NASA's chief astronaut—who chooses crews but can't join them—until two days before Artemis I launched. He regained his flight eligibility just in time. Glover, Artemis II's pilot, was the second-in-command on NASA's SpaceX Crew-1 mission to the ISS, during which he spent 168 days in orbit. Hansen, Koch's fellow mission specialist, was the first Canadian to supervise the training of a NASA astronaut class. Artemis II will be his first spaceflight.

Glover will be the first Black astronaut to venture beyond low Earth orbit. Koch and Hansen will be the first woman and non-U.S. citizen, respectively, to do the same.

Preparations for the mission are well under way. The SLS core stage for Artemis II is nearly ready for its barge ride to Florida. In a bright room in Kennedy Space Center, technicians in white "bunny suits" have been testing and assembling the mission's Orion spacecraft, with the Artemis III Orion taking shape nearby. A team led by astronaut Stan Love has been training to serve as Artemis II's capcoms, the main points of contact between the crew and Mission Control, ready to relay technical directions or detect the quaver in an exhausted astronaut's voice.

Then, as soon as November 2024, NASA plans to start launching pieces of a small space station called Gateway into orbit around the moon. The space station will act as a staging ground for weeks-long missions to a lunar outpost with habitats, power stations, landing pads, and pressurized rovers—all of which are still in the concept stage.

This immense infrastructure would be too much for the United States to build alone. So Artemis is teaming up with foreign partners. For more than 22 years, the ISS has orbited 250 miles above our heads with humans on board, thanks to collaboration among the U.S., Russia, Canada, Europe, and Japan. This union has spread the station's costs around and made canceling the program diplomatically difficult. NASA has drawn on those lessons for Artemis: The European Space Agency (ESA) provides Orion's service module, which contains the spacecraft's solar arrays and main engine. That cooperation also extends to Gateway, which NASA is building with ESA and the space agencies of Canada and Japan.

And NASA is courting private companies to act as moon couriers, in hopes of becoming one of many customers in a lunar economy. A flotilla of privately owned robotic landers will transport science instruments and an ice-hunting rover to the moon. At its base in Texas, SpaceX is developing Starship, a reusable rocket even more powerful than SLS. The Artemis III astronauts who land on the moon will leave Earth in an Orion launched by SLS, but then they'll transfer to a version of Starship's upper stage to make their lunar descent.

THERE'S NOTHING INEVITABLE ABOUT US VENTURING BEYOND EARTH'S ATMOSPHERE, LET ALONE GOING TO THE MOON.

WHETHER THIS VISION will really yield a sustained human presence on the moon, let alone Mars-bound astronauts, is an open question. Artemis is still in its early days. Starship's first full test flight exploded minutes into launch in April. There's also public support to consider. Since 2019, the 50th anniversary of the Apollo 11 moon landing, multiple polls have found that less than a quarter of Americans thought that sending people to the moon should be a top NASA priority. Even during Apollo's days, human spaceflight attracted criticism for spending billions that could address earthbound concerns. Now we're returning to the moon at a time of climate and biodiversity crises, rising political extremism, glaring racial inequalities, and war between Russia and Ukraine.

Against this grim backdrop, NASA astronauts are acutely aware that they're not just public figures but also inspirational symbols: of exploration, of science, of the national spirit. Koch has wrestled with how to handle these expectations. For 328 days, she lived and worked aboard the ISS, setting a record for the longest spaceflight by a woman. Her impulse was to downplay the milestone. Then a former colleague reminded her that her achievement might give people a sense of greater possibilities.

There's nothing inevitable about us venturing beyond Earth's atmosphere, let alone going to the moon. In microgravity our blood breaks down. Our bones get brittle. Our eyesight worsens. Without constant vigilance, we can perish in an instant. Overcoming our biological limits, hundreds of thousands of people have dreamed, planned, and built for decades to make the journey outward not only possible but routine. If Artemis's vision is realized, that could extend all the way to the moon—and maybe even farther. As Koch sees it, these launches are hard-won victories, with setback after setback giving way to one of the purest of human emotions: joy at surpassing our limits.

"How awesome it is that as a species, as humanity, we are undertaking this right now—that we have decided that it's that important," Koch said. "It's because we love exploration. It's because we believe in the power of learning." □

Michael Greshko, a former staff science writer, gave readers a tour of a well-preserved dinosaur fossil in the August 2023 issue. For the November 2022 magazine, **Alberto Lucas López** created detailed graphics of Pharaoh Tutankhamun's layered mummy wrappings and nested coffins.

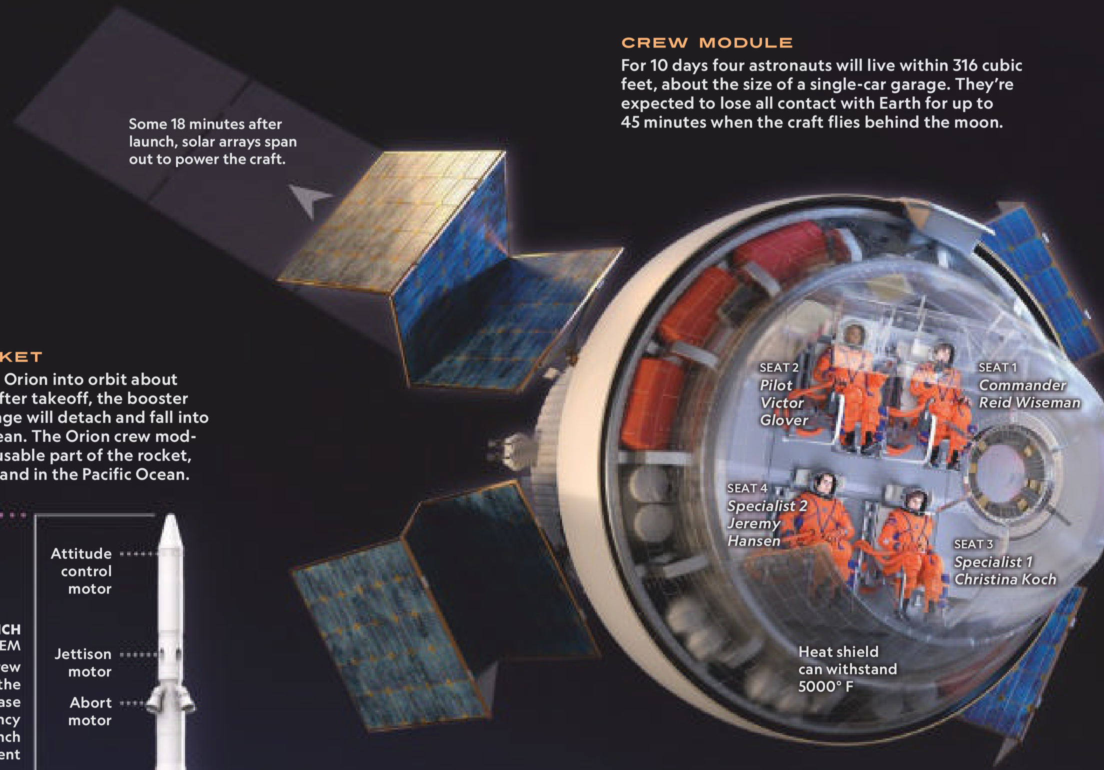
At 1:47 a.m. ET on November 16, 2022, the Artemis I mission roared into the skies, at the time the most powerful rocket launch ever witnessed. To capture this image safely, photographer Dan Winters placed a sound-triggered camera a thousand feet from the launchpad. During the launch, Winters and other spectators had to stand more than three miles away. Even at that distance, the rocket was louder than a rock concert.

BACK TO THE MOON

NASA's newest spacecraft is designed to carry humans not only to the moon but farther into space than ever before. The multi-mission Artemis project's first journey, in 2022, saw the uncrewed Artemis I craft venture thousands of miles beyond the moon and successfully return to Earth. Next up: Artemis II could launch from Florida's Kennedy Space Center as soon as fall 2024 with four astronauts on board. They'll be propelled into flight by an evolvable, super heavy-lift Space Launch System for a 10-day mission around the far side of the moon. The aim: to put systems and astronauts through their paces to prepare for future missions, pushing the boundaries of deep-space exploration to the moon and beyond.

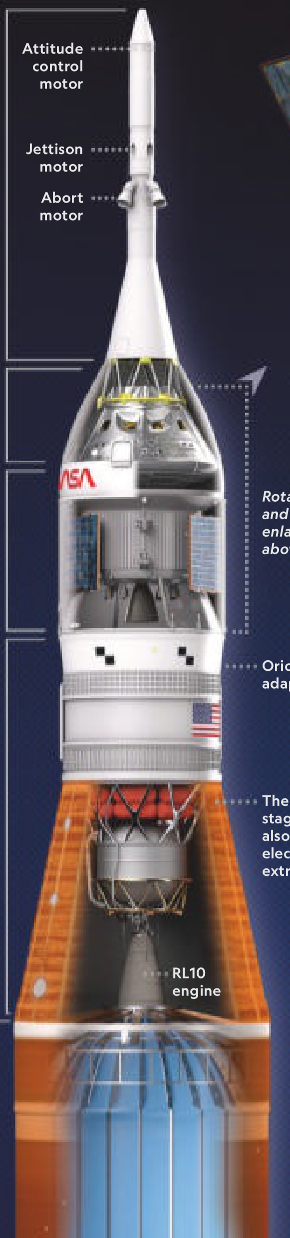
CREW MODULE

For 10 days four astronauts will live within 316 cubic feet, about the size of a single-car garage. They're expected to lose all contact with Earth for up to 45 minutes when the craft flies behind the moon.



MOON ROCKET

Upon launching Orion into orbit about eight minutes after takeoff, the booster rocket's core stage will detach and fall into the Atlantic Ocean. The Orion crew module, the only reusable part of the rocket, will eventually land in the Pacific Ocean.

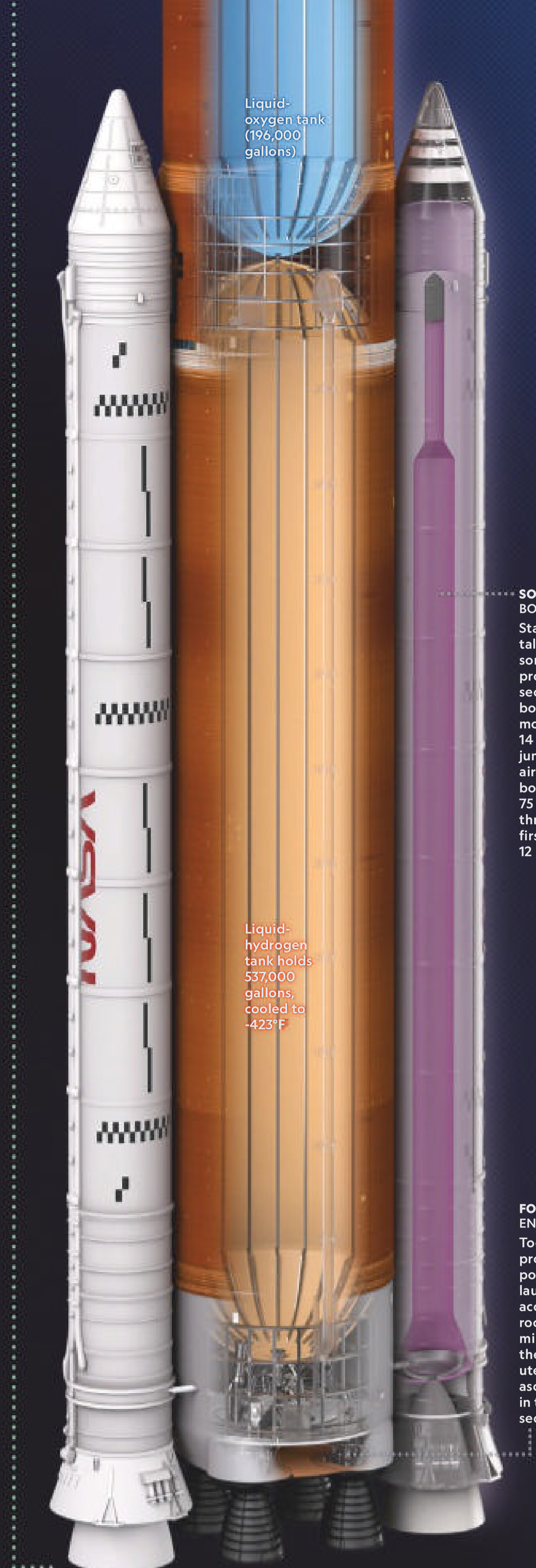


SURVIVAL SUIT

The Orion crew survival system (OCSS) suit for launch, ascent, and reentry protects the wearer from hazards and emergencies.

GOING THE DISTANCE

On the Artemis I mission, the uncrewed Orion reached its maximum distance from Earth: 268,563 miles, a record for any round-trip mission with a spacecraft built to hold crew. Now, for Artemis II, the SLS must safely carry four humans on a similarly ambitious trajectory as they test its evolvable technology for future explorations, including human missions to the moon and Mars and robotic missions to the moon, Mars, Saturn, and Jupiter.

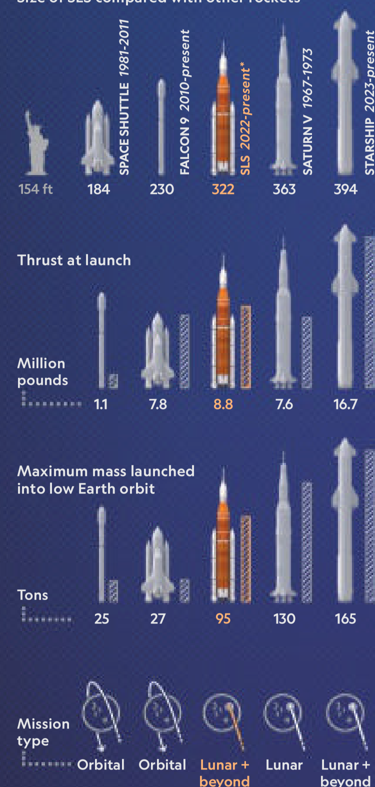


SOLID ROCKET BOOSTER
Standing 17 stories tall and burning some six tons of propellant per second, each booster generates more thrust than 14 four-engine jumbo commercial airliners. The boosters provide 75 percent of total thrust during the first two minutes, 12 seconds of flight.

FOUR RS-25 ENGINES
Together they provide two million pounds of thrust for launch and ascent, accelerating the rocket to 17,000 miles an hour over the first eight minutes of flight and ascending 500 feet in the first seven seconds.

LAUNCH SYSTEMS

The SLS thrust and payload capacities illustrate NASA's progress over time. The agency is also partnering with SpaceX on Starship technology for Artemis moon missions.



*FUTURE VERSIONS OF SLS WILL HAVE HIGHER THRUST AND PAYLOAD CAPABILITIES. BEGINNING WITH ARTEMIS IV, NASA PLANS TO FLY AN UPGRADED VERSION OF SLS WITH A MORE POWERFUL UPPER STAGE. NASA HAS FURTHER PLANS TO UPGRADE SLS'S SIDE BOOSTERS.

ALBERTO LUCAS LÓPEZ, NGM STAFF; KELSEY NOWAKOWSKI; RONALD PANIAGUA. SOURCE: NASA

ARTEMIS II • MISSION PLAN

This mission, a lunar flyby with no landing, is the first crewed flight near the moon since the Apollo missions.

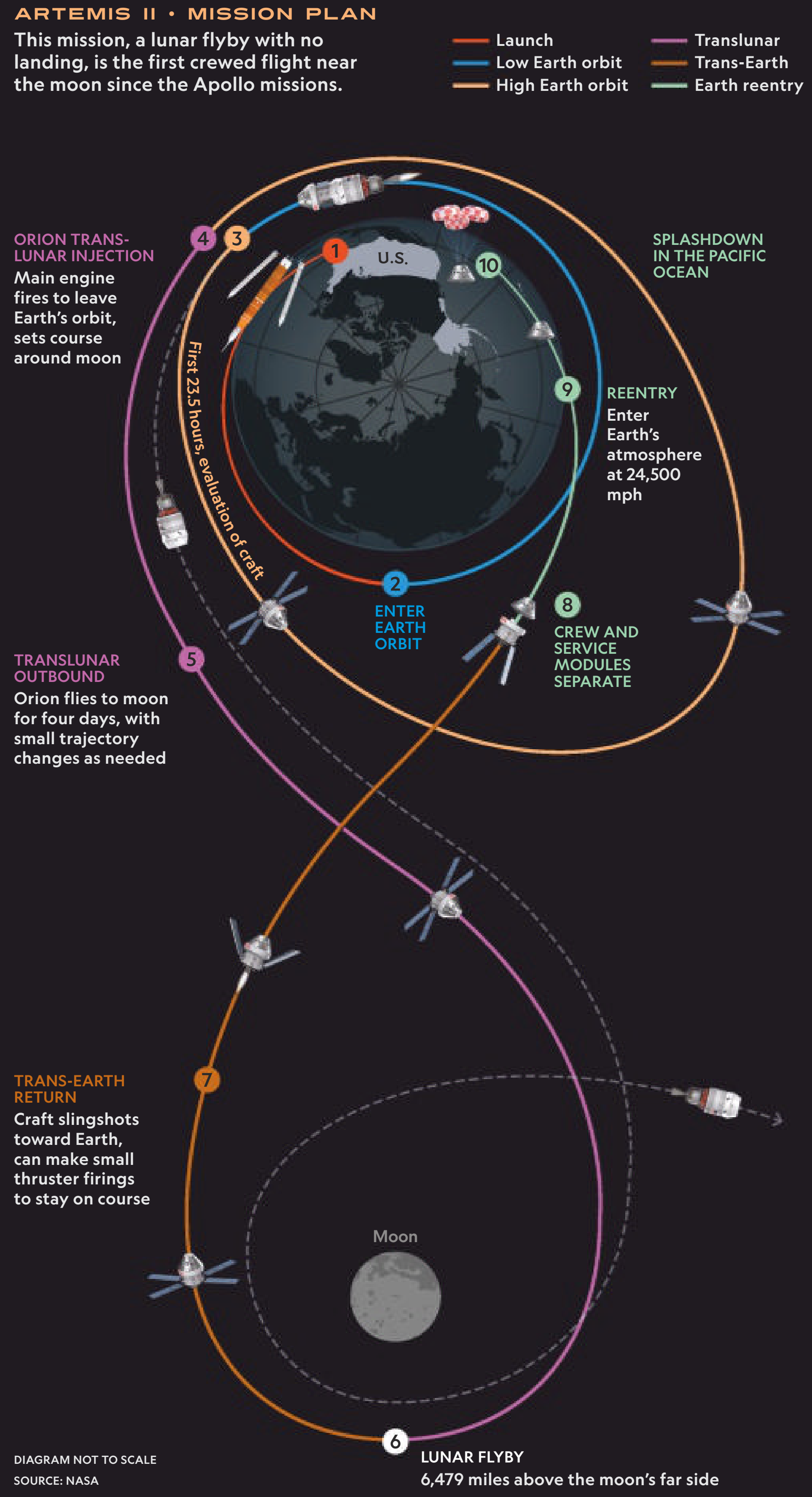
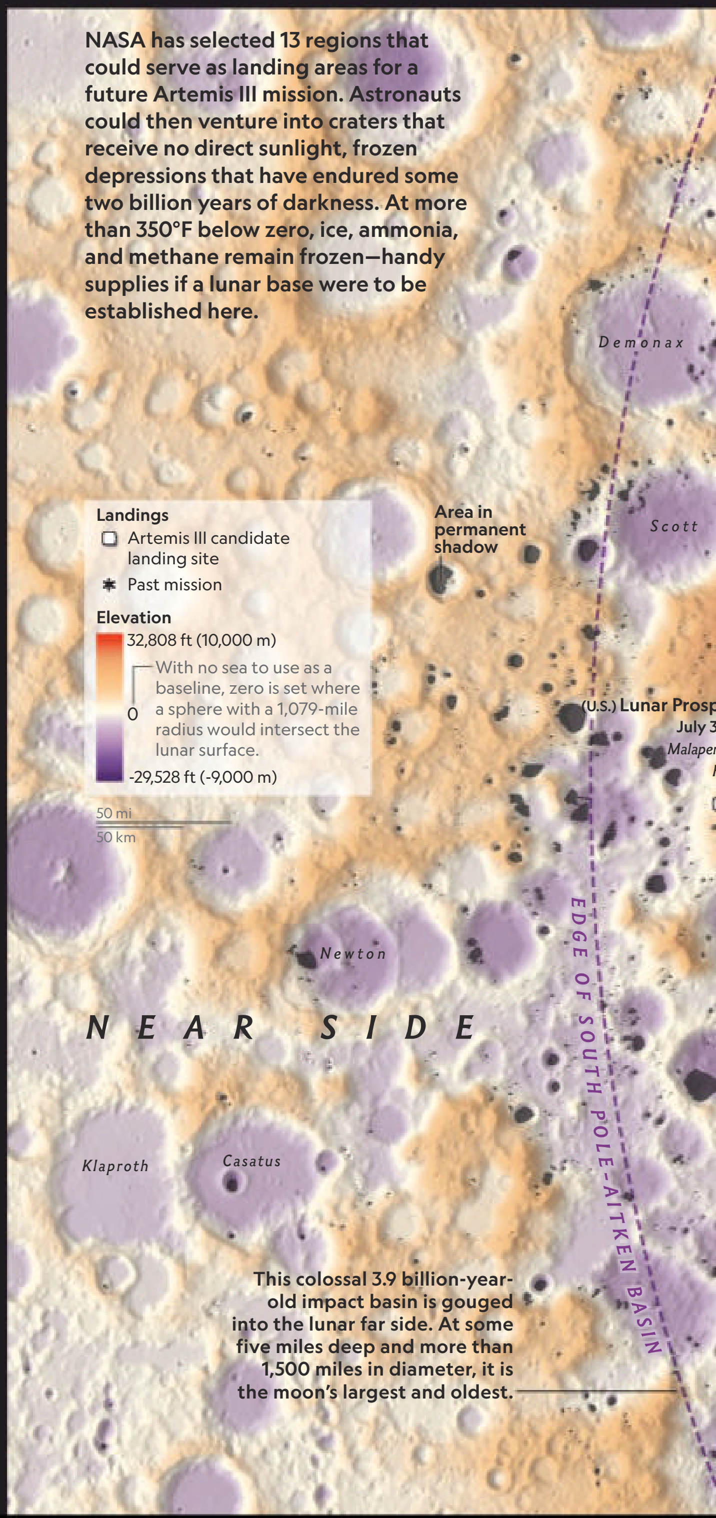


DIAGRAM NOT TO SCALE
SOURCE: NASA

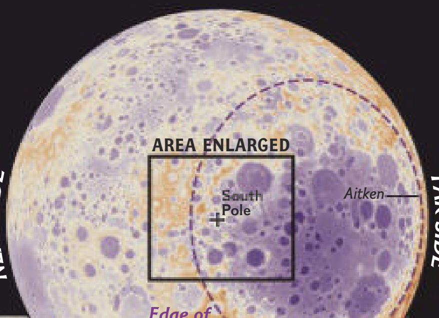
INTO THE SHADOWS

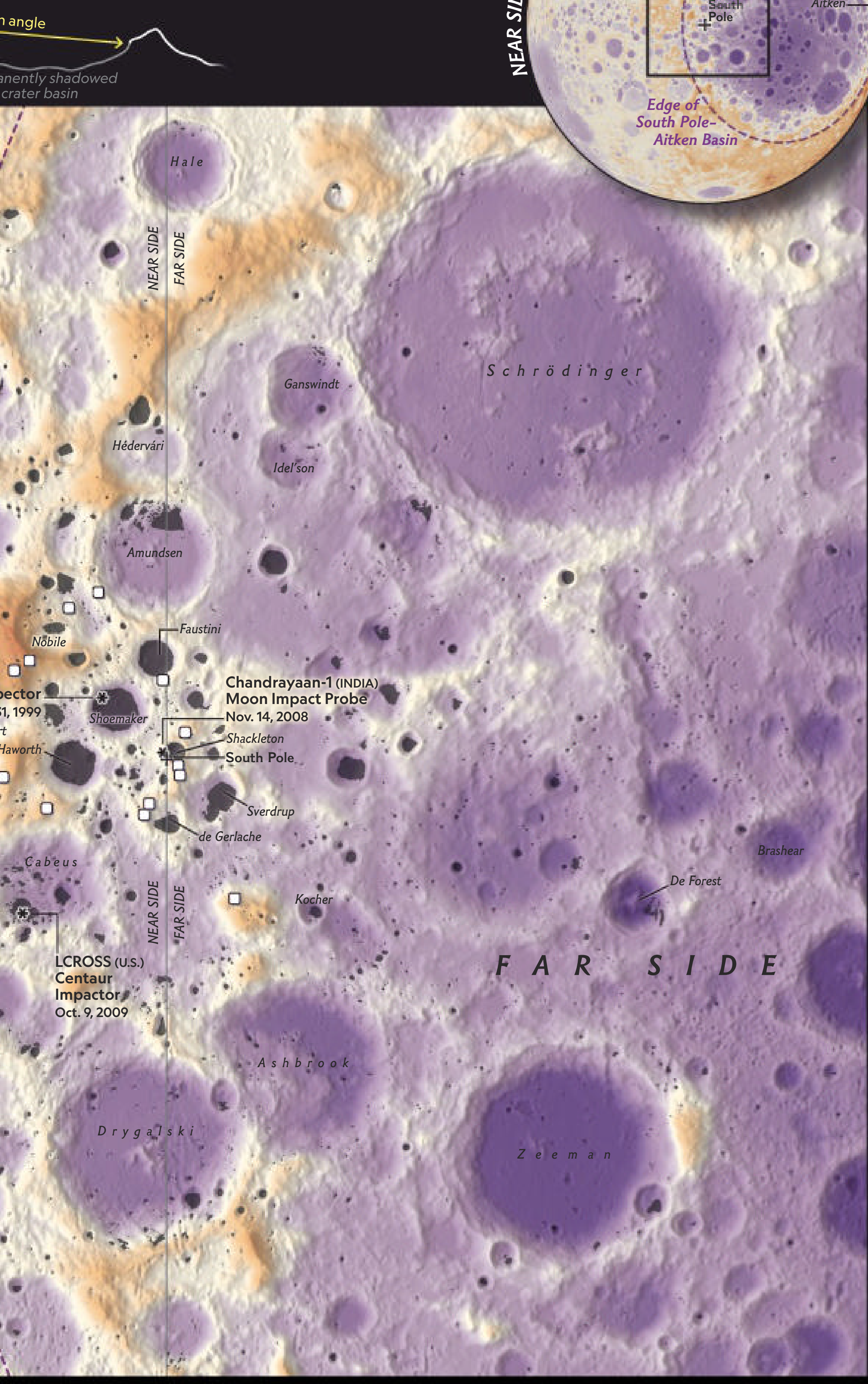
Gravitational locki
facing Earth and li
crater rims at the p
all sunlight, leavin

NASA has selected 13 regions that could serve as landing areas for a future Artemis III mission. Astronauts could then venture into craters that receive no direct sunlight, frozen depressions that have endured some two billion years of darkness. At more than 350°F below zero, ice, ammonia, and methane remain frozen—handy supplies if a lunar base were to be established here.



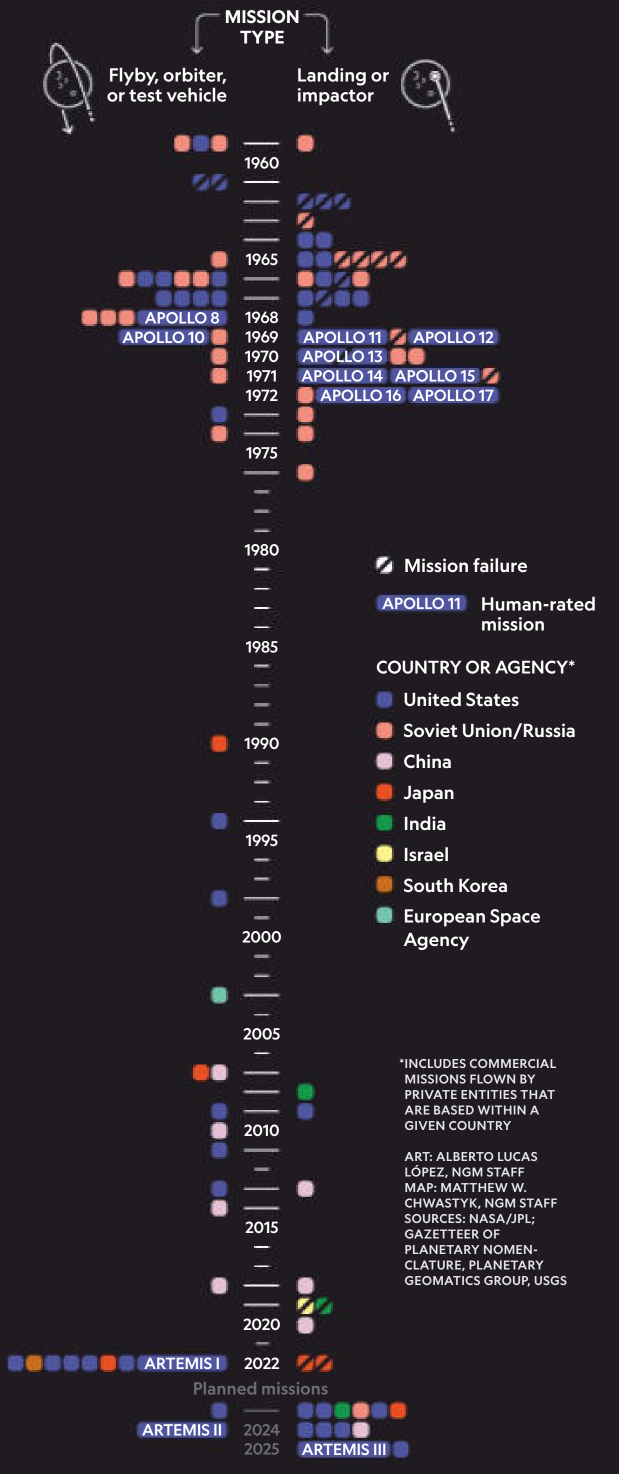
ng keeps the moon's near side
mits tilt on the lunar axis. Some
poles are high enough to block
g basins in perpetual shadow.





THE SPACE RACE CONTINUES

The effort to get humans to the moon—and back—has fueled decades of competition, beginning with the rivalry between the U.S. and the U.S.S.R. in the 1950s and '60s.



*INCLUDES COMMERCIAL MISSIONS FLOWN BY PRIVATE ENTITIES THAT ARE BASED WITHIN A GIVEN COUNTRY

ART: ALBERTO LUCAS LÓPEZ, NGM STAFF
MAP: MATTHEW W. CHWASTYK, NGM STAFF
SOURCES: NASA/JPL; GAZETTEER OF PLANETARY NOMENCLATURE, PLANETARY GEOMATICS GROUP, USGS


NASA
VICTOR GLOVER

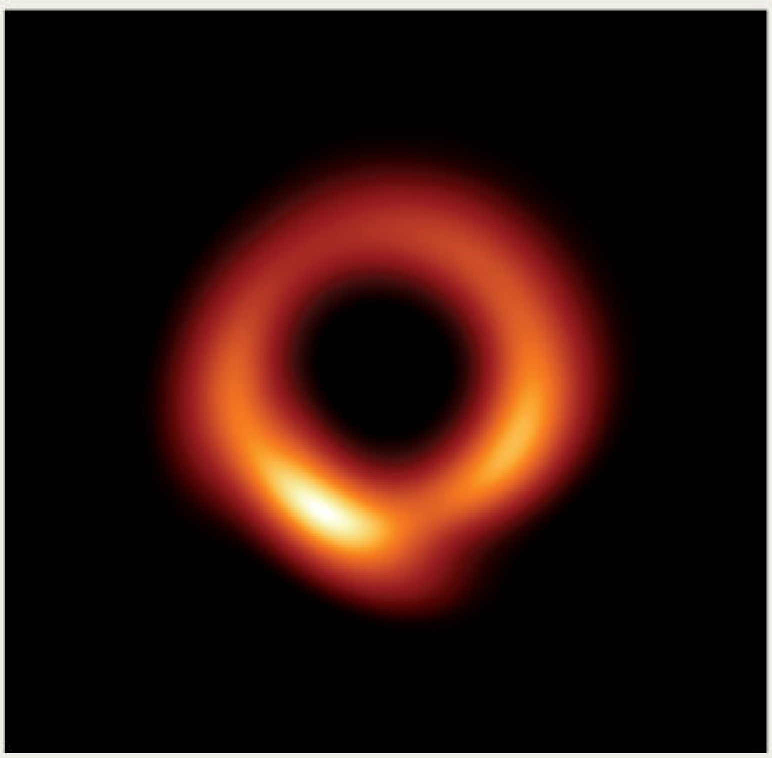
When Artemis II, the program's first crewed mission, flies around the moon, astronaut Victor Glover will be piloting the four-person voyage. The California native has logged more than 3,000 flight hours and nearly six months on the International Space Station. "You hear people refer to 'moon shots' anytime humans do something great," he says. "It's going to be amazing for our generation to have its own actual moon shot."

Last October, NASA's space exploration vehicle, a concept rover that can house two people for two weeks, traversed the Arizona desert for tests conducted with Japan's space agency, JAXA, which may provide similar vehicles to future Artemis crews. Long term, NASA envisions using pressurized rovers to transport astronauts across the lunar surface. One day, such vehicles may even roll across the surface of Mars.

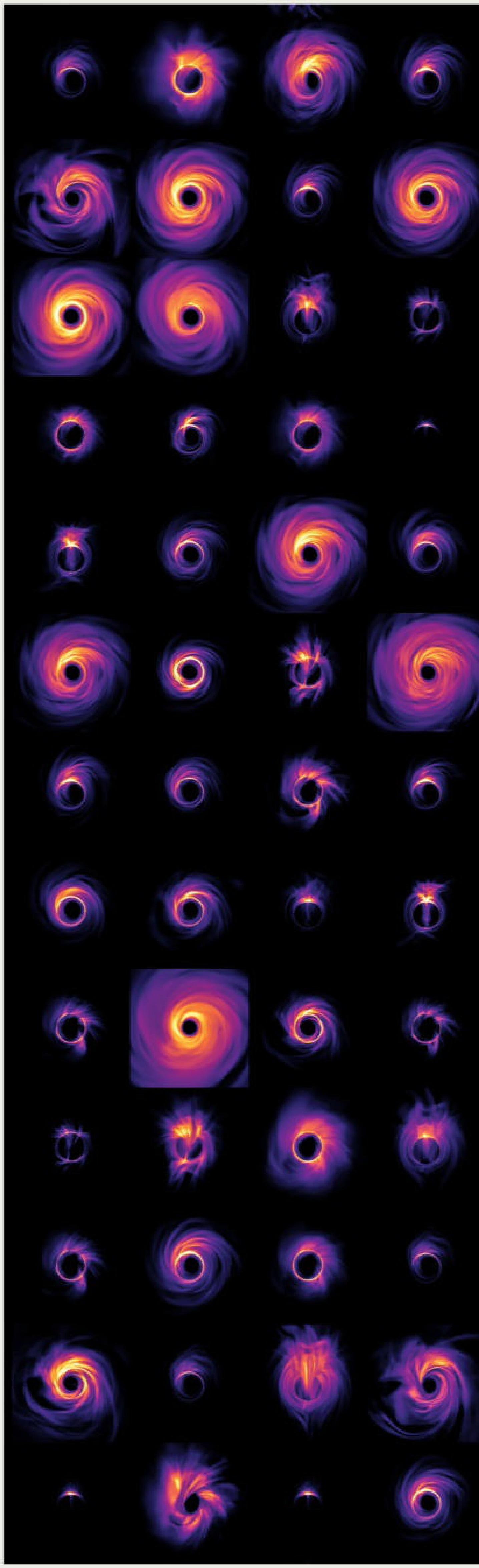

NASA
NASA
NASA

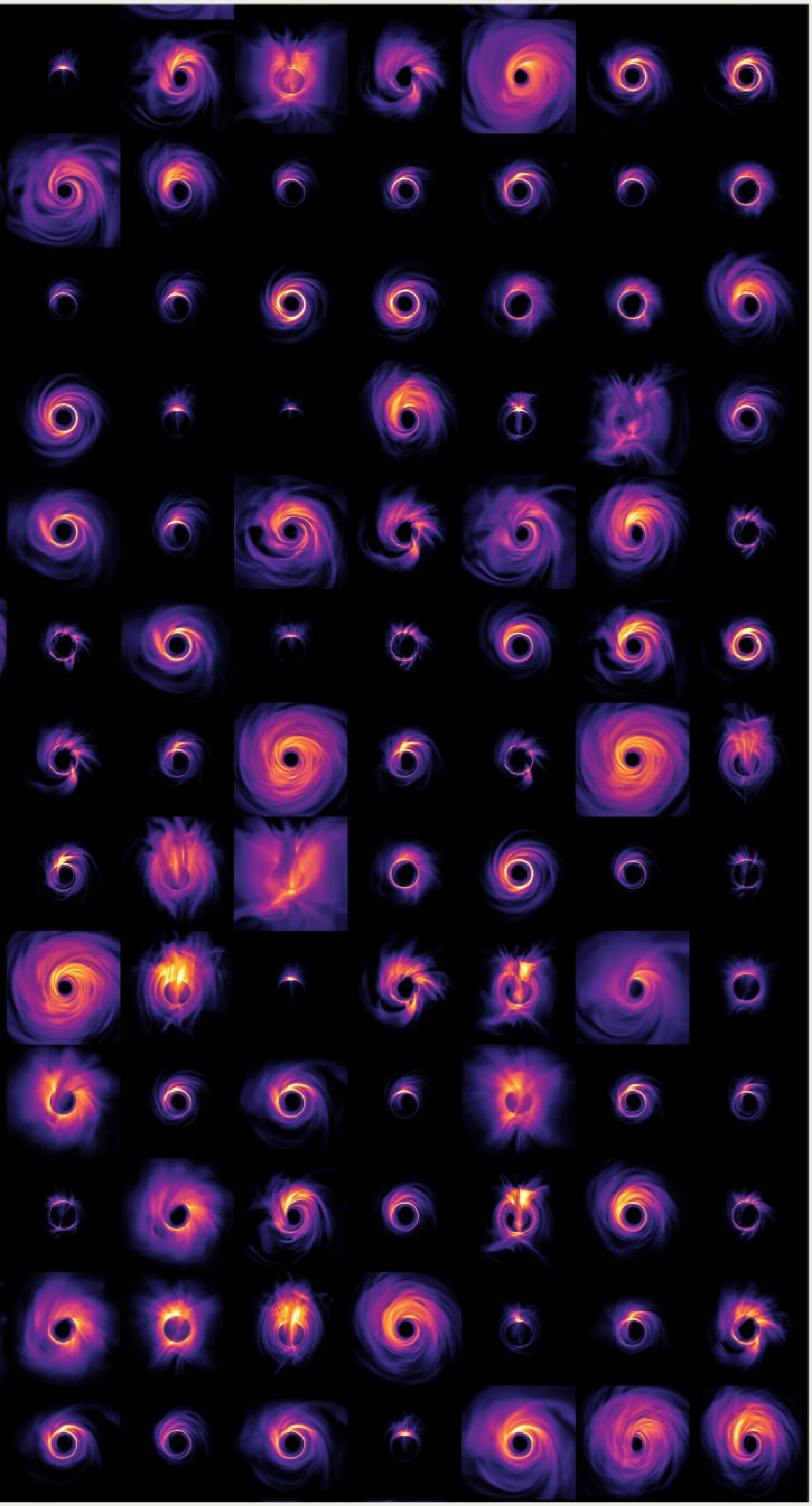
FOCUS

Machine learning is helping us bring mysterious black holes into sharper view.



At top, the first image of the M87 black hole, made in 2019. Above, a more refined image, revealed in 2023, using PRIMO machine learning.





No one has ever seen a black hole, but in 2019, scientists presented the silhouette of one at the center of the Messier 87 galaxy more than 50 million light-years away. Vast amounts of data from a global array of observatories called the Event Horizon Telescope were processed, with computer algorithms filling the gaps. Although a scientific feat, the resulting image—a void surrounded by an orange aura—appeared blurry. Now, a team of researchers has used machine learning to produce a sharper look (at left, some of the program's more than 30,000 simulations). Called PRIMO, this method revealed a thinner ring around the black hole—helpful in understanding how much matter its gravity is pulling in. Three more telescopes have turned their eyes on M87, says Lia Medeiros, an astrophysicist at the Institute for Advanced Study who leads the project. Using PRIMO on the new data may yield even better images, she says, and possibly capture signs of matter swirling around the black hole.

LIA MEDEIROS, INSTITUTE FOR ADVANCED STUDY (ABOVE); L. MEDEIROS, INSTITUTE FOR ADVANCED STUDY, D. PSALTIS, GEORGIA TECH, T. LAUER, NSF'S NOIRLAB, AND F. OZEL, GEORGIA TECH (OPPOSITE)

TIME TRAVEL TO ANCIENT GALA

XIES

BY **JAY BENNETT**

THE MOST POWERFUL SPACE TELESCOPE EVER BUILT IS HUNTING FOR THE ORIGINS OF THE UNIVERSE.

In one of the deepest views into the universe ever achieved, the James Webb Space Telescope reveals thousands of stars and galaxies, including the bright light-warping cluster in the center.

COMPOSITE BY NASA, ESA, CSA, STSCI

In this region of the Orion Nebula where ultraviolet radiation from a nearby star cluster is driving intense chemical reactions, Webb recently discovered methyl cation. The carbon compound—never before detected in space—facilitates the formation of more complex carbon molecules, which are needed for life.

COMPOSITE BY ESA/WEBB, NASA, CSA, M. ZAMANI (ESA/WEBB), PDRS4ALL ERS TEAM

Only four of the five galaxies known as Stephan's Quintet (at right) are truly close together, pulling at one another in a swirling dance. The unprecedented detail provided by Webb gives scientists an opportunity to study how the interaction between galaxies may have driven their early evolution.

COMPOSITE BY NASA, ESA, CSA, AND STSCI

Newborn stars burst forth from cocoons of gas and dust in this Webb image of the Rho Ophiuchi cloud complex, the star-forming region closest to Earth. The area contains about 50 young stars, many with masses similar to the sun's. A larger star in the lower half of the image blasts out a cavern in the thick clouds.

MOSAIC OF SIX IMAGES (180 IMAGES IN SIX FILTERS) BY NASA, ESA, CSA, STSCI, KLAUS PONTOPPIDAN (STSCI)

WHEN THE UNIVERSE WAS YOUNG,

more than 13 and a half billion years ago, no stars shone in the abyss. Astronomers call this era the dark ages, a time when the cosmos was filled with hydrogen and helium gas, the raw material for all the worlds to come.

A mysterious substance known as dark matter existed too, its gravity pulling the gas into an elaborate web. As things expanded and cooled, some of the dark matter consolidated in immense orbs, driving the gas to their cores. The rising gravitational pressure within these halos, as astronomers named them, forced hydrogen atoms to fuse into helium, igniting the primordial universe's first stars.

I watched the spark of cosmic dawn, through 3D glasses. Sitting in front of a projector at the Kavli Institute for Particle Astrophysics and Cosmology at Stanford University, I marveled at filaments of dark matter, a ghostly gray on the screen, branching between halos as the universe stretched. Maelstroms of newly born stars spiraled to the centers of the halos to form the first galaxies.

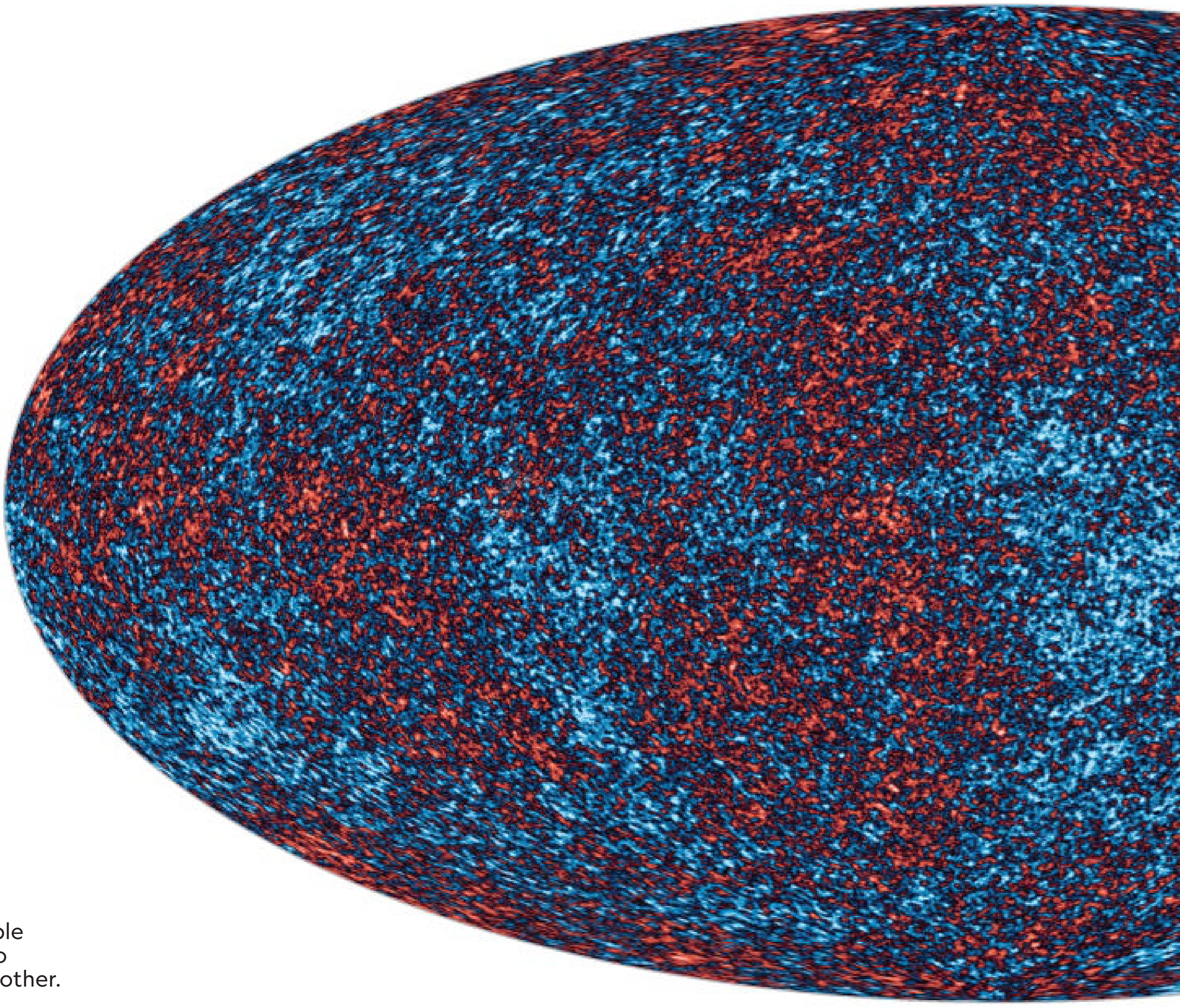
Scientists have been filling in the universe's origin story for decades, but in the past year, the largest and most advanced space telescope ever built has rewritten the first chapters. Ancient galaxies glimpsed by the James Webb Space Telescope (JWST) are brighter, more numerous, and more active

Astronomers Marcia and George Rieke have played key roles in the development and operation of Webb instruments—the near-infrared camera, or NIRCam, and the mid-infrared instrument, or MIRI, respectively, both of which were used to create the projected image of dusty clouds ejected from a burning star.

CHRIS GUNN (RIEKES); COMPOSITE OF 104 IMAGES BY NASA, ESA, CSA, STSCI, WEBB ERO PRODUCTION TEAM

PRIMORDIAL VIEW

The Planck space telescope (2009-2013) surveyed the entire sky for cosmic microwave background radiation, the oldest light in the universe. This residue of the big bang dates to only 380,000 years after the event. Minute differences in temperature dot this map, indicators of where all the stars and galaxies we can see today eventually would form.



At absolute zero—0 kelvin (**K**)—matter reaches the lowest possible temperature where molecules no longer transfer energy to one another.

than anticipated, revealing a frenetic opening to the saga of space and time.

Webb cannot see the first stars, though, as they weren't bright enough to detect individually. These early monsters blazed hot and grew immense before erupting in supernovae a few million years after flaring to life—a blip in astronomical time.

"We really slowed things down a little bit here," said Tom Abel, a computational cosmologist and my guide through the simulations. He wore an earring of a human figure curled in the fetal position; it reminded me of the closing shot of *2001: A Space Odyssey,* where a child in a womb floats in space. "It's just so crazy fast. The full realistic version would have been much faster flashes."

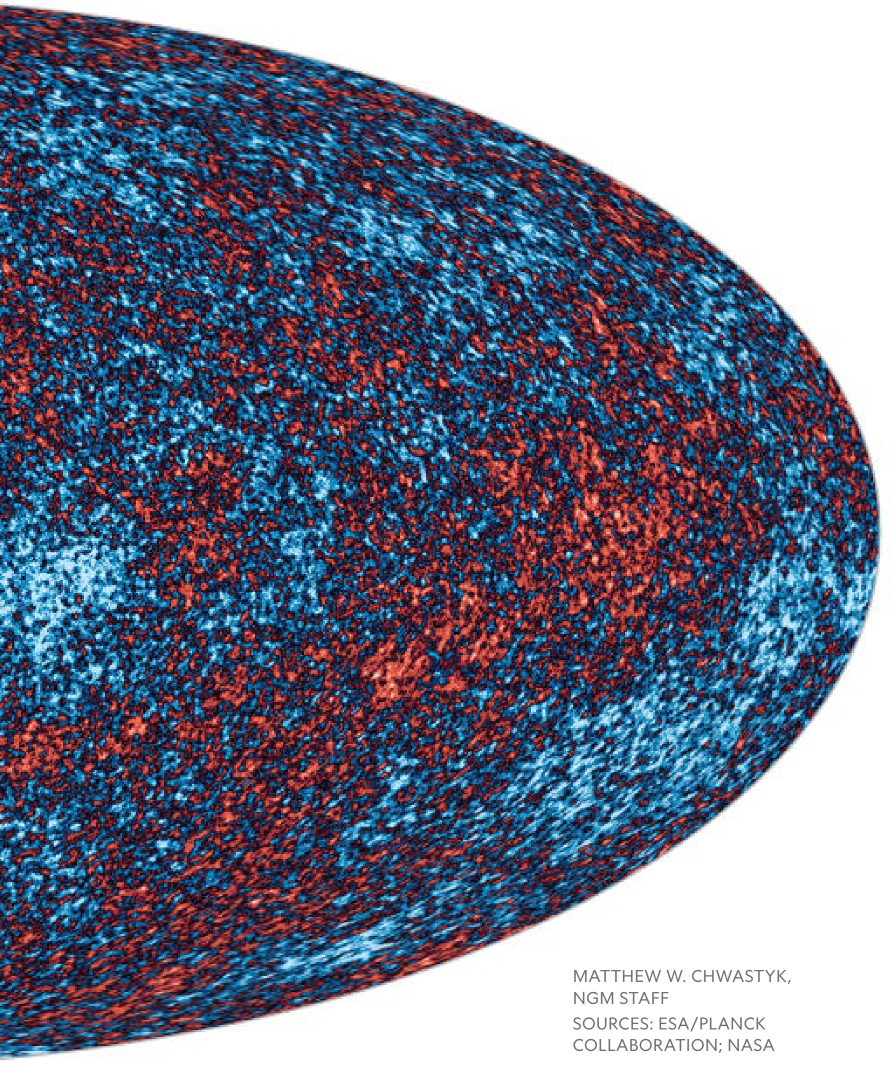
Those flashes, the supernovae of stars up to hundreds of times the mass of the sun, transformed the universe. New elements were generated—oxygen to make water, silicon to build planets, phosphorus to power cells—and scattered throughout the expanse. The first stars also broke apart the atoms of the surrounding hydrogen gas, burning away the cosmic haze and making things transparent—a key time known as reionization. As the fog lifted, pockets of stars merged, swirling into bigger and bigger assemblages, including the seed of our own Milky Way.

Abel began modeling the birth of the first stars in the 1990s, when no one knew what the earliest astronomical object was, whether a black hole or a Jupiter-size body or something else. Through computer simulations, he and his colleagues helped determine that the first things had to be stars, kindled in places where gravity slowly won out over gas pushing outward. But eventually Abel moved on from star-birth simulations; he thought there was nothing more to learn.

Then came Webb.

Launched on Christmas morning in 2021, the space telescope is now positioned nearly a million miles from Earth. Its 21-foot-4-inch gold-coated primary mirror captures the light of ancient galaxies, which has been traveling through space for more than 13 billion years, revealing the galaxies as they were in the distant past.

Astronomers expected to find some of these infant galaxies with Webb. They didn't expect to find so many—or that the discoveries could shake their understanding of galactic history.



MATTHEW W. CHWASTYK, NGM STAFF
SOURCES: ESA/PLANCK COLLABORATION; NASA

THE DEEPEST GALAXY survey of the universe ever undertaken kicked off in September 2022, when an international collaboration known as JADES, or the JWST Advanced Deep Extragalactic Survey, began using Webb to observe patches of sky for dozens of hours at a time. Two weeks after observations began, the collaboration gathered in Tucson at the University of Arizona to discuss the first results.

In a modern five-story building with a large, open-air atrium designed to evoke a slot canyon, some 50 astronomers packed into a classroom. A handful stood at the back or brought in extra chairs to sit along the walls. "I'm going to have to start reserving bigger rooms," said Marcia Rieke, an astronomer at the university and one of the leaders of the collaboration.

The scientists, from tenured professors to twentysomething graduate students, were preoccupied with the mosaic on their laptops: hundreds of images freshly captured by Webb and stitched together. The picture, shared with the team only days before, contained tens of thousands of galaxies and other celestial objects. Excited murmuring ran through the group as they pointed out things to one another that had never been seen: active star-forming regions, glowing galactic centers where black holes might be, and reddish blobs of light from galaxies so distant only Webb could spot them.

"This is a little bit like kids in the candy shop," Rieke said to me.

Unlike the Hubble Space Telescope, our previous window into the universe's distant past, Webb was designed to observe in the infrared, which makes it ideal for capturing early starlight. Those rays left their source as ultraviolet but were stretched to redder wavelengths by the expansion of the universe, a phenomenon known as redshift. The higher the redshift, the farther and older the target.

Rieke managed the proceedings with a combination of unfeigned delight and sage reflection, chiming in to answer a technical question or ambling over to a team member between talks to discuss the workings of the telescope. Besides being a lead scientist on JADES, she's the principal investigator of Webb's near-infrared camera, or NIRCam—the source of the mosaic of galaxies on everyone's laptop. She oversaw its design, a 330-pound assemblage of mirrors, lenses, and detectors to drink in the light of the universe and study it through different filters.

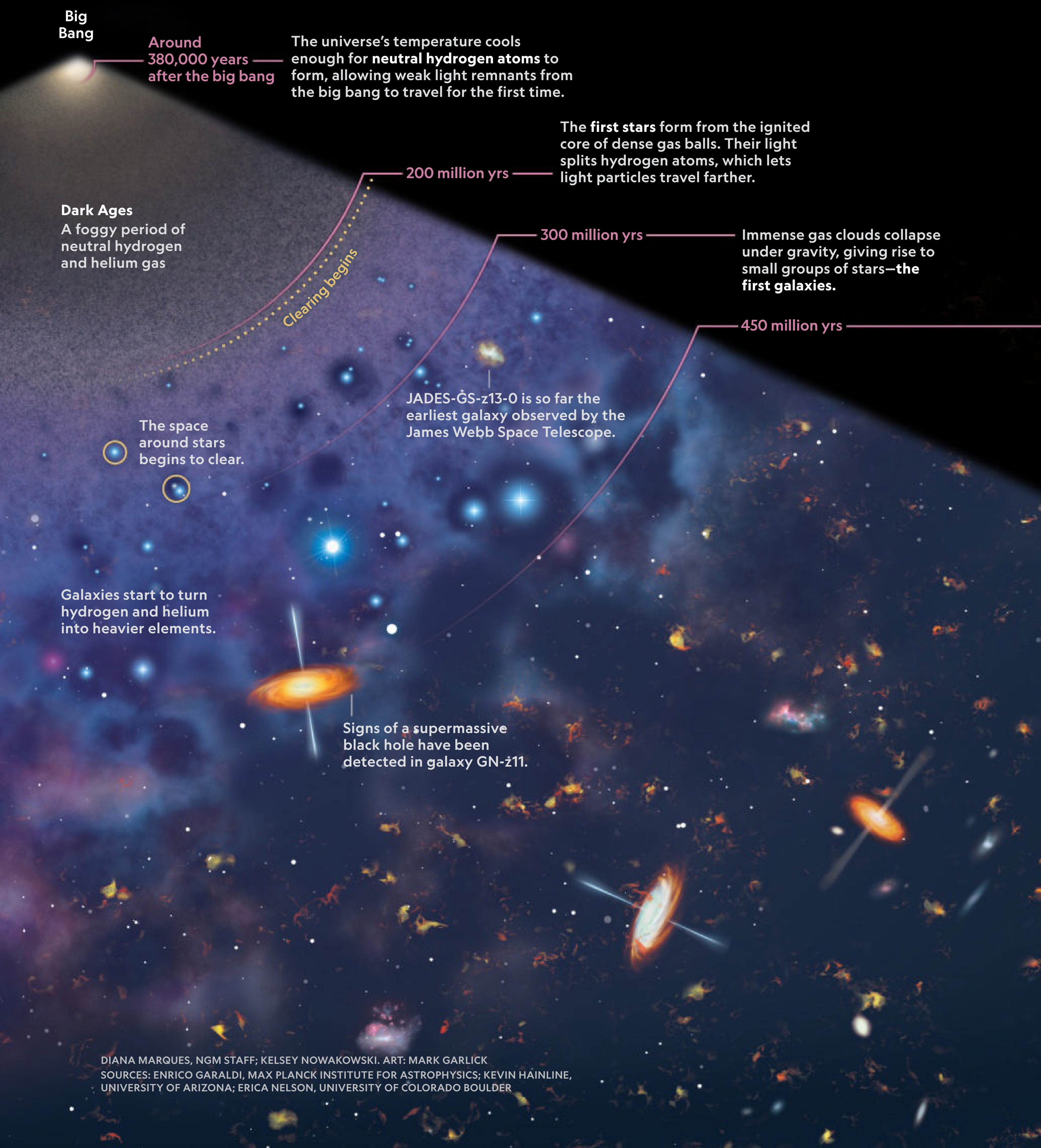
"These images are everything we could have hoped for," she said.

But not everything on the telescope was functioning perfectly. JADES's near-infrared spectrograph, or NIRSpec, had been experiencing electrical shorts that created spots of light and drowned out astronomical targets in some of the observations. The instrument splits light into spectra, allowing scientists to piece together the chemical composition of a galaxy and precisely measure its redshift. While the NIRCam images could be used to estimate the distances to galaxies, NIRSpec was needed to confirm them.

The electrical shorts delayed some of the team's observations, a development that turned out to be serendipitous. The astronomers had planned to use NIRSpec to examine objects already known from Hubble, but now they could change the targets to galaxies only just discovered by NIRCam.

DECODING THE DAWN

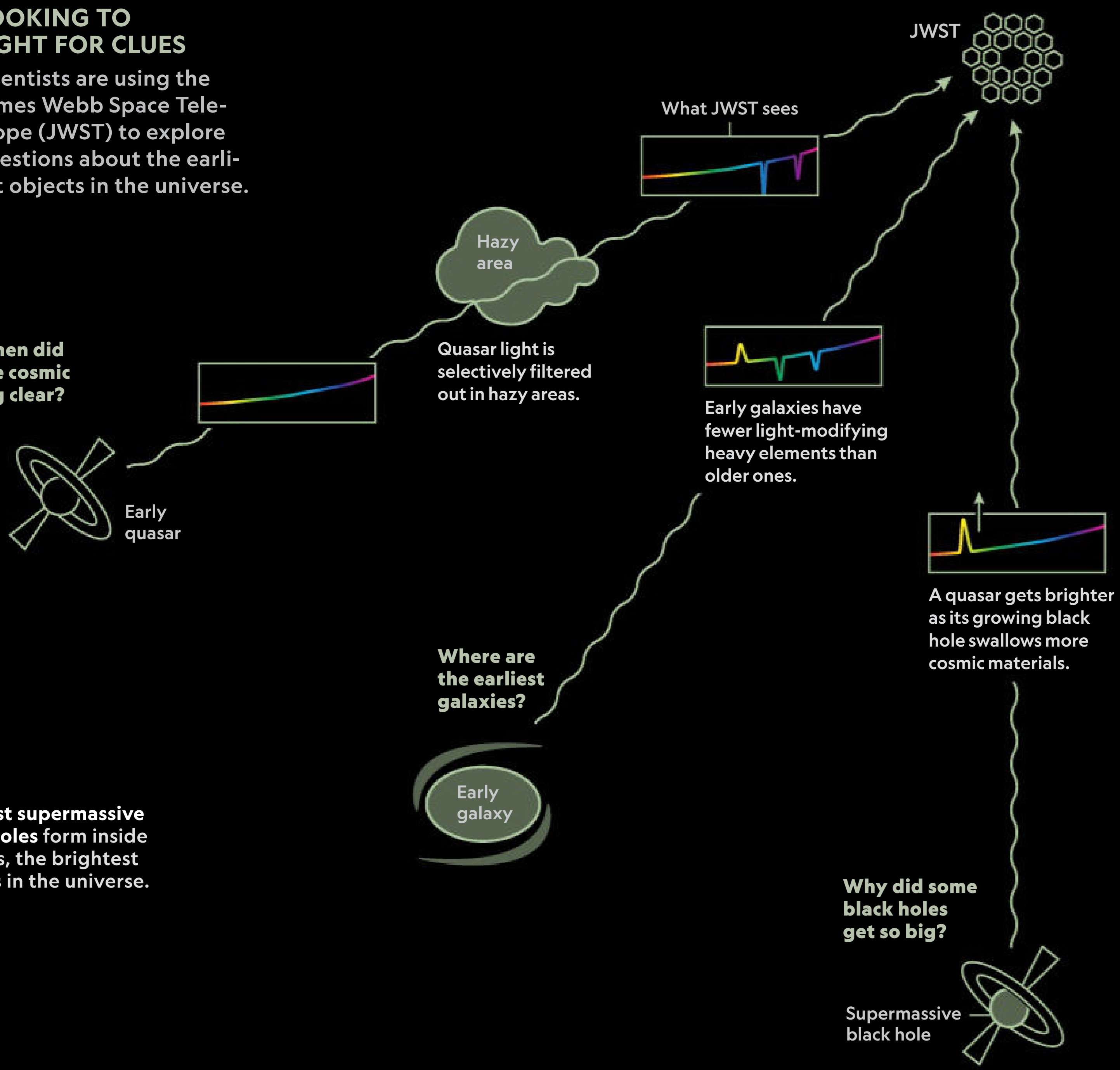
The universe's hazy infancy, known as the dark ages, ended with the arrival of the first stars. Their light launched a process that broke up and cleared the cosmic fog, fueling a billion-year transformation of the universe into a host of galaxies, black holes, and other phenomena across our night sky.



DIANA MARQUES, NGM STAFF; KELSEY NOWAKOWSKI. ART: MARK GARLICK
SOURCES: ENRICO GARALDI, MAX PLANCK INSTITUTE FOR ASTROPHYSICS; KEVIN HAINLINE, UNIVERSITY OF ARIZONA; ERICA NELSON, UNIVERSITY OF COLORADO BOULDER

LOOKING TO LIGHT FOR CLUES

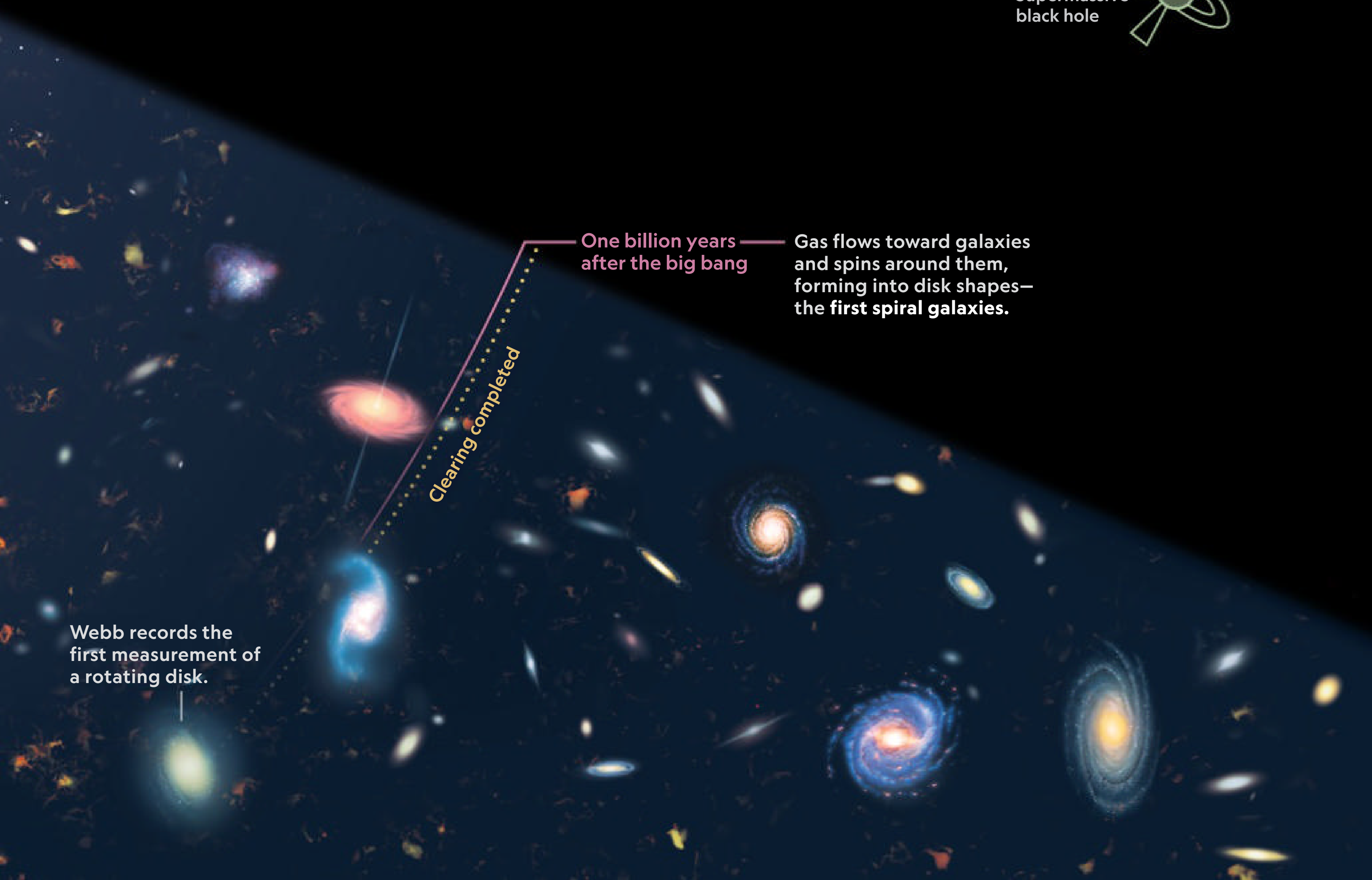
Scientists are using the James Webb Space Telescope (JWST) to explore questions about the earliest objects in the universe.

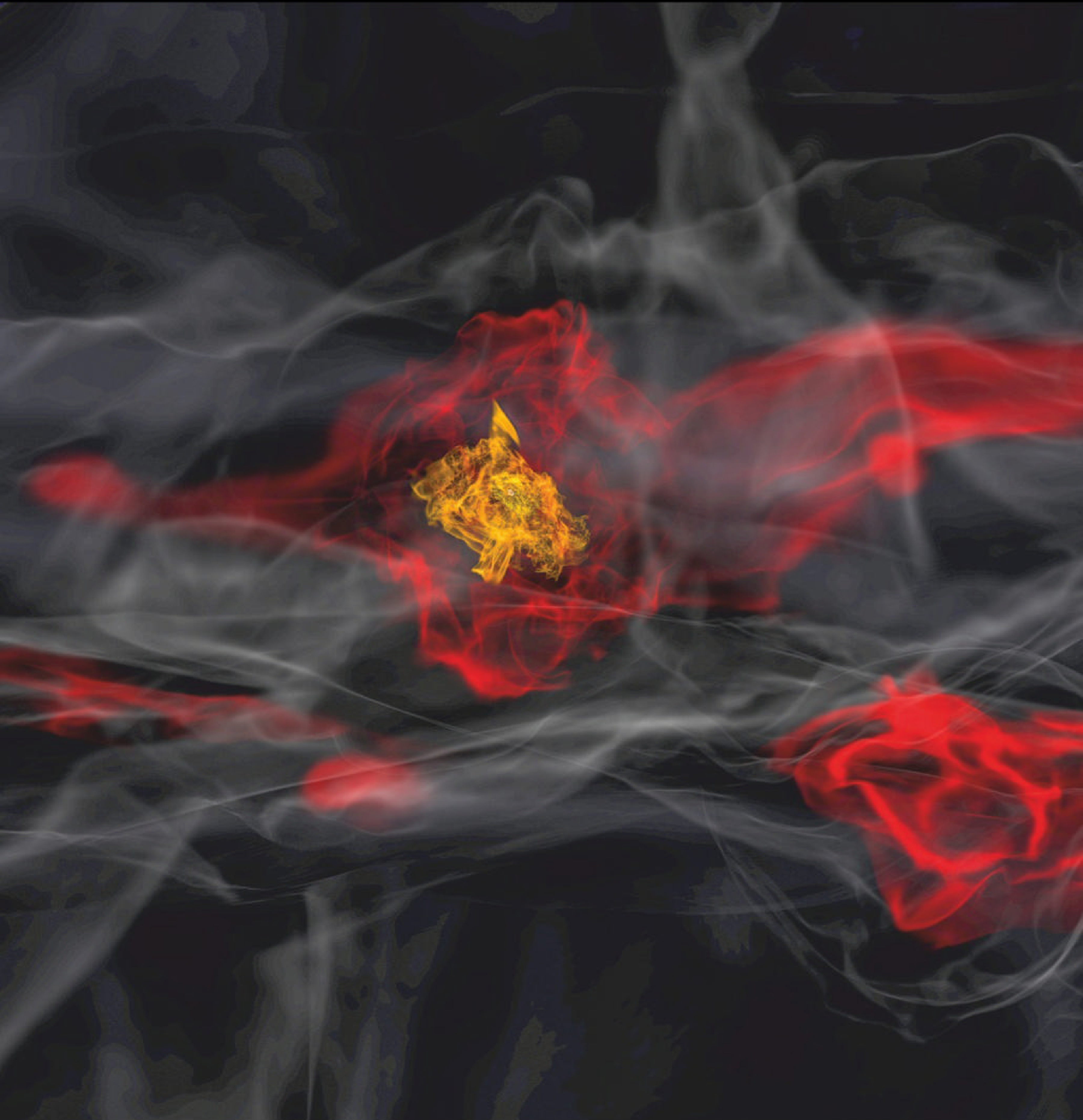


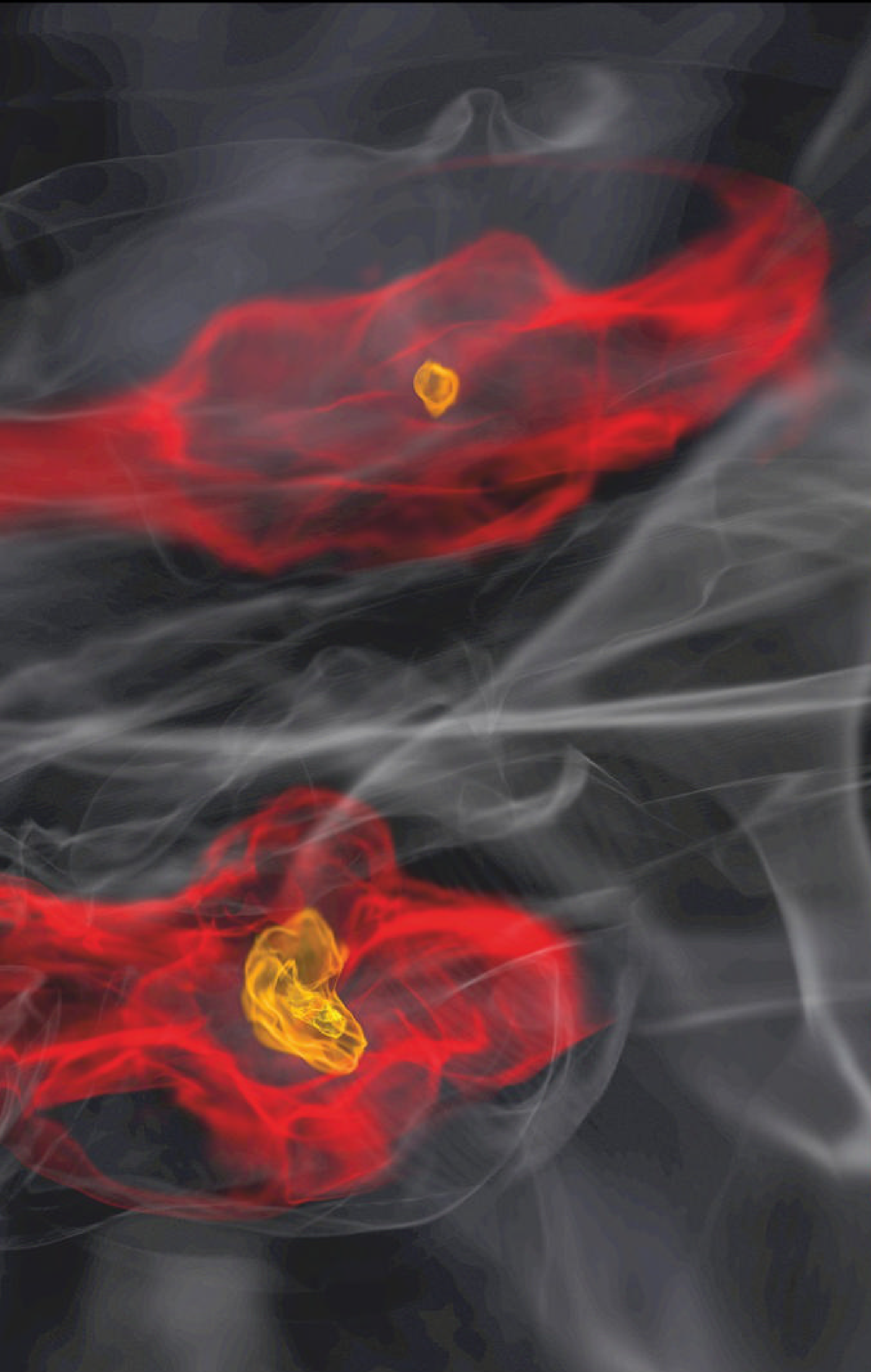
The **first supermassive black holes** form inside quasars, the brightest objects in the universe.

One billion years after the big bang

Gas flows toward galaxies and spins around them, forming into disk shapes—the **first spiral galaxies.**

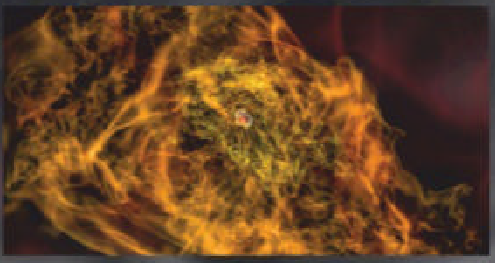




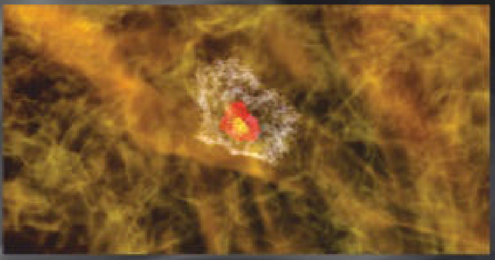


THE FIRST STARS

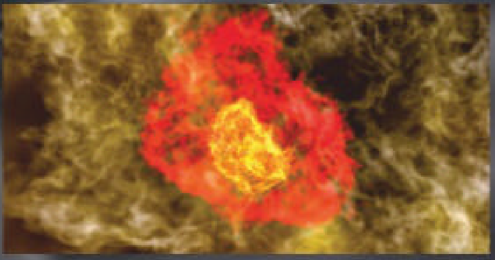
A computer simulation depicts three primordial clouds—early star-forming regions—just 100 million years after the big bang, beyond what Webb can see.



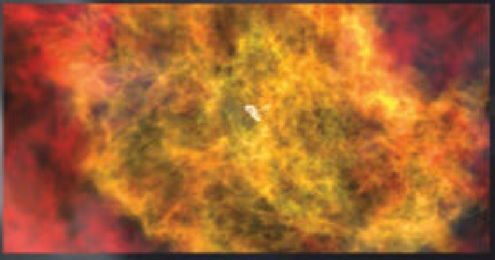
A close-up (above) of the cloud on the far left reveals billowing layers of hydrogen and helium gas being driven inward by surrounding halos of unseen dark matter. The gas accumulates in higher and higher densities, shown in red and yellow.



Deeper in the cloud's structure, hydrogen molecules cool the gas, allowing it to collapse. Within this cold cloud, massive stars will form.

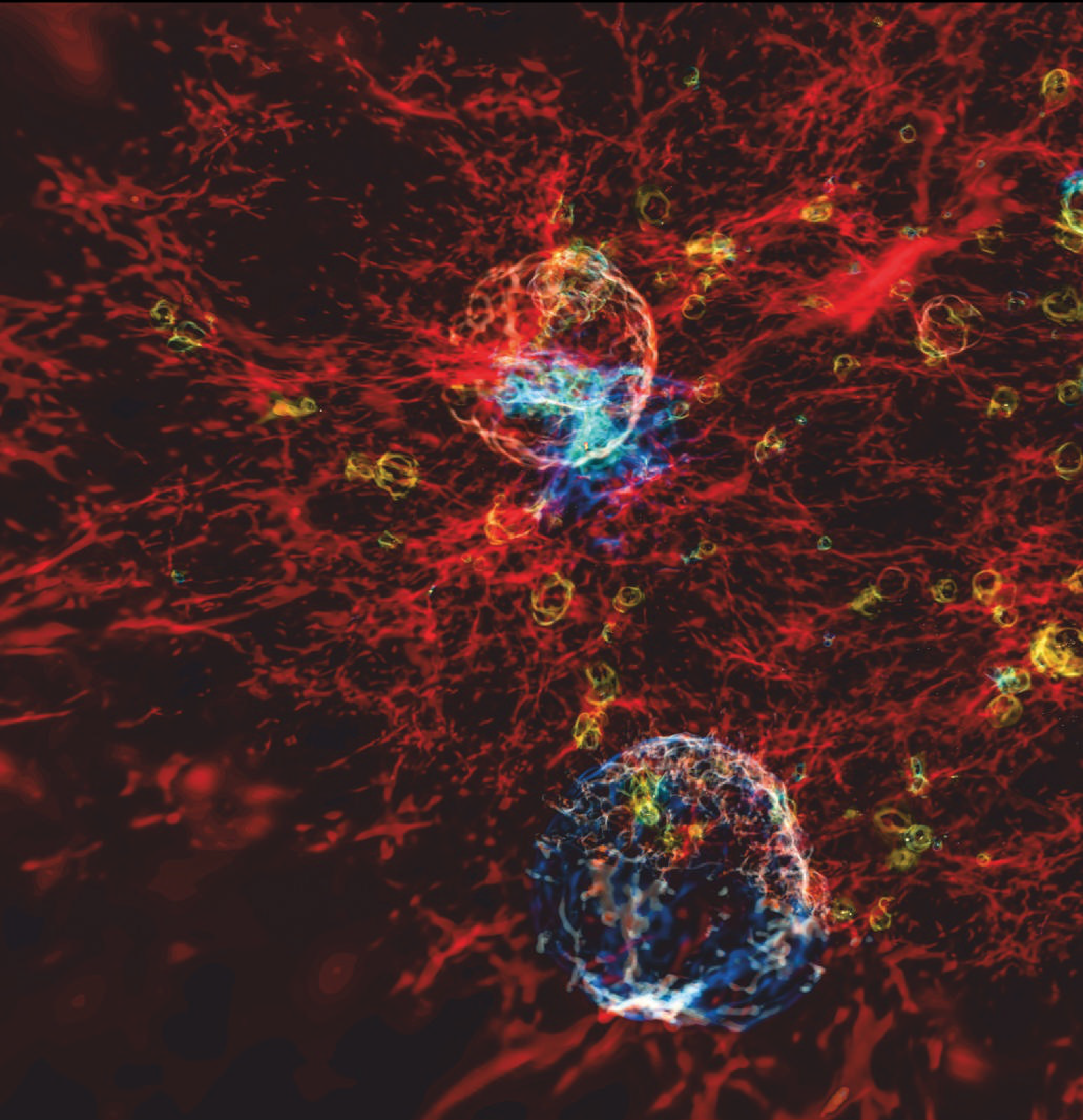


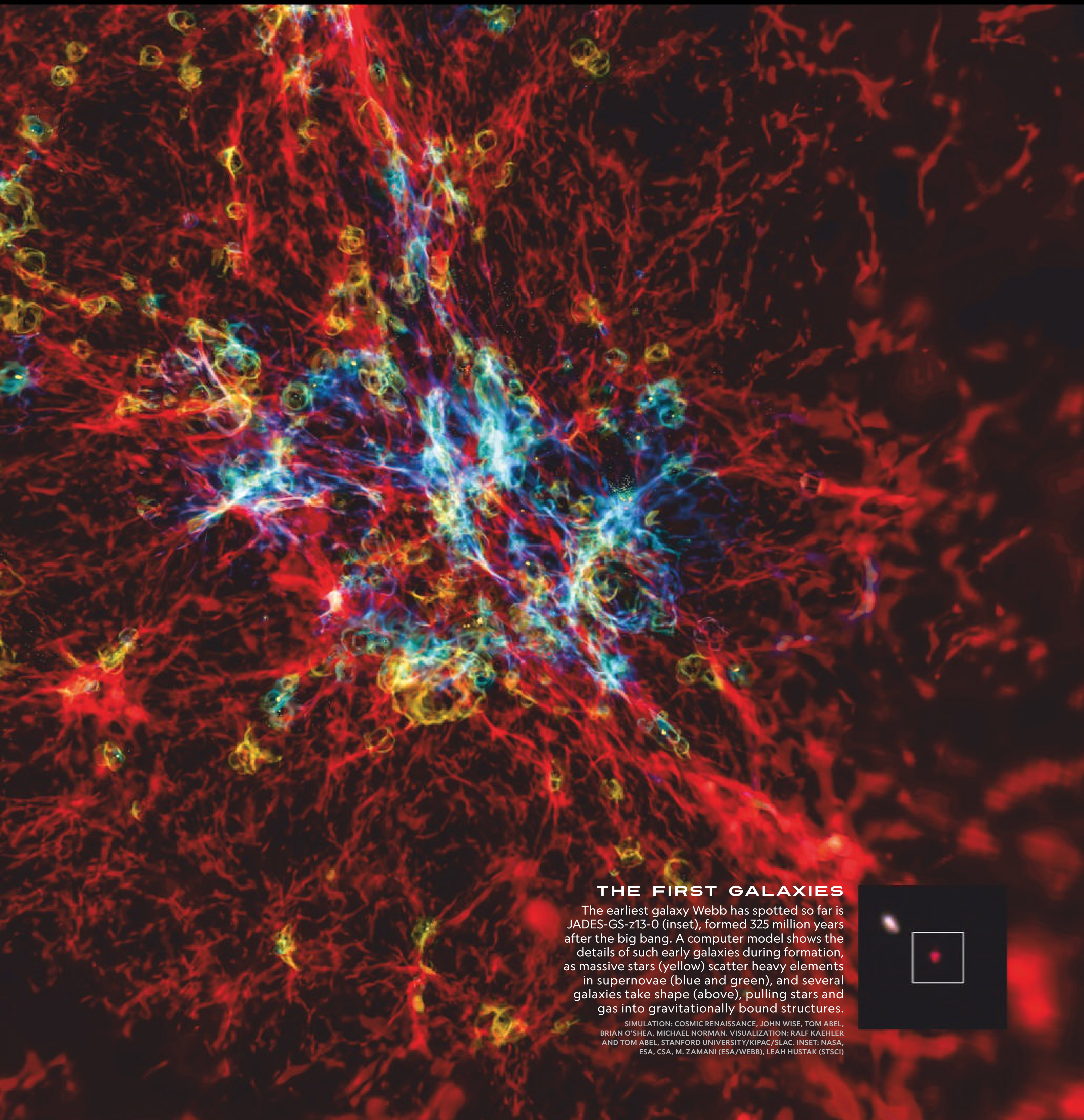
Hundreds of solar masses compress in the yellow area. Most of them will end up in the first stars.



The small bright region in the center of this cosmic pileup is roughly the size of the solar system. The hydrogen eventually fuses into helium, birthing the first stars in the universe.

RALF KAEHLER AND TOM ABEL, STANFORD UNIVERSITY/KIPAC/SLAC





THE FIRST GALAXIES

The earliest galaxy Webb has spotted so far is JADES-GS-z13-0 (inset), formed 325 million years after the big bang. A computer model shows the details of such early galaxies during formation, as massive stars (yellow) scatter heavy elements in supernovae (blue and green), and several galaxies take shape (above), pulling stars and gas into gravitationally bound structures.

SIMULATION: COSMIC RENAISSANCE, JOHN WISE, TOM ABEL, BRIAN O'SHEA, MICHAEL NORMAN. VISUALIZATION: RALF KAEHLER AND TOM ABEL, STANFORD UNIVERSITY/KIPAC/SLAC. INSET: NASA, ESA, CSA, M. ZAMANI (ESA/WEBB), LEAH HUSTAK (STSCI)

"We just went crazy looking through this data that no one had ever seen, looking for these candidates," Kevin Hainline, an astrophysicist at the University of Arizona, told me later in his office.

One thing the team couldn't do was change where the telescope was pointing. It had to find objects already in the field of view—and thanks to a bit of luck, four faraway galaxies detected by NIRCam were sitting in the right spot. Two of those, NIRSpec observations would later confirm, were more distant and ancient than any known before.

The most far-flung of the bunch, called JADES-GS-z13-0, had been formed only 325 million years after the big bang. "I still have the Slack message where I first saw this object in the data and sent it to the group," Hainline said. "In the craziness of it, I didn't realize the profundity of this moment of sitting there and being like, Oh, that's the farthest galaxy that humans have ever seen."

Two things are already clear about these early galaxies: There are more of them than expected, and they are surprisingly bright for their age. These anomalies could be because the first stars formed more efficiently than thought or there was a larger proportion of big stars than hypothesized. "However star formation gets going in the early universe, it's not quite like how we might have predicted," Rieke says.

One early galaxy, GN-z11 from some 440 million years after the big bang, is bright enough that Hubble spotted it in 2016. Now Webb has observed the object as well, including taking its spectrum with NIRSpec.

"This one has everyone sort of confused and excited," says Emma Curtis-Lake, an astrophysicist at the University of Hertfordshire in England and a member of the NIRSpec team.

Certain elements create bright emission lines in a galaxy's spectrum, like fingerprints by galactic material. The spectrum of GN-z11 revealed a surprising amount of nitrogen—confounding scientists, who can't explain its source. Perhaps a population of raging hot stars known as Wolf-Rayet stars scattered nitrogen in pulses of stellar wind. Or maybe several large stars collided, mixing up the material in their cores and surfaces and releasing nitrogen in the process.

GN-z11 may also host a supermassive black hole, which would be remarkable for this early time. It'd be "the most distant black hole that we've seen," Curtis-Lake says.

Obscured at the center of the bright galaxy, it was exposed by spectral lines that Curtis-Lake calls "little hidden monsters." These lines suggest that material is moving rapidly in a dense area, swirling at roughly a million miles an hour—the kind of thing you would expect to see near a black hole. But how one of these objects could have grown so rapidly remains unsolved.

THIS

AIN'T LIKE IT used to be," said Rieke's husband, George, as he stepped into a control room that doubled as a kitchenette. "No," Marcia agreed. "There's five times as many monitors."

The couple had offered to show me an old telescope in the mountains near Tucson, where they spent much of their early careers. Both astronomers at the University of Arizona, they'd met in 1972, when George hired Marcia out of grad school. The 61-inch telescope on Mount Bigelow was fairly new then, used to make maps of the lunar surface. It became one of the leading observatories in the budding field of infrared astronomy, a grandfather of sorts to Webb.

The Riekes helped facilitate this succession. While Marcia oversaw the development of NIRCam, George is the lead scientist on Webb's mid-infrared instrument, or MIRI. The Riekes were trained to stay awake through the night, slowly adjusting the telescope to keep a target in sight as Earth rotated. Their acolytes today can do most of their work from laptops.

"Just a bunch of wimps," George quipped.

In the 1970s Marcia and George used the telescope on Mount Bigelow to make some of the first infrared observations of the Milky Way's center. Scientists had assumed this part of our galaxy was "a collection of old, uninteresting stars," Marcia explained. But in infrared light, turbulent pockets of gas with rapid star formation were revealed. "That whole picture got changed," George added.

At the time, the infrared light of the cosmos was only just coming into view. New sensors tuned to the infrared revealed this previously hidden part of the electromagnetic spectrum, which is the full range of light, from gamma rays to radio waves. The telescope on Mount Bigelow helped fill a gap in observations of the local universe, and Webb has similarly plugged a hole in our view of the deep cosmos.

Many of the early-career astronomers working on Webb are nearly frantic in their excitement, breathlessly discussing new discoveries and racing to publish scientific papers. Marcia and George, who helped reveal new wonders of our own galaxy, don't seem to be in that kind of rush. The space observatory is working well, and the cosmic missives it has begun to receive will be deciphered in due time.

But to fully understand our cosmic origins, we will need more than just Webb.

'I DIDN'T REALIZE THE PROFUNDITY OF THIS MOMENT OF SITTING THERE AND BEING LIKE, OH, THAT'S THE FARTHEST GALAXY THAT HUMANS HAVE EVER SEEN.'

KEVIN HAINLINE, ASTROPHYSICIST

ON A RECENT APRIL morning, I squinted in the sunlight on an expansive plateau between snowcapped volcanoes in Chile's Atacama Desert. Plastic tubes tickled my nostrils with the flow of oxygen, a requirement for anyone visiting the 16,400-foot-high site of the Atacama Large Millimeter/submillimeter Array (ALMA).

The sky was a deeper shade of blue up there, with fewer molecules in the atmosphere to scatter the light—the very thing that makes this place perfect for astronomy. Towering before me were dozens of four-story-tall radio dishes, white sentinels scattered across the Chajnantor plateau. They pivoted in unison to lock onto a new target.

Among the most advanced radio observatories on the planet, ALMA is also one of the few tools capable of examining the early galaxies being discovered by Webb, albeit in a different light. Webb captures starlight punching through the dust of these galaxies, while ALMA searches for the glow of the dust itself, heated by the stars within.

"These first dust grains come from supernova explosions, so you can indirectly obtain information about the first supernova explosions and the first population of stars," says María Emilia De Rossi, an astrophysicist at the Institute for Astronomy and Space Physics (IAFE) in Buenos Aires.

ALMA has trained its radio dishes on some of the early galaxies, but in most of its first attempts, the array wasn't able to find any dust emissions. This could mean that the galaxies are in their infant stages and have not yet produced much dust through stellar explosions, or it could mean that some are actually closer than thought.

In one case, ALMA detected an emission line just beside a target from Webb, perhaps indicating that the galaxy's stars had blown the dust away or that two galaxies in different phases of their lives were in the process of merging.

ALMA's first attempts to detect the galaxies discovered by Webb were only glances, short-duration observations slotted into its busy schedule. Astronomers plan to point the array at some of these galaxies for longer periods, searching for faint signals that could reveal how much dust they have generated and, crucially, how many heavy elements they have produced—an indication of how far along they are in galactic evolution.

Toward the end of my visit, I stopped by an enormous hangar at ALMA's operations facility, lower at 10,000 feet. Two of the towering radio dishes had been brought down from the high site on a 28-wheel transporter vehicle. Workers on lifts were busy replacing some of the dishes' components, part of a series of upgrades to make the observatory even more capable.

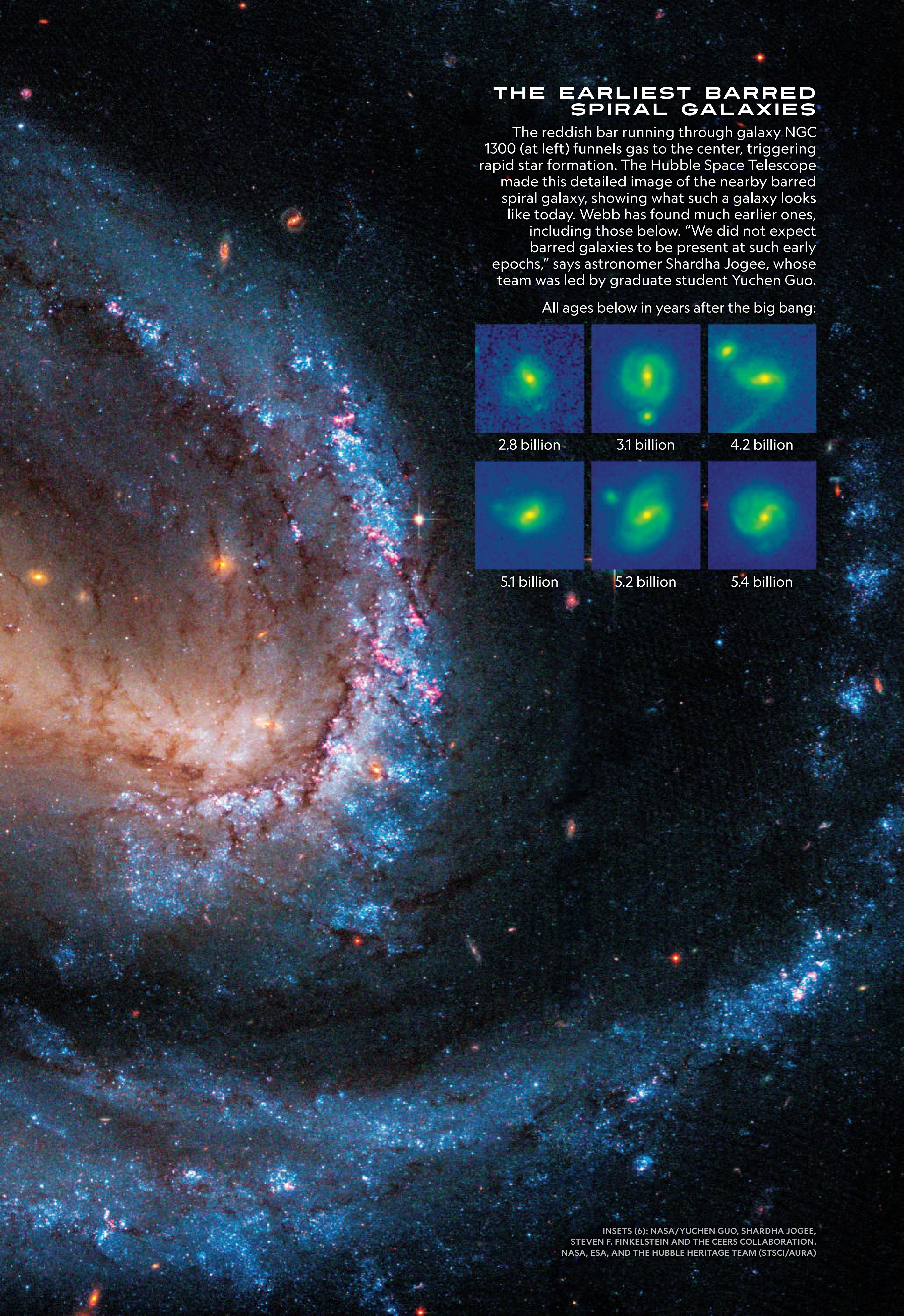
Soon the dishes would be returned to the plateau—ready to swing their gaze back to the firmament, primed to tackle the mysteries of primordial galaxies.

Senior science editor **Jay Bennett** most recently wrote about how early cultures used meteorites.

A GALAXY FROM THE DAWN OF TIME

Distant galaxies are not the only way to learn about the primordial cosmos. Nearby dwarf galaxies, such as Wolf-Lundmark-Melotte (top left, in an image from the European Southern Observatory's VLT Survey Telescope in Chile), contain small stars that formed early in the universe and are still around today. Webb has now peered into the galaxy (both images below) to study some of these ancient, slow-burning stars—fossils from earlier eras.

TOP LEFT: EUROPEAN SOUTHERN OBSERVATORY (ESO). BOTTOM (2): NASA; ESA; CSA; KRISTEN MCQUINN, RUTGERS UNIVERSITY; ZOLT G. LEVAY; ALYSSA PAGAN (STSCI)



THE EARLIEST BARRED SPIRAL GALAXIES

The reddish bar running through galaxy NGC 1300 (at left) funnels gas to the center, triggering rapid star formation. The Hubble Space Telescope made this detailed image of the nearby barred spiral galaxy, showing what such a galaxy looks like today. Webb has found much earlier ones, including those below. "We did not expect barred galaxies to be present at such early epochs," says astronomer Shardha Jogee, whose team was led by graduate student Yuchen Guo.

All ages below in years after the big bang:

2.8 billion | 3.1 billion | 4.2 billion

5.1 billion | 5.2 billion | 5.4 billion

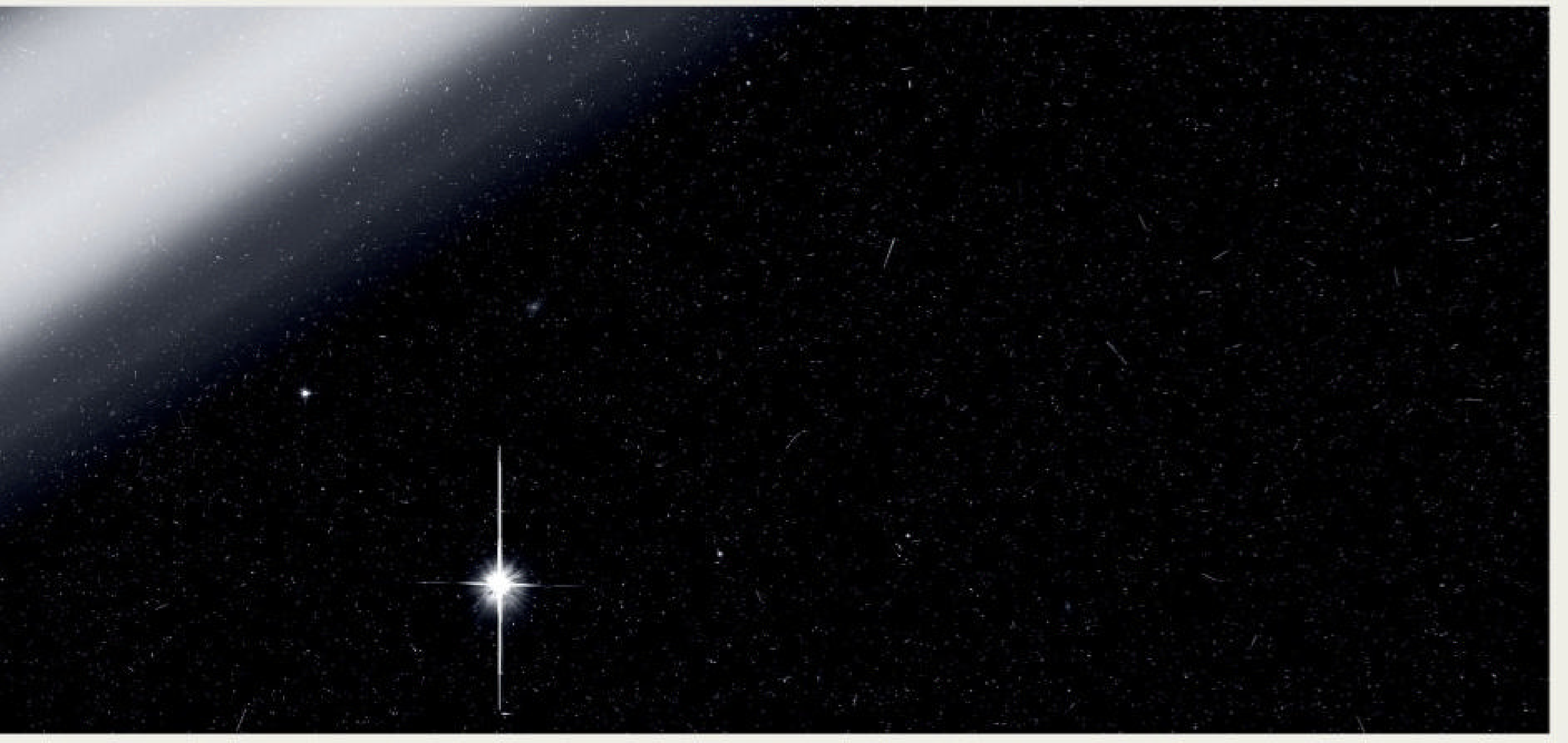
INSETS (6): NASA/YUCHEN GUO, SHARDHA JOGEE, STEVEN F. FINKELSTEIN AND THE CEERS COLLABORATION. NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

LIGHT

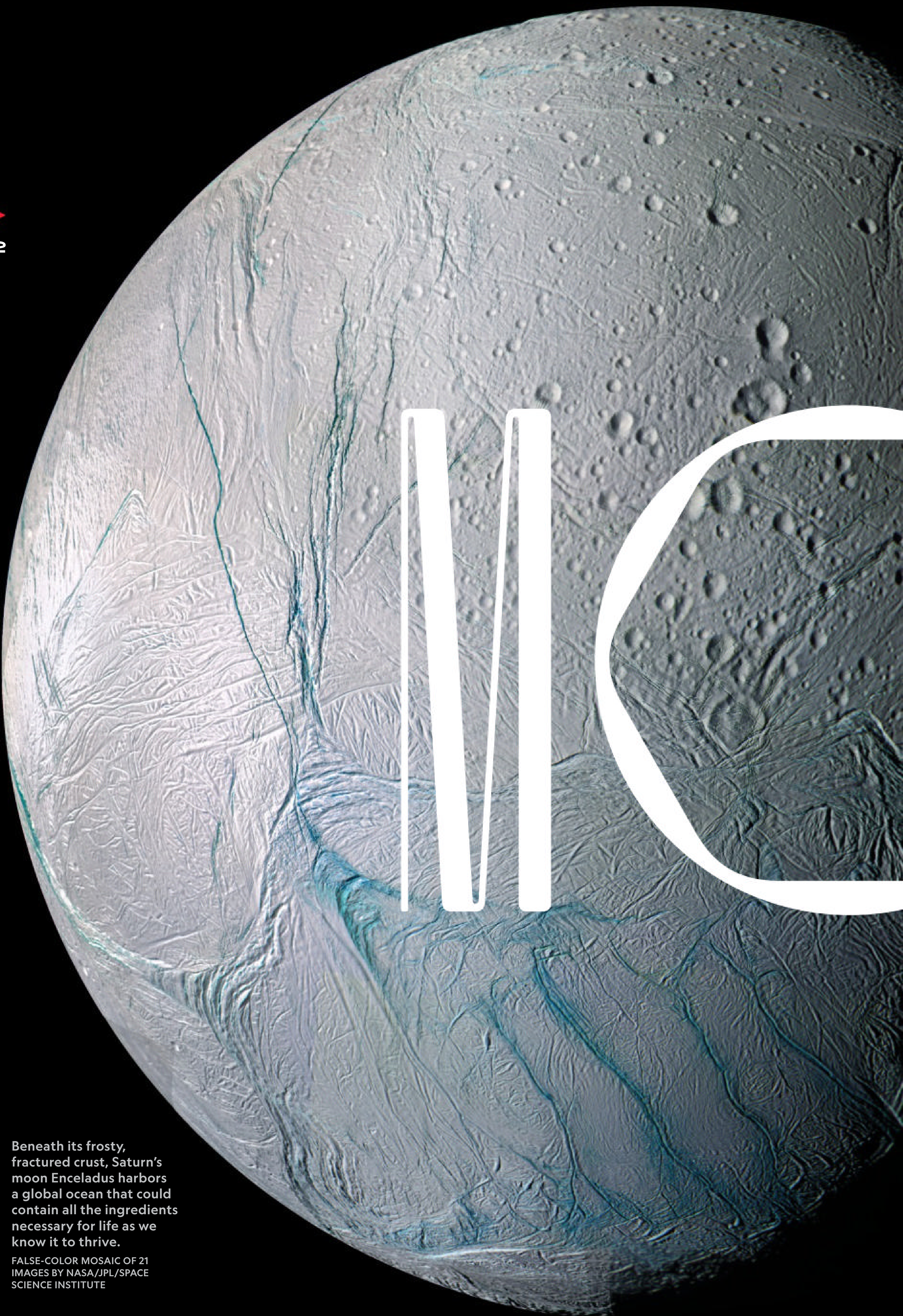
Vying for room at the edge of space, growing satellite traffic is crowding the skies.

The new generation of satellites orbiting close to Earth allows for high-speed internet across the planet. But booming connectivity begets congestion: There are more than 11,000 satellites in the skies. Within this decade, that number could top 100,000. Appearing as streaks of light in telescopic photography, satellites can obscure stars and overexpose images, making it a challenge for astronomers to study the cosmos. A recent study published in *Nature Astronomy* found that, on average, some 3 percent of individual images captured by the Hubble Space Telescope between 2002 and 2021, including those at right, contained at least one satellite trail. While the rate is still relatively low, the study estimates that by the 2030s, up to 50 percent of Hubble's photographs may be marred by satellite streaks.

Streaks from orbiting satellites, as in this image of the Orion Nebula, have long been a problem for ground-based telescopic photography.

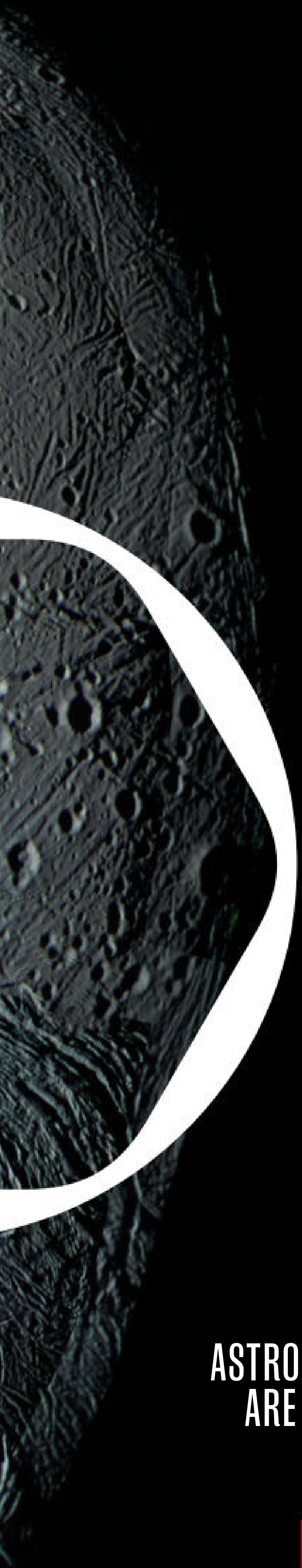


COMPOSITE BY A.H. ABOLFATH (OPPOSITE); NASA, ESA, KRUK AND OTHERS (3 PHOTOS THIS PAGE)



Beneath its frosty, fractured crust, Saturn's moon Enceladus harbors a global ocean that could contain all the ingredients necessary for life as we know it to thrive.

FALSE-COLOR MOSAIC OF 21 IMAGES BY NASA/JPL/SPACE SCIENCE INSTITUTE



THE

ALIEN OON SHOT

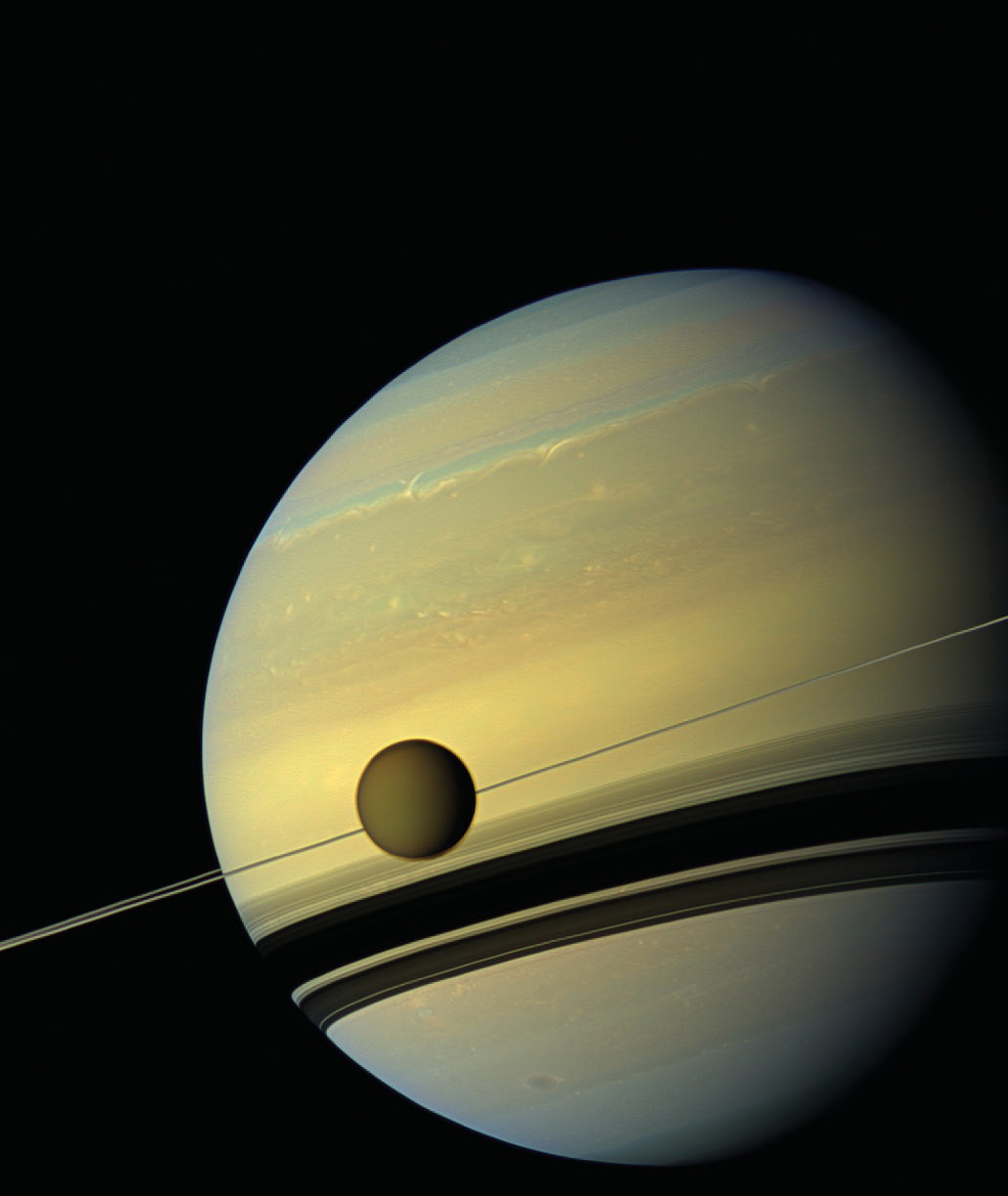
BY **NADIA DRAKE**

PHOTOGRAPHS BY **CARSTEN PETER** AND **CHRIS GUNN**

ASTROBIOLOGISTS ARE SEARCHING THE SOLAR SYSTEM'S ICY MOONS FOR LIFE. BUT FIRST, THEY MUST TEST THEIR TECHNIQUES HERE ON EARTH.

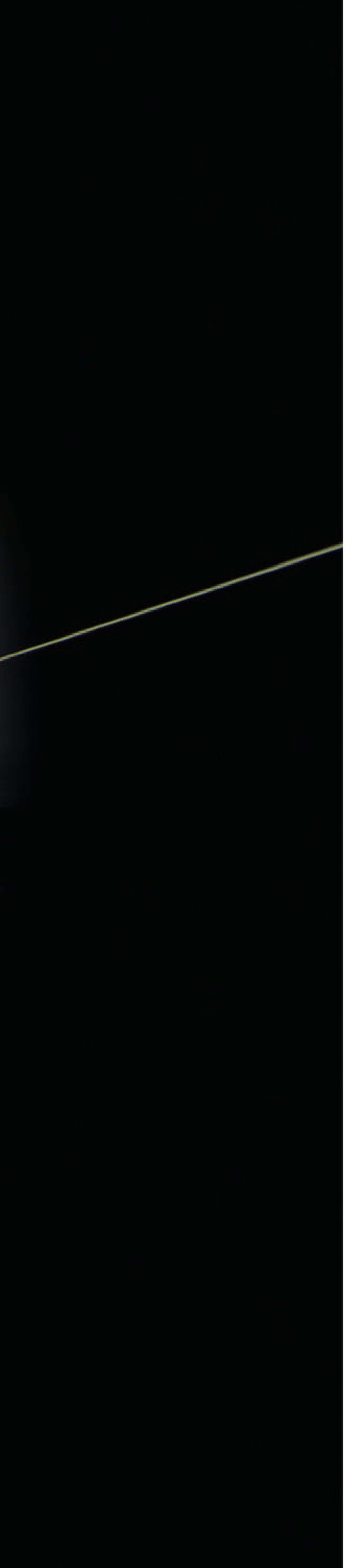
In Svalbard, Norway, photographer Carsten Peter, lit by snowmobiles, flies a drone to capture the size of this dome-shaped landform, called a pingo, which is the largest in the area. Microbiologist Dimitri Kalenitchenko, who studies the microbes that live in a reservoir beneath the pingo and in its ice, works on a nearby ledge, shrouded by the Arctic twilight.
CARSTEN PETER

Astrobiologist and National Geographic Explorer Kevin Hand, (kneeling, right) helps Kalenitchenko (far right) collect an ice core from one of Svalbard's pingos near the town of Longyearbyen. In their dark, frigid habitats, communities of microbes living within the pingos could exist using strategies analogous to life-forms that might populate icy moons.
CARSTEN PETER



Titan—one of Saturn's moons—is giant, hazy, and among the most astrobiologically intriguing places in the solar system. Scientists used to characterize a world's ability to host life based on its distance from the sun. But moons like Titan are warmed by the gravitational pull of the planets they orbit, and they could be home to fertile environments.

MOSAIC OF SIX IMAGES BY NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE



AS I THUMB THE THROTTLE on my snowmobile, it skitters and glides across a sea of snow and ice. In the dusky twilight, the landscape is painted in shades of ethereal blue. I'm heading back to town after spending the day crisscrossing a frozen fjord, one of many in Norway's Svalbard archipelago, a cluster of mountainous islands in the high Arctic where auroras often dance overhead and narwhals, belugas, and walruses patrol the seas.

It's March, and the sun finally returned to the sky here about a month ago. I'm with a half dozen scientists who are hunting peculiar landforms called pingos—or, more specifically, the microbes that live within them. Anchored in permafrost, these domes range in size from mounds to small hills and seasonally expand and contract as water seeping through them freezes and thaws. They're like an icy eruption in slow motion. Temperatures hover around minus 15°F as the bundled-up, rifle-toting scientists make multiple trips each day to their study sites, where they collect ice cores and water samples while keeping an eye out for polar bears.

The microbes populating the pingos could offer a glimpse at how alien life might survive on other worlds in the solar system—icy moons with global seas tucked beneath frozen rinds. That's because, in winter, life inside the pingo "doesn't rely at all on solar energy—it's only using chemical energy,"

With support from caver Valentina Mariani (top left), National Geographic Explorer Kenny Broad (center) and Nadir Quarta prepare to dive into Lago Verde in central Italy's Frasassi cave system. In these dark, toxic waters, microbial populations unexpectedly thrive, with some perhaps using smelly hydrogen sulfide to power one of Earth's most ancient metabolic processes. Such sunlight-starved ecosystems could offer a glimpse into the potential life-fueling chemistry in alien seas.
CARSTEN PETER

says microbiologist Dimitri Kalenitchenko of Norway's University of Tromsø, who is leading the project.

The story of sunlight-starved life on Earth is relatively new. For a long time, "we still thought life on this planet was largely restricted to the surface ... and entirely dependent on photosynthesis," says Barbara Sherwood Lollar, a geologist at the University of Toronto who studies microbes living deep within the Earth. Then, in the late 1970s, the *Alvin* submersible explored a dark oceanic hydrothermal vent near the Galápagos Islands, discovering a flourishing ecosystem about a mile and a half beneath the ocean's surface, and forever changed our conceptions of life's limits. "It's one of the things that forces us to be humble," Sherwood Lollar says. "To think that even on our own planet we are still finding processes, still finding environments that we didn't know existed."

Similarly, scientists used to think a world's habitability depended on its distance from the sun. But that picture is incomplete. Now three faraway moons, warmed by the gravitational tug and pull of the giant planets they orbit, tempt scientists with their promises of alien life in their oceans: Jupiter's moon Europa, where a salty sea containing more water than Earth's oceans sloshes beneath an ice shell; and Saturn's moons Enceladus—a small, ice-encrusted world with a global ocean that erupts through fractures in its south pole—and Titan, with its unearthly terrain of liquid hydrocarbon lakes on its surface and an ocean nestled within its interior. Observations suggest that each moon has the chemistry, water, and energy needed to support life as we know it, and maybe don't know it.

We might soon learn if these seas are inhabited. A European Space Agency spacecraft called JUICE is on its way to the Jovian system to surveil

Geomicrobiologists Dani Buchheister (at left) and Jennifer Macalady process samples of biofilm collected in Lago Verde. These mysterious microbial populations sometimes form dark, stringy structures—alien cave goo—that spooked the divers who discovered them. The samples are currently being DNA sequenced.
CARSTEN PETER

the giant planet and its icy moons, including Europa. Next year, NASA's Europa Clipper spacecraft will also set sail for Europa, on a quest to solve the mysteries of its crust and salty sea. And later this decade, the U.S. space agency's Dragonfly mission will send an octocopter to Titan, carrying a suite of instruments that could detect signs of life on the hazy moon's surface. Missions to Enceladus are being planned too. "It's a really exciting time to be a planetary scientist," says Morgan Cable of NASA's Jet Propulsion Laboratory (JPL). "We could, for the first time in human history, find life somewhere else."

Decades in the making, these missions collectively cost billions of dollars. To prepare for astrobiological exploration so far afield, scientists are testing their instruments and techniques in the cold, dark corners of our own backyard. Even though Titan's surface chemistry is hard to replicate in the field, the seas in the innards of these three moons may not be so unlike our watery environments. From Earth's surface to its subterranean caverns, these investigations study some of the most alien creatures on our planet. Their discoveries could even write the story of life's beginnings here, and maybe elsewhere.

That evening in Longyearbyen, Svalbard's largest town, wrapped in blankets and recovering from the bite of the Arctic, I looked out the window just in time to catch a man aiming his phone at the celestial light show. Outside, in the chill, serpentine ribbons wriggled overhead. Shimmering cosmic lights above an otherworldly landscape? It was almost too perfect.

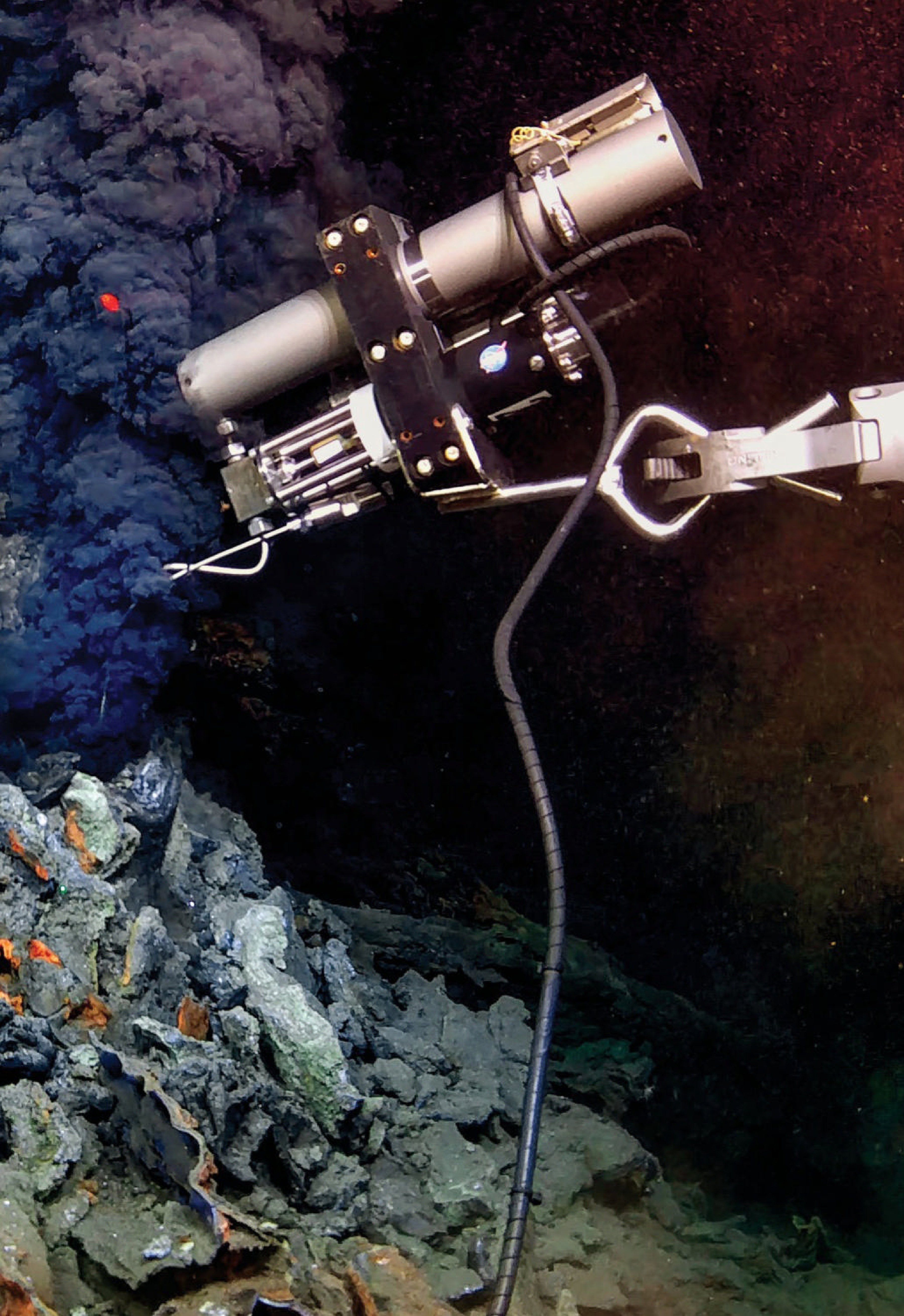
I FIRST

PRESSED A BOOT PRINT into the Svalbard snow four years ago, as I prepared to board the Norwegian icebreaker *Kronprins Haakon*—a shiny new vessel back then—along with three dozen scientists and engineers. We launched from Longyearbyen and sailed toward a fractured patch of seafloor north of Greenland. There, some two and a half miles down, the Earth heaves searing dark fluids into the sea, forming what is known as the Aurora hydrothermal vent field. Salt water mingling with hot rocks beneath the seafloor powers these eruptions, which produce the heat and chemistry needed for organisms to thrive. "They can host all kinds of weird and wonderful life-forms," said Chris German, a marine geochemist from the Woods Hole Oceanographic Institution who has spent nearly four decades hunting hydrothermal vents, as we cruised north. Under permanent ice cover, the field could be a superlative earthly analogue for the seafloors of Europa and Enceladus.

To explore Aurora, German and his colleagues brought one of the most advanced uncrewed submersibles on Earth: an orange, minivan-size vehicle called *NUI,* short for *Nereid Under Ice.* Festooned with stickers, some reflecting a recent collaboration between Woods Hole and NASA, the three-million-dollar machine is designed

Two and a half miles beneath the Arctic Ocean, under permanent ice cover, the Aurora hydrothermal vent field is almost as unearthly as the seafloors of Enceladus and Jupiter's moon Europa. To learn more about the geochemistry—reactions that can power ecosystems in the absence of sunlight—scientists collected vent fluid from an active black smoker named Ganymede using the ROV *Aurora* in 2021.

STILL FROM VIDEO BY REV OCEAN/HACON



to explore under-ice ecosystems. It can dive three miles down, swim more than 25 miles, and operate for half a day without recharging. *NUI* functions autonomously, but it can also be remotely piloted; scientists watching live feeds from its cameras can direct it to collect particular sediments or organisms.

"Our hope is that *NUI* is kind of like the *Australopithecus* or *Homo habilis* to the robotic spacecraft that would one day go to Europa," Kevin Hand, a National Geographic Explorer and astrobiologist at JPL, told the team as the ship plowed through our planet's frozen crust. For him, Europa is a tantalizing target in the quest to know whether we are alone in the universe.

For days, thick ice—too bulky for the ship to break—had slowed our journey to the vents. Although the going was tricky, the Arctic Ocean's relatively thin icy rind is a friendlier version of the crusts encasing alien oceans. The shell at Enceladus may be less than a mile thick at the south pole, where the geysers erupt, but estimates for Europa's rind suggest it's considerably thicker. Characterizing Europa's frozen shell and the compounds on its surface is one of the highest priorities for both the Europa Clipper and JUICE missions. Those spacecraft will make multiple flybys of Europa to measure the ice shell's thickness and study its layers and ocean beneath, in hopes that with more information, future missions can get through the rind and access the water.

When NASA's Cassini spacecraft zoomed around the Saturn system from 2004 to 2017, it sampled the Enceladian plume multiple times and found salts, silica, organic molecules, and molecular hydrogen, all telltale signs of seafloor activity. It also detected phosphorus, an element that's crucial for life on Earth. *NUI*'s job on this cruise was to get the first good look at the Aurora vent field and help figure out whether it's fueling

On the desolate Arctic seafloor near the Aurora vent field, life makes do with what it can get. Here a red shrimp swims above a glass sponge, which is a filigreed creature made mostly of silica—material abundant on the ocean floor.

STILL FROM VIDEO BY OFOBS, AWI TEAM

chemical reactions that can support abyssal lifeforms—perhaps the kind of life that might evolve in dark, permanently ice-covered alien seas.

Two days after arriving at the Aurora seamount, *NUI* dived to Aurora. As the orange sub sank in the long Arctic twilight, a gentle snow fell on fields of frost flowers carpeting the ice. It took hours for the submersible to descend to the seafloor. In the control room a pilot maneuvered the vehicle. At one point he handed me the joystick, and for a few moments we joked that I held the record for the deepest Arctic remotely operated vehicle dive piloted by a woman. (It was 9:19 a.m., and the sub was at 9,104 feet, but who's keeping track?)

An hour later, the trouble started. As *NUI* neared its destination, its onboard systems blinked off one by one. Then the pilot reported that he'd lost control of the submersible. After a bit, the team commanded the vehicle to drop its dive weights and begin rising to the surface. Instead, *NUI* sank. A few minutes later, the sub's depth reading marched across the screen in an ominous flat line—it was on the seafloor. Maybe the weights didn't drop; or maybe a crucial housing had sprung a leak, the sub had flooded, and it was now too heavy to rise to the surface.

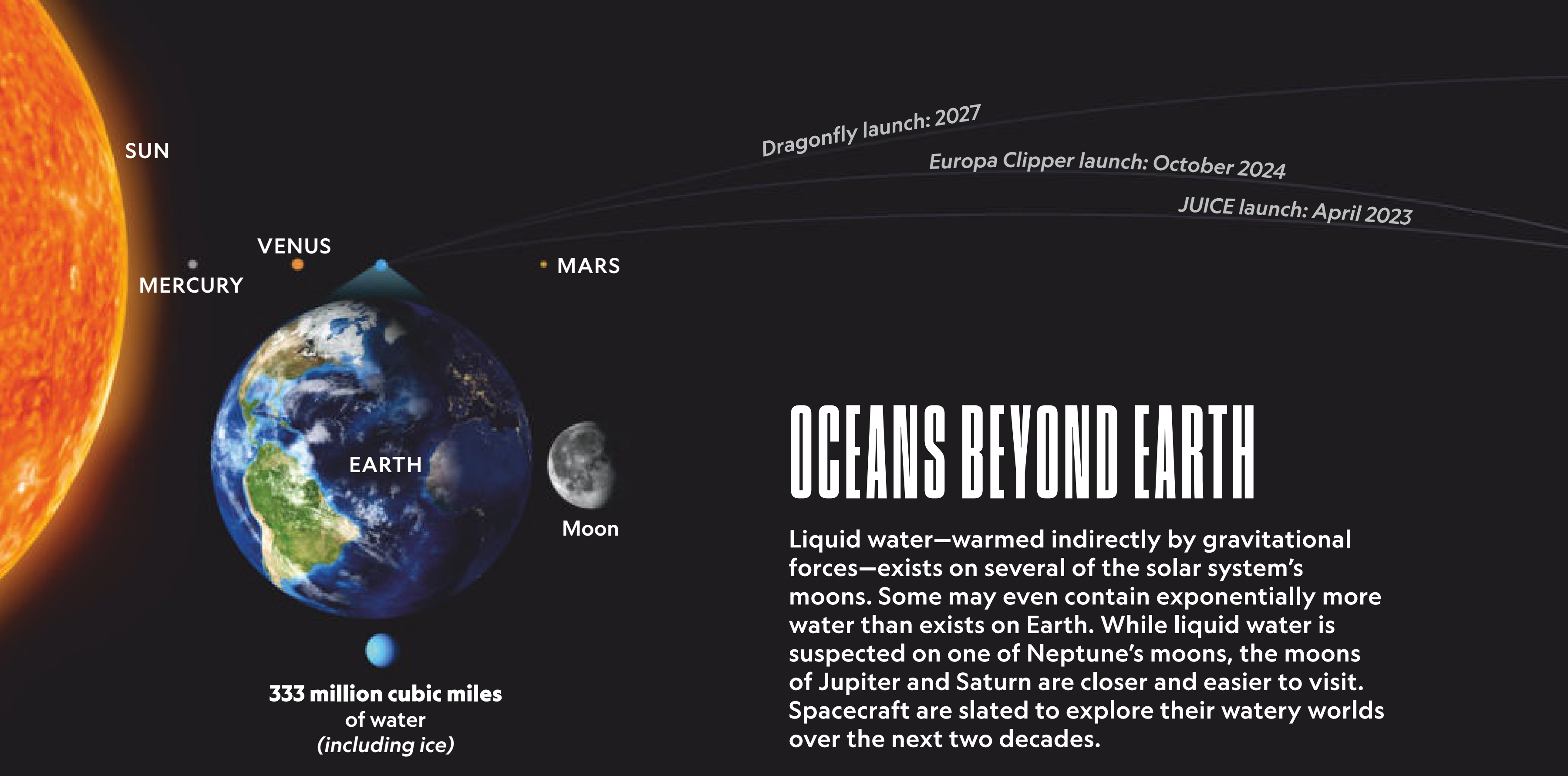
On a scale of zero to 10, I asked German, how worried are you? "Ten," he said. "Ten. There's a legitimate risk of a very bad thing." Returning home without *NUI*—the team's prized instrument, the potential forebear of tomorrow's spacefaring submersibles—would be "pretty atrocious," he said. It's so close to the vents that if we could turn on *NUI*'s camera, he continued, we'd probably be staring Aurora in the face.

THREE

DAYS WENT BY. The *NUI* team monitored the sub's location for any changes while Hand and several other people MacGyvered an orange, shoebox-size underwater vehicle from spare parts. They were planning a desperate rescue mission that, as far as I could figure, involved fishing for *NUI* with the makeshift device.

But that morning there was good news: *NUI* was on its way back up. The final fail-safe—a corrodible wire attaching the dive weights to the submersible—had worked. It had just taken longer than the anticipated 24 to 48 hours for salty seawater to gnaw through the wire, probably because chemistry happens at a slower pace in subfreezing Arctic seawater. By that afternoon, *NUI* was back on board, having helpfully surfaced under a rare patch of thin ice rather than the thick floes covering the area. ("I think it's sentient," German said.)

NUI wouldn't explore Aurora during this cruise, but it turned out that the vents were still within reach. That same evening, the ice drift cooperated, and the ship sailed right over the vent field, towing a high-tech camera just above the seafloor. Aurora, the imagery revealed, was home to a massive black smoker, a rupture more than five feet across that hurled hot, sulfidic minerals into the sea. But as far as hydrothermal vents



OCEANS BEYOND EARTH

Liquid water—warmed indirectly by gravitational forces—exists on several of the solar system's moons. Some may even contain exponentially more water than exists on Earth. While liquid water is suspected on one of Neptune's moons, the moons of Jupiter and Saturn are closer and easier to visit. Spacecraft are slated to explore their watery worlds over the next two decades.

go, Aurora seemed remarkably unpopulated, said Eva Ramirez-Llodra, the cruise's co-chief scientist. We only spotted a handful of snails and crustaceans—none of the dramatic tube worms or clams that cluster around other deep-sea vents. Amid the desolation, though, a garden of glass sponges bloomed. These filigreed creatures, seemingly the only organisms in abundance down there, are sometimes said to be barely alive. Their skeletons are made mostly of silica rather than calcium carbonate. And that makes sense. In the deep sea, silica is common. Life—these otherworldly sponges—found a way to use it.

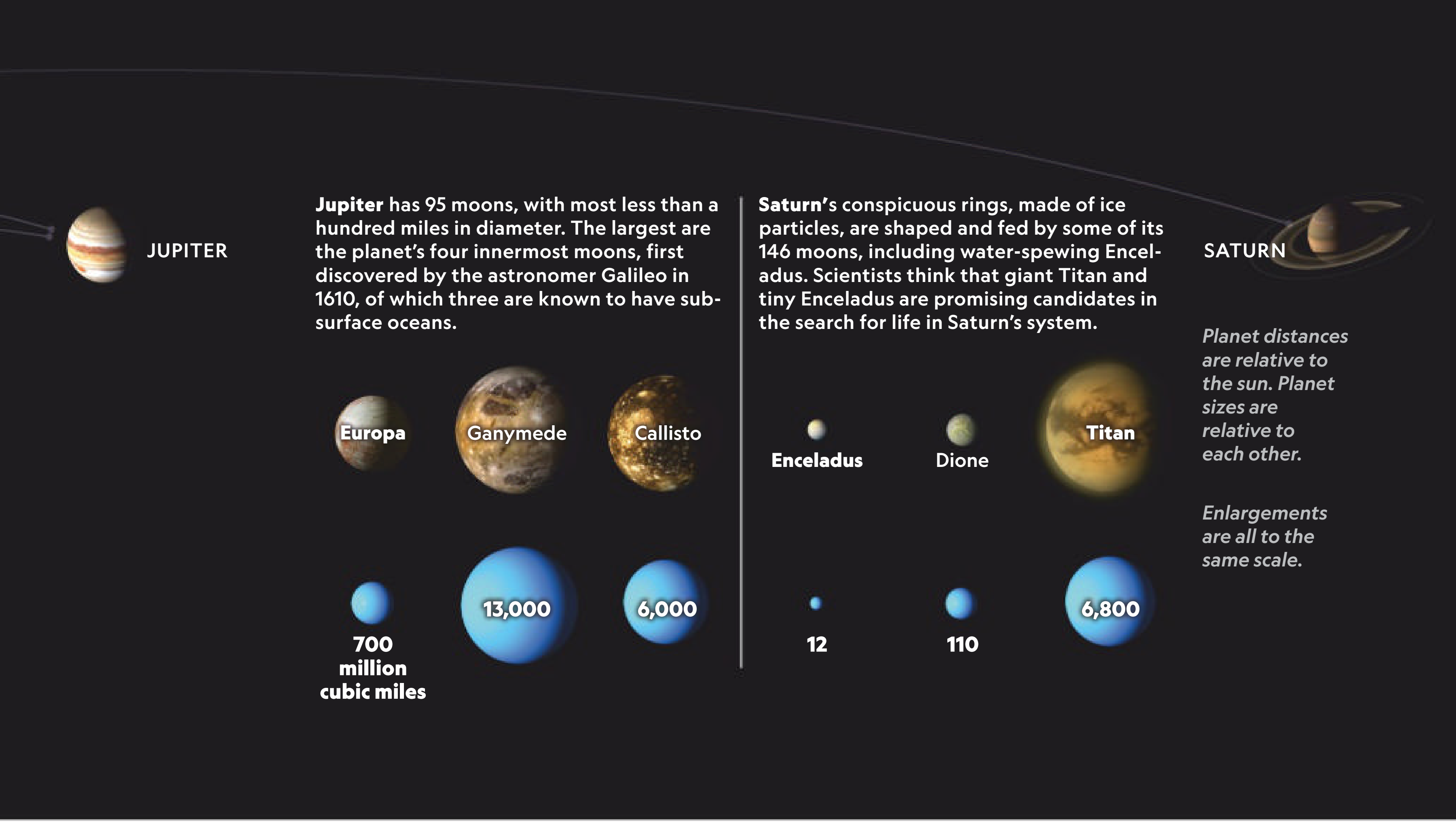
Despite all the trouble on this cruise, the group managed to get its first good look at Aurora. And the vents were active and more mysterious than expected. The largest vent in the field, German said, was among the biggest black smokers he'd seen in his career.

AT TIMES IT'S COLDER in the Arctic than in those alien seas. This is not fun for someone as sensitive to the cold as I am. However, the damp, lingering chill of an Italian cave turned out to be even worse. It burrowed straight into my bones and refused to leave. Wouldn't it be nice if the solar system's alien incubators were more tropical?

This past February I visited central Italy's Frasassi cave system with scientists searching for some of Earth's least known creatures: microbes that live deep within the cave's underwater passages. Growing in toxic, oxygen-starved waters, these improbable communities are powered by the slow burn of water interacting with the rock itself, producing metabolic fuels such as hydrogen sulfide and methane—just like the organisms that depend on oceanic hydrothermal vents.

Scientists think these chemical reactions could exist on icy moons. They also suspect that Frasassi's chemistry is similar to Earth's ancient oceans, where the seeds of terrestrial biology might have sprouted. "Earth was a very different planet when it was born," said Jennifer Macalady, a geomicrobiologist at Penn State University who's been visiting the cave system for more than 20 years. "If we think this aquifer was like Earth's early oceans, and we think that Earth's early oceans might have some similarities with oceans on other planets, this is a great place to hone our skills for life detection."

The system's largest chamber was discovered



in the 1970s and is 65 stories tall. It's so big that the cathedral of Milan, an important unit of measurement for Italians, would fit inside. But the only gargoyles here have been sculpted, one drop at a time, by the slow seepage of mineral-rich water. Walking through this chilled, humid chamber is a bit like scoring a golden ticket to Willy Wonka's Chocolate Factory—except the confections are crafted by limestone, water, and acid. Glistening, slimy, and sparkling with crystals, some of the stalagmites are 65 feet tall and as big around as old-growth redwood trees.

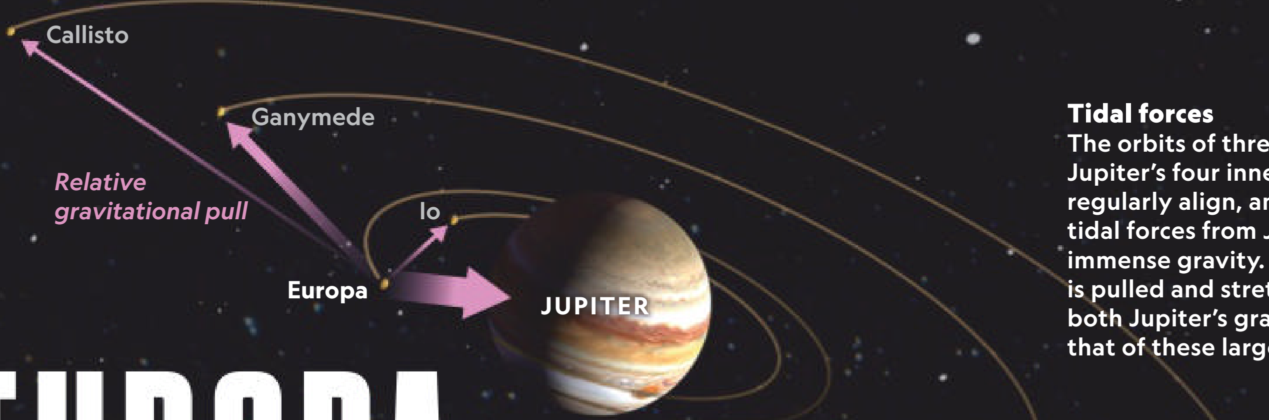
No one knows the extent of Frasassi's network of lakes, which are connected by a vast subterranean aquifer. "There hasn't been much diving in the Frasassi aquifer because, one, it's toxic. Two, it's hard to obtain access. You have to be very good on a rope, and you have to be a pretty sturdy individual. And then you have to be a diver," Macalady told me. When she first visited Frasassi, she had zero caving experience; now she's a skilled caver and speaks fluent Italian—her dog is named Lavastoviglie, which is Italian for "dishwasher" (as many dogs are).

In the aquifer's depths, a layer of clear fresh water sits atop salt water that's saturated with toxic hydrogen sulfide. That lower layer bubbles up from deep within the Earth, and in addition to being smelly, it's anoxic—there's no dissolved oxygen to power microbial metabolisms. "In that hydrogen sulfide layer, we expected to find almost nothing," Macalady said. "Instead, we found a forest of microbes unexpectedly making a living."

In 2004, Italian divers discovered that the toxic layer in one of the Frasassi lakes, Lago Infinito, was surprisingly inhabited. Black, stringy biofilms—cooperative communities of microbes—hung from the underwater rocky ceiling like tattered Gothic curtains, some of them three feet long. In the lake's seemingly sterile depths, the divers were spooked and fled. "If you see alien cave goo, your first instinct is to turn around," Macalady said, deadpan.

The Frasassi microbes Macalady is curious about are autotrophs, or organisms that make their own food from gases and minerals. These microbes have turned up in several underground lakes, sometimes looking dark and tentacular, other times gray and feathery. Preliminary work points to thousands of species collaborating to craft these eerie appendages. Some have recognizable genetic sequences, but none are fully known to science. And a good fraction are what Macalady calls "genetic dark matter"—the single-celled unknown. Finding those unknowns is not unprecedented, but as scientists sequence more microbes, it's "more rare to find a community that has so much of this genetic dark matter," she said. *(Continued on page 137)*

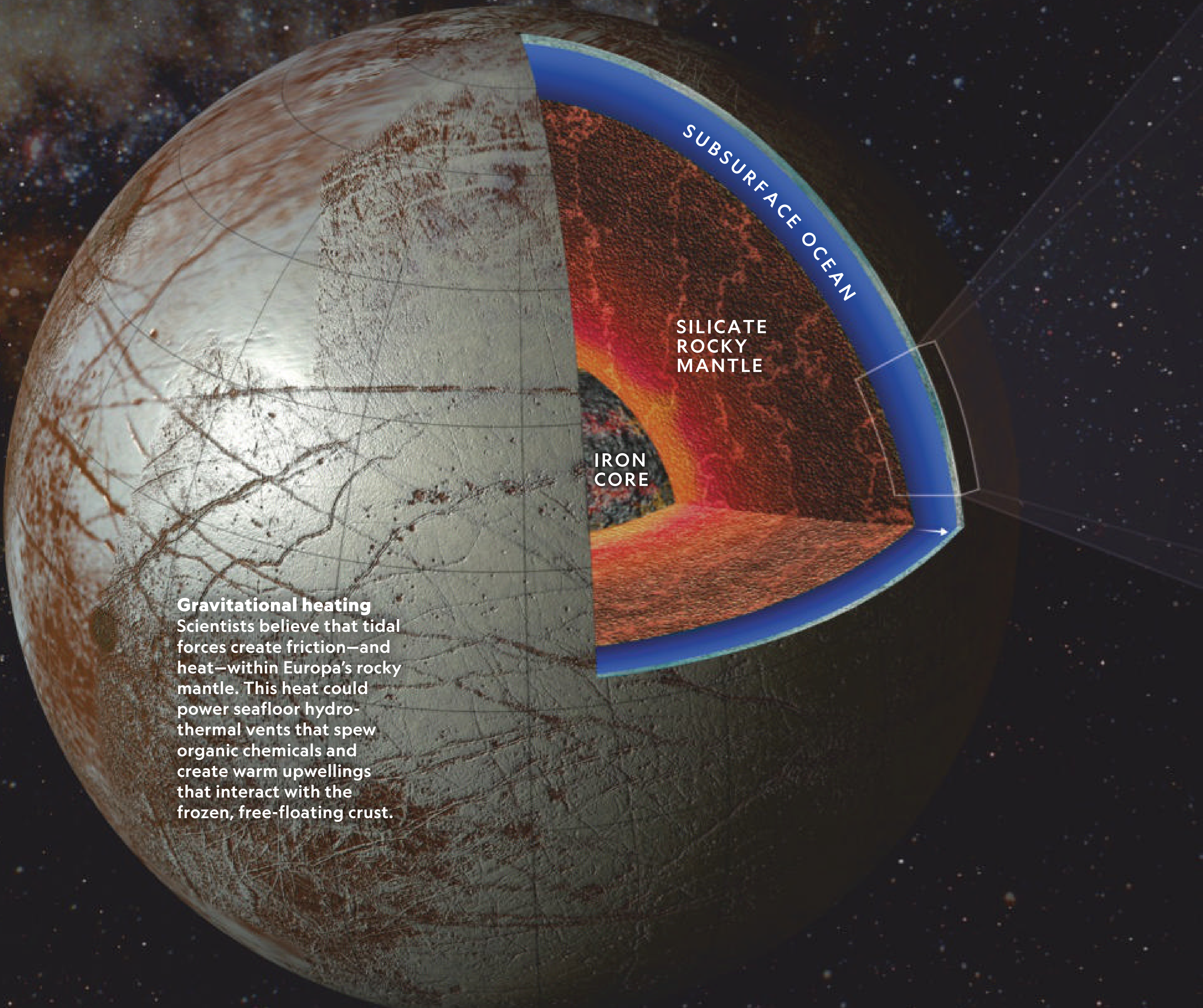
JASON TREAT, NGM STAFF; SEAN MCNAUGHTON
ART: DANA BERRY. SOURCES: STEVEN D. VANCE, NASA/JPL; NASA



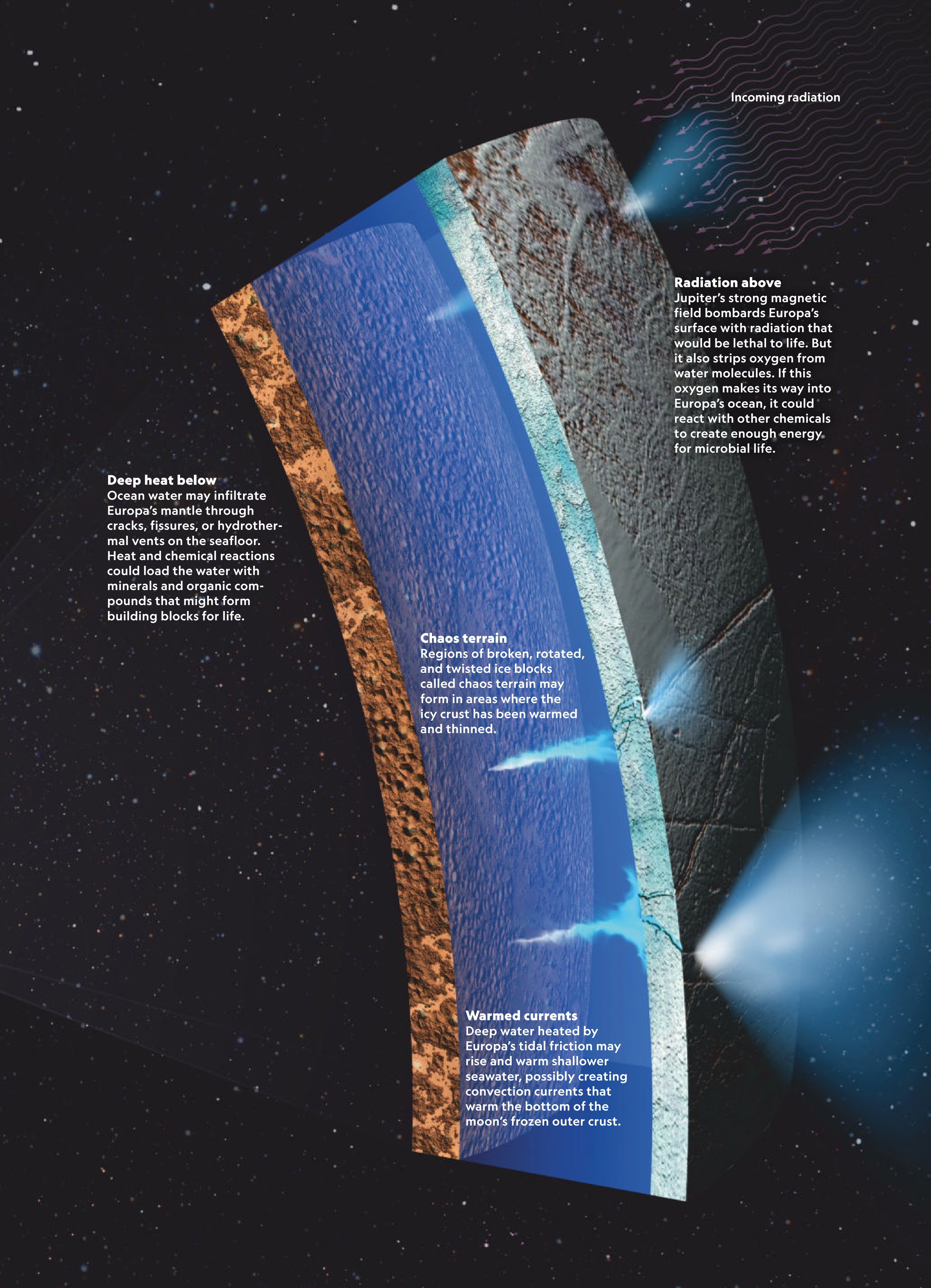
Tidal forces
The orbits of three of Jupiter's four inner moons regularly align, amplifying tidal forces from Jupiter's immense gravity. Europa is pulled and stretched by both Jupiter's gravity and that of these larger moons.

EUROPA

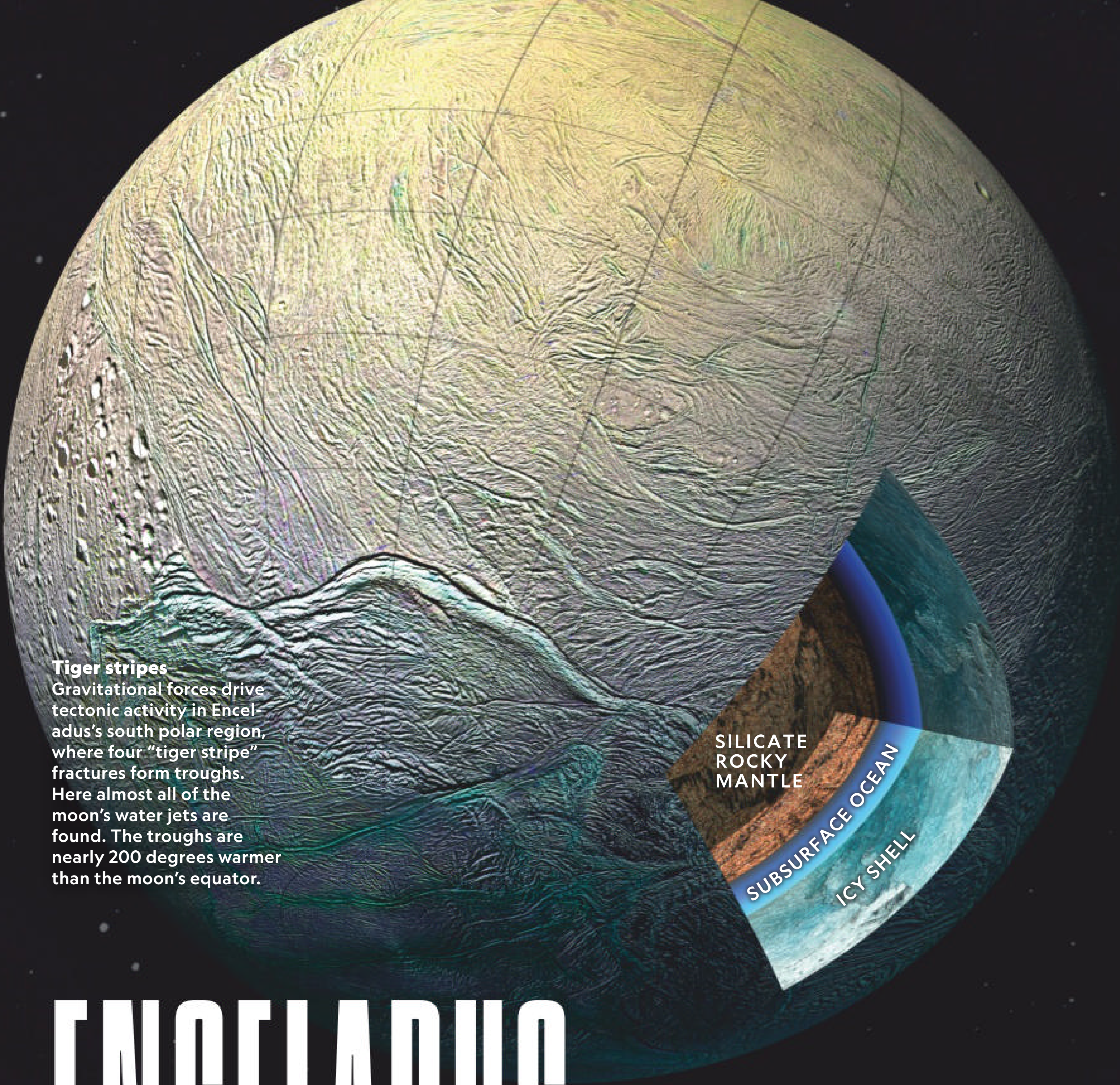
Scientists suspect that hiding beneath Europa's frozen surface is a saltwater ocean with twice the volume of all Earth's oceans combined. Flying as close as 16 miles above the moon's surface, NASA's Europa Clipper spacecraft, scheduled to launch in late 2024, will use ice-penetrating radar and other sensors to seek out signs of liquid water within Europa's ice shell and study organic molecules on its surface.



Gravitational heating
Scientists believe that tidal forces create friction—and heat—within Europa's rocky mantle. This heat could power seafloor hydrothermal vents that spew organic chemicals and create warm upwellings that interact with the frozen, free-floating crust.



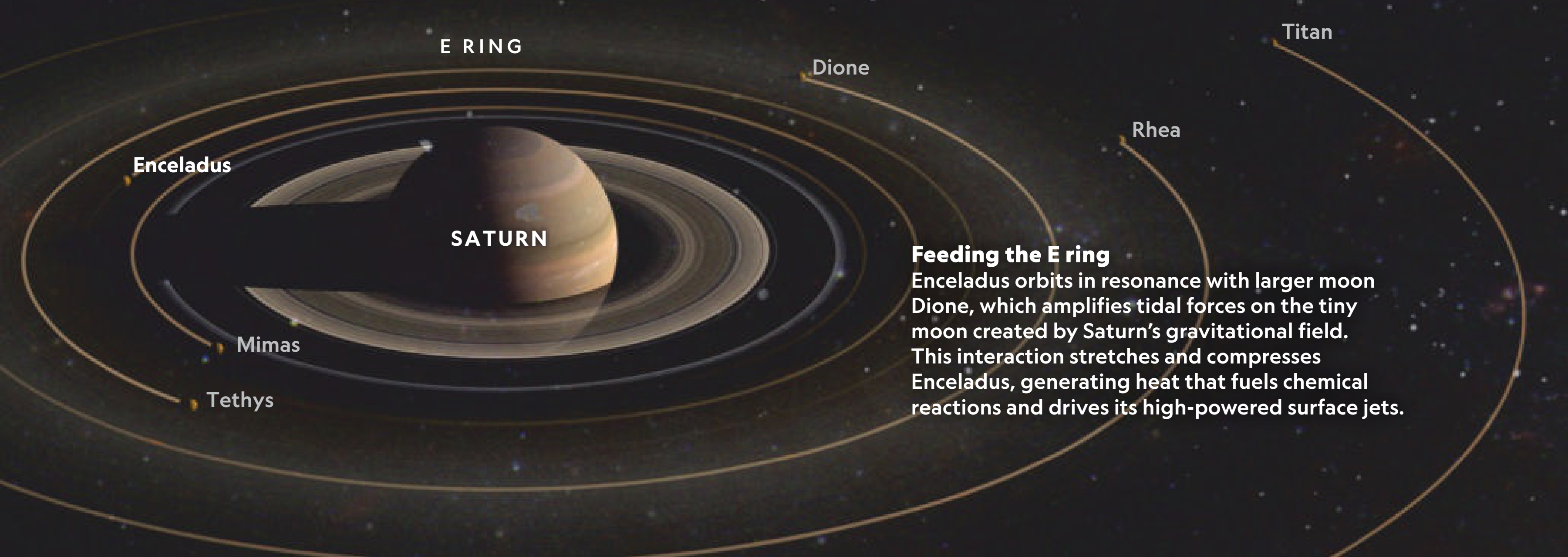
JASON TREAT, NGM STAFF; SEAN MCNAUGHTON
ART: DANA BERRY. SOURCES: STEVEN D. VANCE, NASA/JPL; NASA



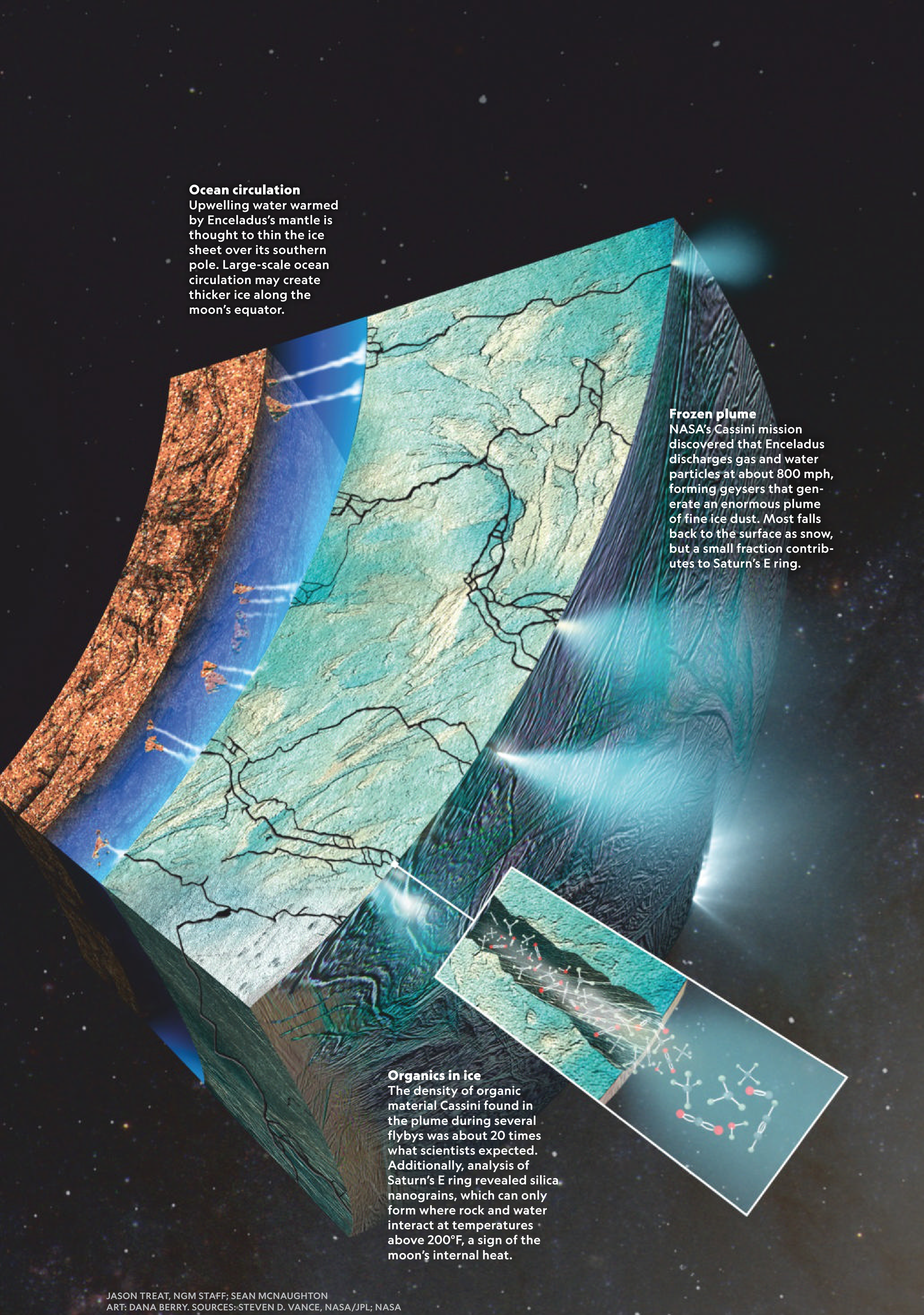
Tiger stripes
Gravitational forces drive tectonic activity in Enceladus's south polar region, where four "tiger stripe" fractures form troughs. Here almost all of the moon's water jets are found. The troughs are nearly 200 degrees warmer than the moon's equator.

ENCELADUS

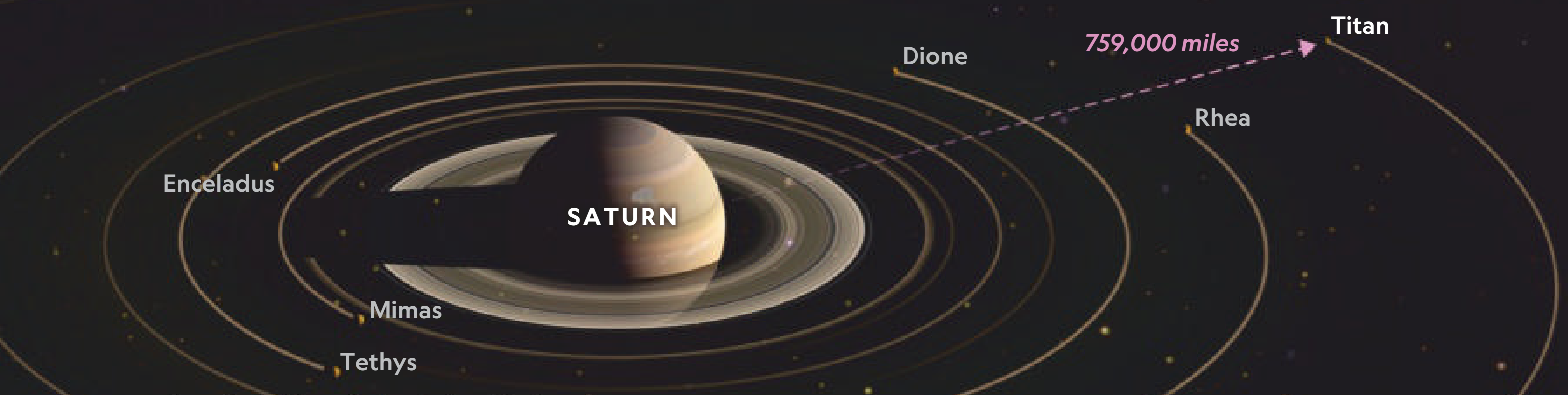
Scientific observations strongly suggest that Titan, Europa, and other moons in the solar system have liquid water beneath their surfaces. Saturn's moon Enceladus, however, showcases its ocean by spraying so much salty water into space that it forms the planet's diffuse, massive, and beautiful E ring.



Feeding the E ring
Enceladus orbits in resonance with larger moon Dione, which amplifies tidal forces on the tiny moon created by Saturn's gravitational field. This interaction stretches and compresses Enceladus, generating heat that fuels chemical reactions and drives its high-powered surface jets.



JASON TREAT, NGM STAFF; SEAN MCNAUGHTON
ART: DANA BERRY. SOURCES: STEVEN D. VANCE, NASA/JPL; NASA



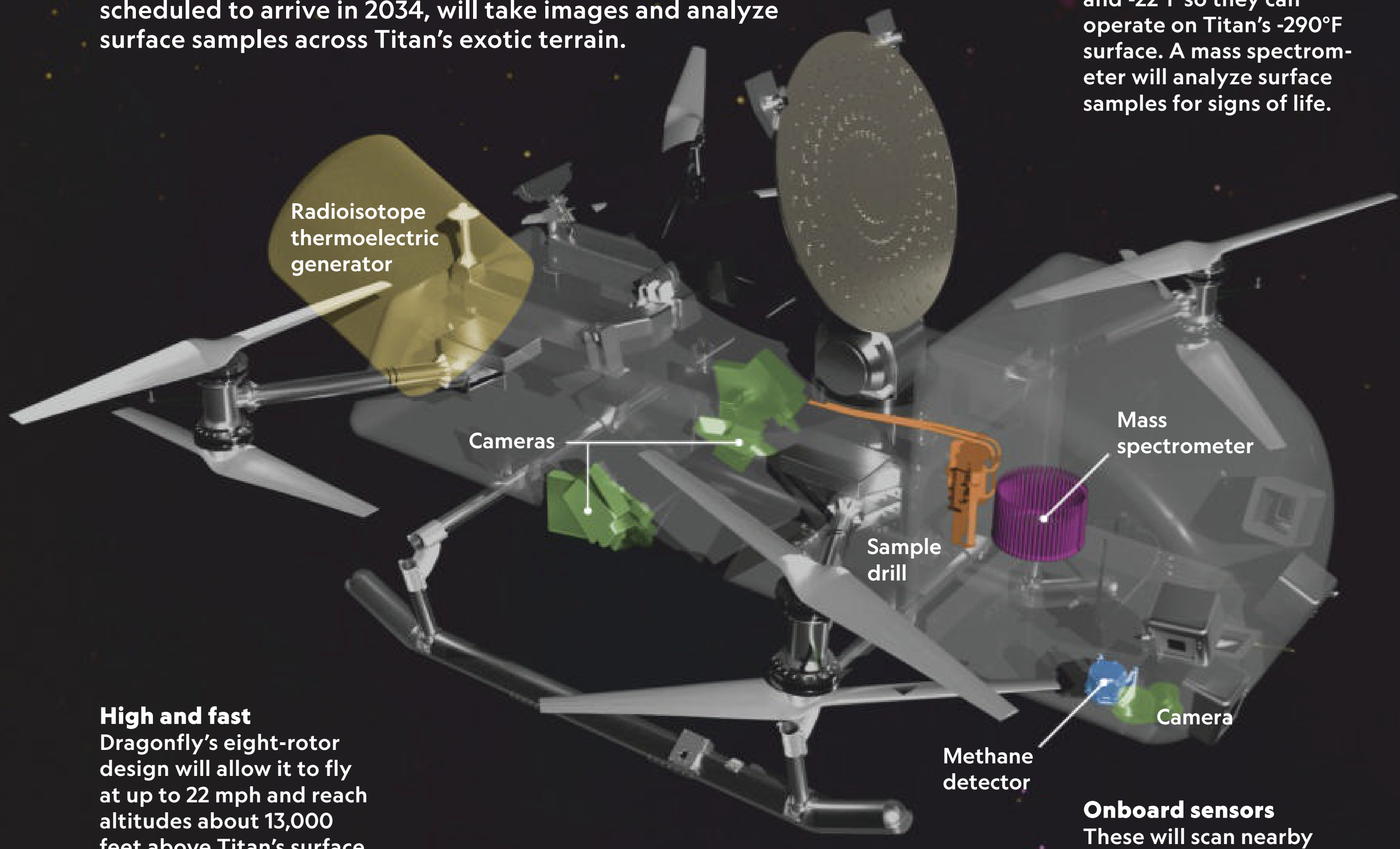
TITAN

Like Europa and Enceladus, Saturn's moon Titan is believed to have an interior saltwater ocean. But that's not the only reason the solar system's second largest moon may harbor life. Where Earth has a water cycle, Titan's methane cycle rains complex molecules onto its surface, creating methane lakes, rivers, and massive surface dunes made not of sand but of granular hydrocarbons.

DRAGONFLY

Titan's atmosphere is 60 percent denser than Earth's at its surface, making the moon a perfect candidate for drone exploration. Powered by a 94-pound radioactive fuel source, NASA's thousand-pound Dragonfly octocopter, scheduled to arrive in 2034, will take images and analyze surface samples across Titan's exotic terrain.

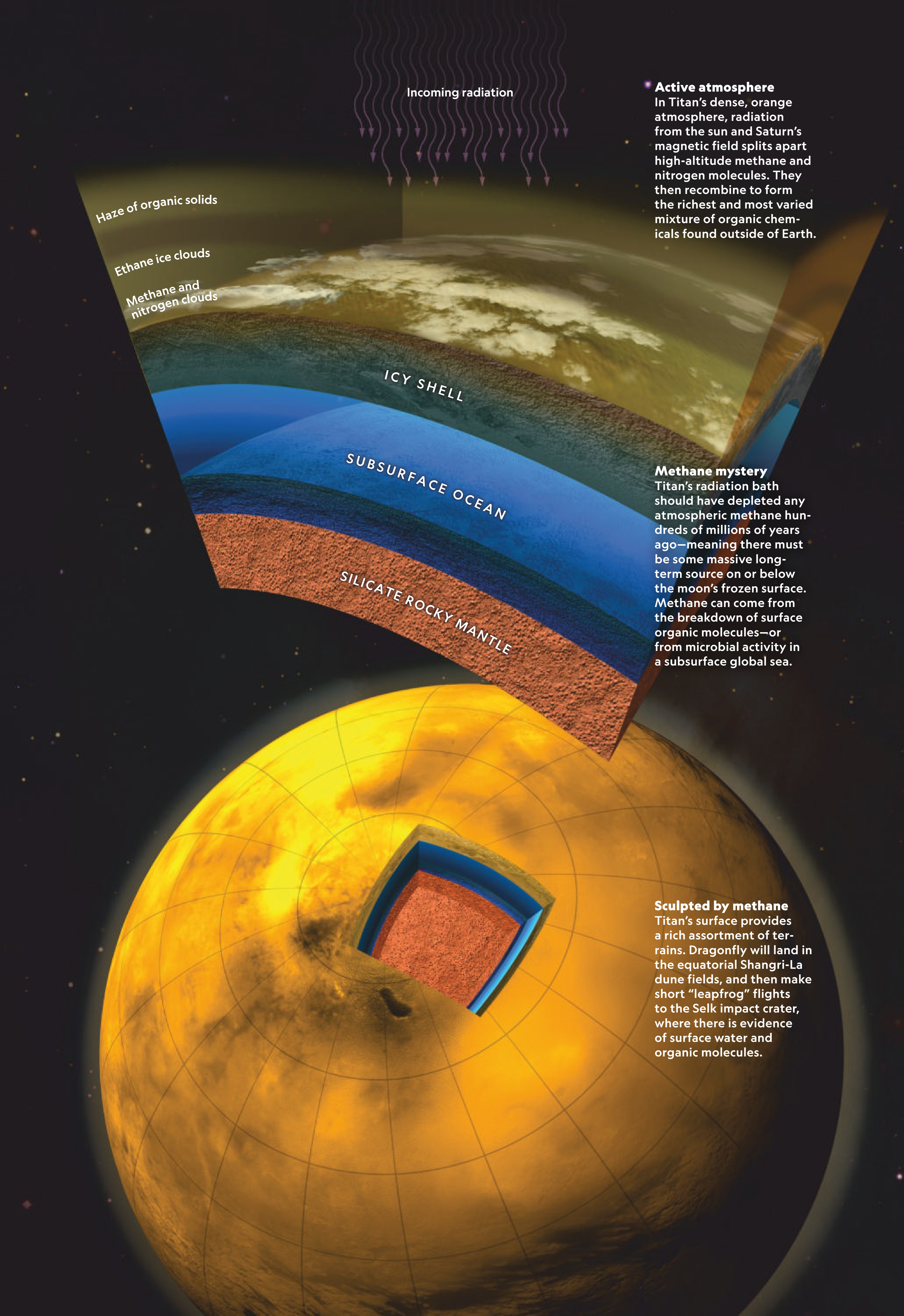
Onboard lab
Thick insulation and a durable power source will warm Dragonfly's instruments to between -40°F and -22°F so they can operate on Titan's -290°F surface. A mass spectrometer will analyze surface samples for signs of life.



High and fast
Dragonfly's eight-rotor design will allow it to fly at up to 22 mph and reach altitudes about 13,000 feet above Titan's surface, enabling it to scout sites for surface analysis.

Onboard sensors
These will scan nearby surface minerals, search for subsurface liquid water, and monitor "Titanquakes" for signs of tectonic activity.

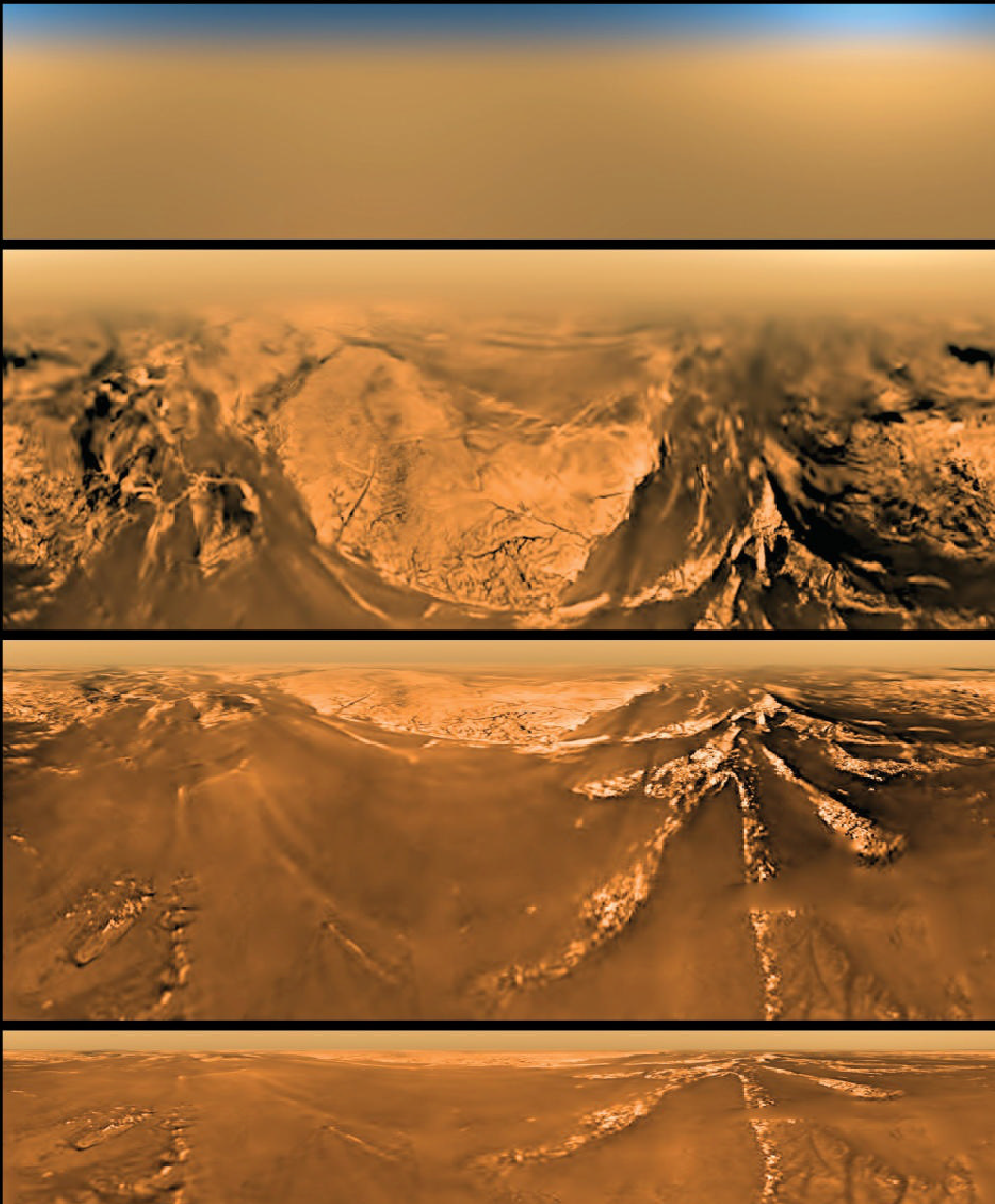
JASON TREAT, NGM STAFF; SEAN MCNAUGHTON
ART: DANA BERRY. SOURCES: STEVEN D. VANCE, NASA/JPL; STEVE GRIBBEN, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY; NASA

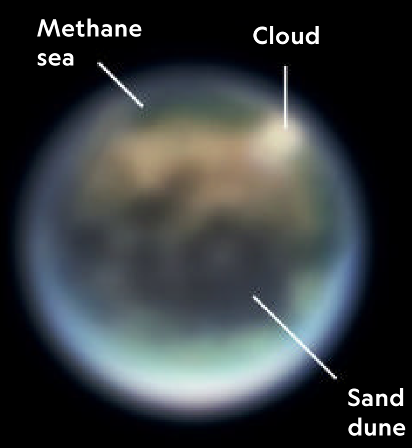


Active atmosphere
In Titan's dense, orange atmosphere, radiation from the sun and Saturn's magnetic field splits apart high-altitude methane and nitrogen molecules. They then recombine to form the richest and most varied mixture of organic chemicals found outside of Earth.

Methane mystery
Titan's radiation bath should have depleted any atmospheric methane hundreds of millions of years ago—meaning there must be some massive long-term source on or below the moon's frozen surface. Methane can come from the breakdown of surface organic molecules—or from microbial activity in a subsurface global sea.

Sculpted by methane
Titan's surface provides a rich assortment of terrains. Dragonfly will land in the equatorial Shangri-La dune fields, and then make short "leapfrog" flights to the Selk impact crater, where there is evidence of surface water and organic molecules.



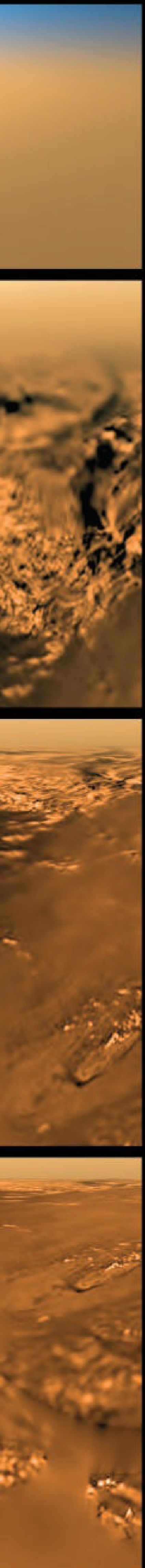


ATMOSPHERE AND SURFACE

ABOVE

Among our solar system's 290 known moons, Titan is the only one with a dense atmosphere. In November 2022, the James Webb Space Telescope made this color-composite image of Titan showing several of the moon's surface features: prominent clouds, a sand dune field, and a methane sea.

IMAGE BY NASA, ESA, CSA, WEBB TITAN GTO TEAM; IMAGE PROCESSING BY ALYSSA PAGAN (STSCI)



LEFT

In 2005, NASA's Cassini spacecraft dropped a European Space Agency probe into the nitrogen atmosphere surrounding Titan. During its two-and-a-half-hour descent, it snapped images presented here at four altitudes in Mercator projection. They revealed the moon's surface is a deceptively Earthlike landscape. But the chemistries are alien: Liquids are methane and ethane, while pebbles are rock-hard water ice.

ESA/NASA/JPL/UNIVERSITY OF ARIZONA

On this trip, Dani Buchheister, one of Macalady's graduate students, was hoping the divers could collect biofilms so she can try to coax the mysterious autotrophs to grow in a lab. If she can do that, perhaps she can solve the mysteries of the microbes' identities and figure out how they survive in these pungent, suffocating waters—with an eye to what that means for life farther afield. "[I've become] more and more convinced that if we find life in our solar system, it's probably in subsurface environments," said Buchheister, who grew up in Florida and could sometimes see the fiery streaks of rockets launching from nearby Cape Canaveral. "And my draw to microbiology was the idea that microbes are our best examples of the extremes of life poking at the edges of what's possible with the life we know."

And that's how we found ourselves on the muddy edge of Lago dell'Orsa, an 80-foot rappel from the tourist walkway above. Two divers had sunk beneath the cold, aquamarine waters to collect biofilm samples, but 10 minutes later, only one diver, Kenny Broad, had returned. He went back to search for his partner, Nadir Quarta, among the poorly mapped passages. "Why they're not both up here, I don't understand," Macalady said, aiming her headlight into the darkness as she balanced on a slippery rock. We all went quiet, and the *plink, plink, plink* of water hitting the cave floor echoed through the chamber.

After an eternity (or perhaps several minutes), we heard the gurgling of two cave divers returning to the surface. "Well, that was slightly terrifying," Broad said to the crew as he floated. The 2011 Rolex National Geographic Explorer of the Year and an environmental anthropologist at the University of Miami, Broad was one of a handful of divers qualified for this expedition, which required proficiency with a rebreather as well as experience with underwater photography and scientific sample collection. Quarta had driven down from Switzerland. As they dived, the pair got split up, with Quarta heading down a passage he called "a mess." Underwater, amid poor visibility, Broad couldn't find him—a worrying situation during any dive.

Once it was clear they were OK, Macalady asked, "Did you see some fuzzy gray stuff?"

DURING

BROAD'S SECOND DIVE in frigid Lago dell'Orsa—a 65-foot plunge that he described as "pretty shallow"—he filled five large syringes with diaphanous biofilms, material so fragile it fell apart at the slightest jiggle. Back at the field station, he thawed and stretched. "It wasn't visually stunning," Broad reflected. "But there's this otherworldly element to caves that's undeniable. They're a portal to some other place."

When we met up with the others in the field station's lab, Macalady had some of the biofilms under a microscope. Through the eyepiece, I finally came face-to-face with these perplexing intraterrestrials. Their cottonlike, wispy gray tendrils were punctuated by dark clumps of pyrite—perhaps the telltale sign of a primordial metabolic pathway that converts smelly hydrogen sulfide into pyrite and hydrogen gas. Scientists suspect such an energetically cheap pathway powered the first life-forms on Earth, but no one has found any evidence for it. Maybe until now. "Those are pyrite framboids, the waste product of this metabolism we're looking for," Macalady said, indicating the dark sphere. "It's a clue."

Solving that mystery and identifying the microbes will depend on whether Buchheister can persuade them to grow in a lab. That might be tricky for multiple reasons, one being that the team's preliminary estimates suggest these microbes divide on very long timescales, perhaps once every century or millennium. There's so little energy available in the depths of the Frasassi aquifer that, like the glass sponges populating the Arctic abyss, these microbes have figured out how to survive on what they can get.

"That's kind of my sweet spot," Buchheister said. "Learning about the limits of life on Earth, the weird places they live, and how that information might influence where and how we search beyond Earth."

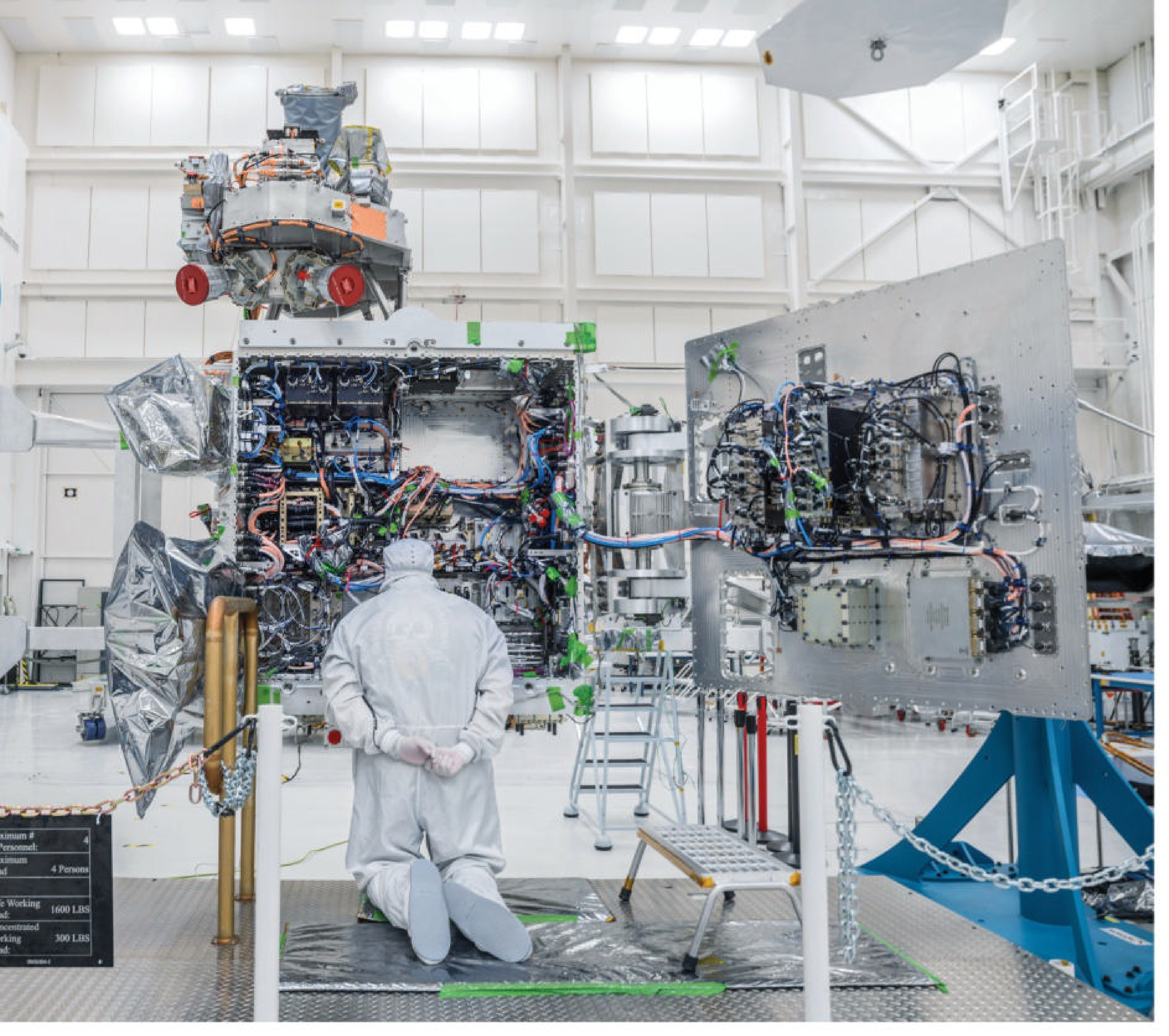
A technician studies the vault or "brains" of NASA's Europa Clipper spacecraft, which is being assembled at the Jet Propulsion Laboratory in California and will launch next year. As it flies by Europa, the craft will study the moon's ice shell and characterize the salty sea below. Europa has "the best potential for actually answering, Is there life in the solar system besides us?" said Europa Clipper team member Britney Schmidt.

CHRIS GUNN

WHEN I RETURN TO Longyearbyen in March, Kalenitchenko—who'd been aboard the *Kronprins Haakon*—is collaborating with Hand, who is here again too. (Tom Cruise is also in town to shoot a sequel to *Mission: Impossible*.) A lot has changed since we last met in the frozen north. And Ramirez-Llodra, co-chief scientist from my cruise, and her crew had revisited the Aurora vent field in 2021 and collected the deep-sea lifeblood erupting from two black smokers. Those vents now have names: Enceladus and Ganymede, the latter a reference to Jupiter's giant icy moon, the largest in the solar system.

But our target on this trip is terrestrial ice—in the pingos—not sea ice. Over several field seasons, this team will collect ice cores and characterize the microbial communities populating three sites near town—both in the pingos' reservoirs and locked in their ice. The work already suggests these microbes share characteristics with species that normally live in deep-sea biodiversity hot spots. That's because what occurs in the pingos is "what we see in the deep sea," Kalenitchenko says.

As in the Frasassi aquifer, hydrogen sulfide leaves its smelly calling card in some pingo reservoirs. The ice is full of methane, a compound Hand refers to as "life's first lunch." These two molecules can be both microbial food and microbial waste. Appropriately, the metabolic pathways that consume and excrete hydrogen sulfide and



methane dominated the chemistry of the earthly environments I visited for this story. These pathways are arguably among the simplest and least energetically demanding in the single-celled repertoire, meaning they are, perhaps, a good model for what might arise elsewhere.

By melting ice cores and studying that methane, Hand can determine whether the gas is biologically produced or is the work of geology and chemistry—the exact kind of science we might someday do with a slice of alien ice. But identifying life's work on another world isn't as simple as studying the carbon atoms in methane. Remotely finding the fingerprints of extraterrestrial biology, perhaps locked in ice or floating in a teaspoon of seawater, will mean looking for multiple biosignatures.

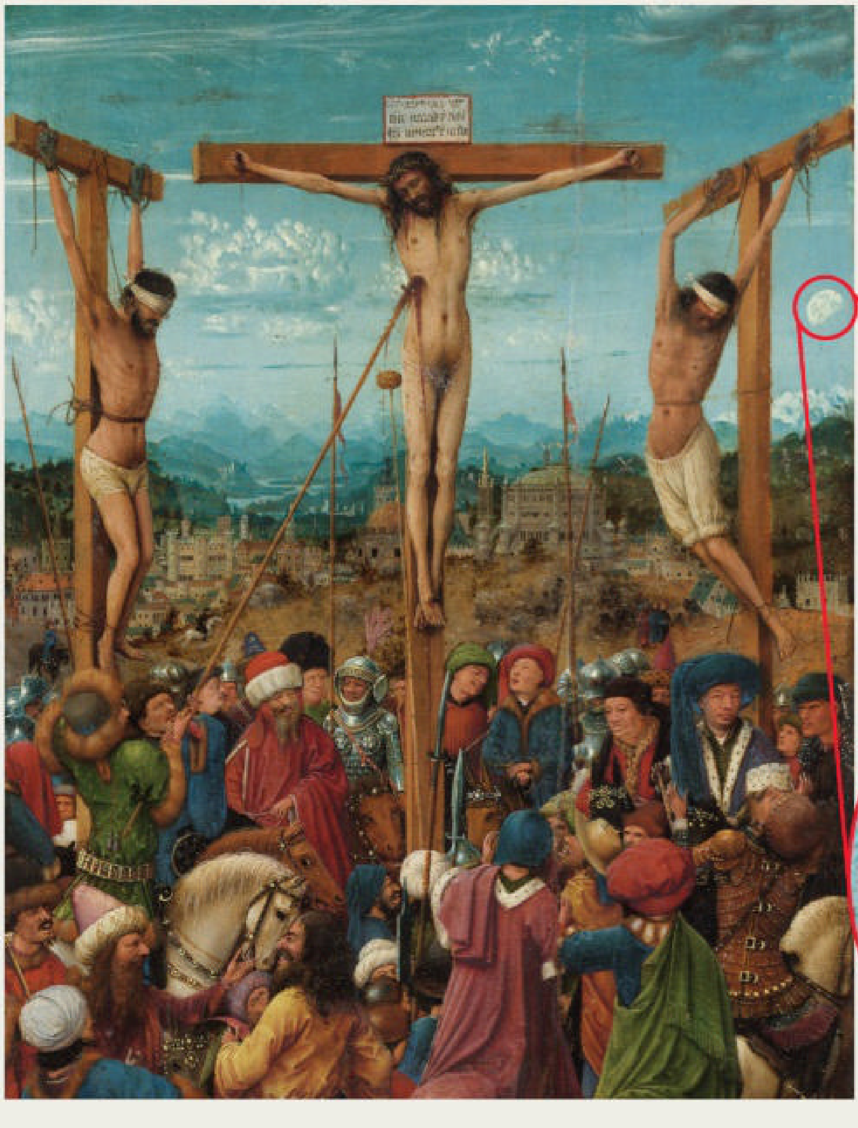
On moons like Europa and Enceladus with chemistries like Earth's, scientists can make educated guesses about what they're looking for. But on Titan's surface, which Dragonfly will explore, the terrain might look deceptively Earthlike, but the chemistry is anything but familiar. There it's so cold that liquid methane and ethane fill the lakes and seas, while the landscape is rock-hard water ice. Identifying life's fingerprints on Titan will be a different challenge. "One just has to be very patient in the outer solar system," says planetary scientist Elizabeth "Zibi" Turtle of Johns Hopkins University Applied Physics Laboratory, who's spearheading the Dragonfly mission to Titan. "It's the nature of the part of the solar system we're exploring."

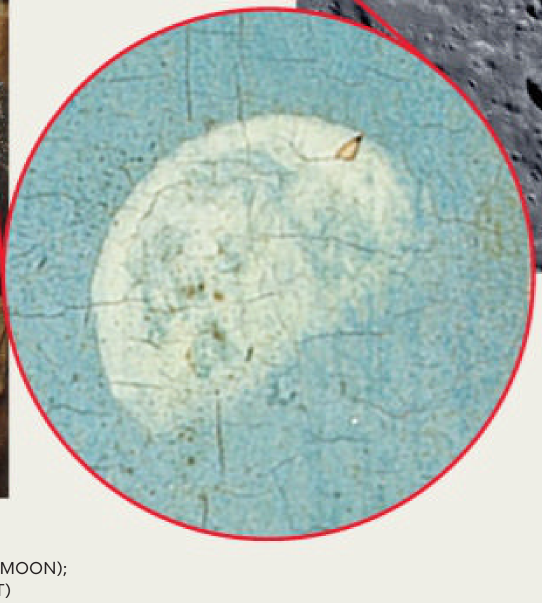
Learning whether these moons—or any world in the solar system—are inhabited is worth the challenge. "We need to find out," says JPL's Robert Pappalardo, science lead for the Europa Clipper mission. "It really could bring a new Copernican revolution in our understanding of our place in the universe." □

LOOK

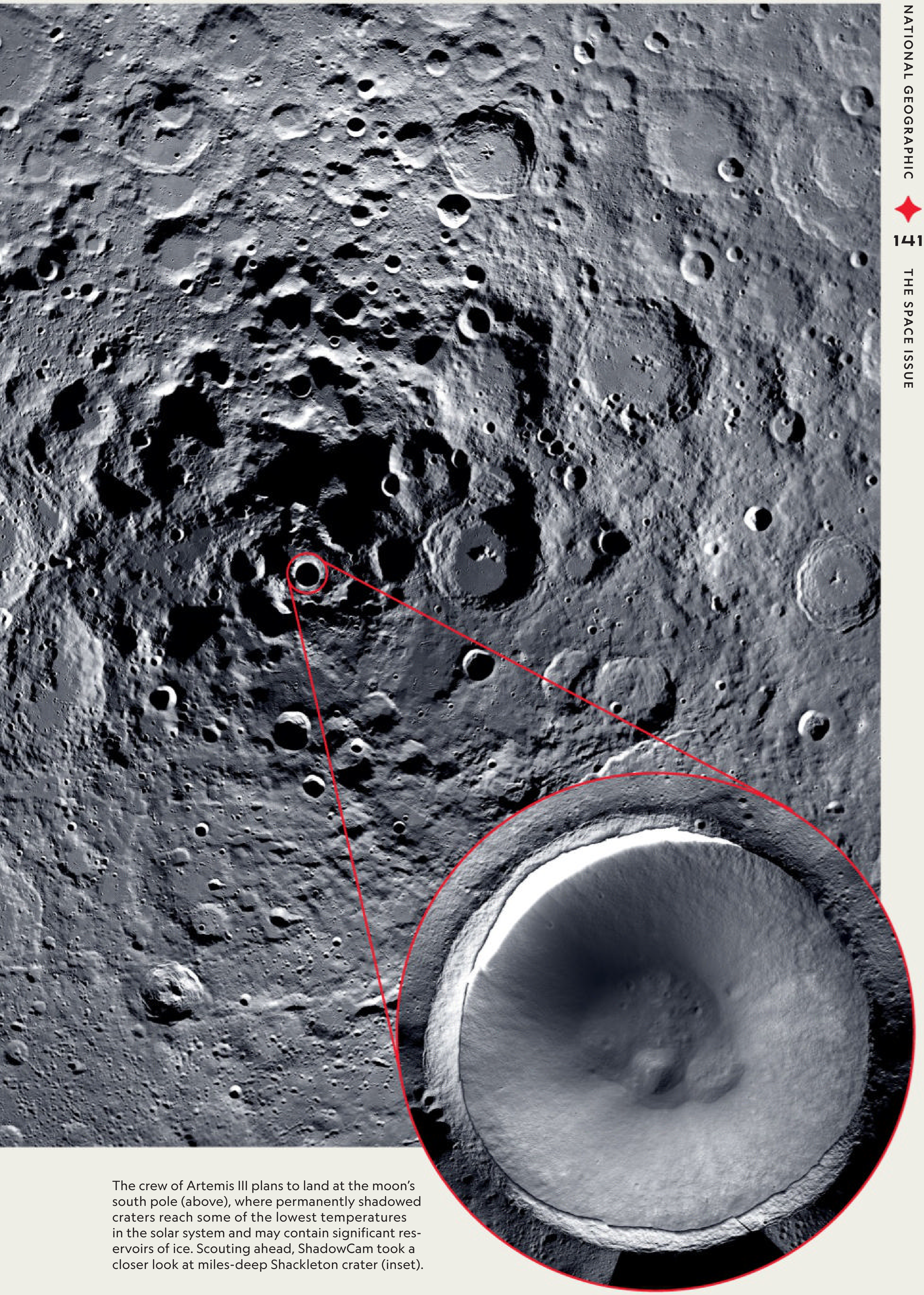
People have been gazing at the moon for millennia. A new camera shows us what we've never seen.

The first realistic depiction of the moon is believed to be in Jan van Eyck's painting, "The Crucifixion," below. Completed by 1441, it shows Earth's nearest neighbor in a gibbous phase, punctuated by lunar seas. We've been refining our understanding of the moon ever since. But mysteries remain. Many craters at the poles are shrouded in permanent darkness, barely explored—until now. ShadowCam, 200 times more sensitive than previous cameras, has been mounted to a satellite for almost a year, photographing inside these craters. Most mornings, Arizona State University professor Mark Robinson, lead scientist for the NASA-funded camera, gets a cup of coffee, sits at his computer, and pores over the 25 or so photographs that came in that day, seeing clearly for the first time what lies in the moon's darkness. "I don't know what we're going to find," Robinson says.





METROPOLITAN MUSEUM OF ART (PAINTING); MOSAIC BY NASA/GSFC/ARIZONA STATE UNIVERSITY (MOON); MOSAIC BY ARIZONA STATE UNIVERSITY, KOREA AEROSPACE RESEARCH INSTITUTE, AND NASA (INSET)



The crew of Artemis III plans to land at the moon's south pole (above), where permanently shadowed craters reach some of the lowest temperatures in the solar system and may contain significant reservoirs of ice. Scouting ahead, ShadowCam took a closer look at miles-deep Shackleton crater (inset).

INSTAGRAM

COLLEEN PINSKI

FROM OUR PHOTOGRAPHERS

WHO

A Colorado-based photographer who focuses on landscapes and architecture

WHERE

Albuquerque, New Mexico

WHAT

Canon EOS 7D camera with a telephoto lens set at 1200mm

Eclipses are all about timing. In advance of 2012's annular solar eclipse, when the moon obscures most of the sun, Pinski drove to New Mexico for a better view. She found a local park, framed her camera on the horizon, and waited. As the celestial event progressed, a man walked into her shot and placed himself perfectly. Pinski got chills as she snapped, capturing the moment before it was gone. You can catch an annular eclipse on October 14 and a total eclipse on April 8, 2024, in parts of the United States.

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