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WITH COVERAGE FROM nature

FROM THE EDITOR

Liz Tormes

Unblinking View of the Universe

Not even six months ago astronomers achieved a major milestone by successfully launching the shiny new James Webb Space Telescope. This summer we expect the observatory to start streaming data back to Earth, sharpening our eyes on the cosmos. And in May a planet-spanning, state-of-the-art observational tool—the Event Horizon Telescope—yielded the first image of the black hole at the center of our own Milky Way galaxy, Sagittarius A*. Chief features editor Seth Fletcher attended the announcement of the image in Washington, D.C. (see “The First Picture of the Black Hole at the Milky Way’s Heart Has Been Revealed”). You can also go online to learn more about why the picture looks like it does and listen to Fletcher explain the science behind capturing the black hole. Never before have our sights been so trained on the astounding universe.

And we’re just at the start. Next-gen rocket ships herald even more revolutionary space telescopes and bold space missions, as writer Jonathan O’Callaghan reports in this issue (see “SpaceX’s Starship and NASA’s SLS Could Supercharge Space Science”). Keep your eyes open—big space discoveries are heading our way.

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Space & Physics

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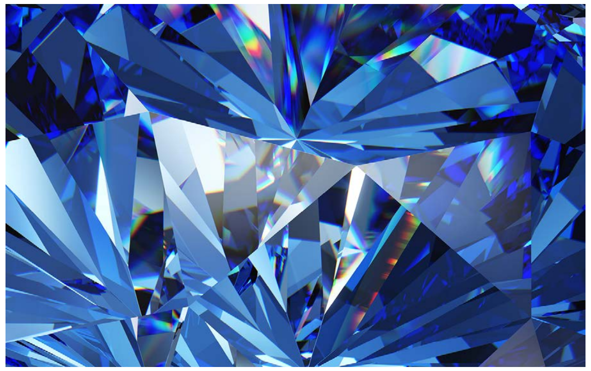

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Long an abstract idea, these bizarre constructs have finally been made in a lab

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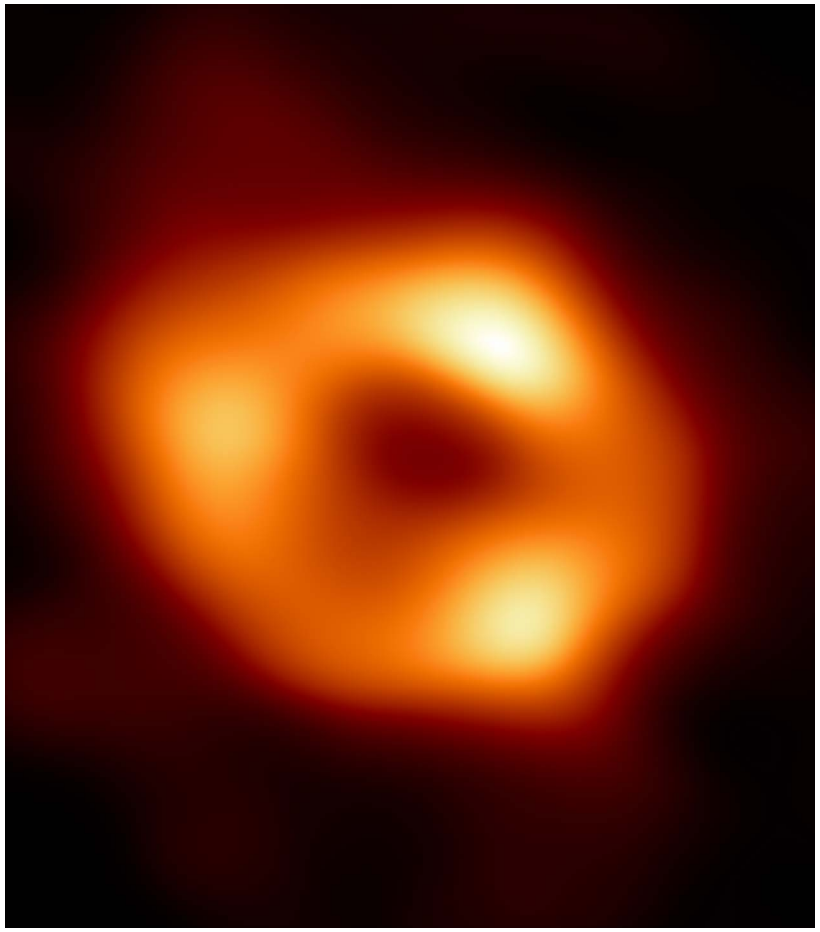
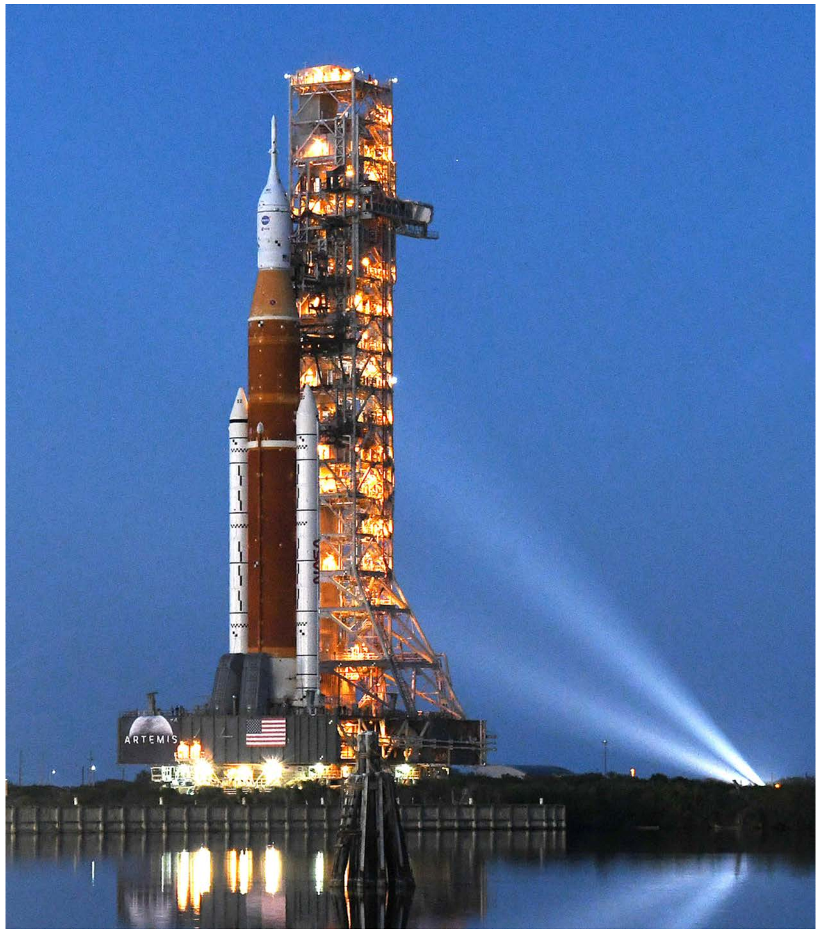


EHT Collaboration



Paul Hennessy/Anadolu Agency via Getty Images

FEATURES

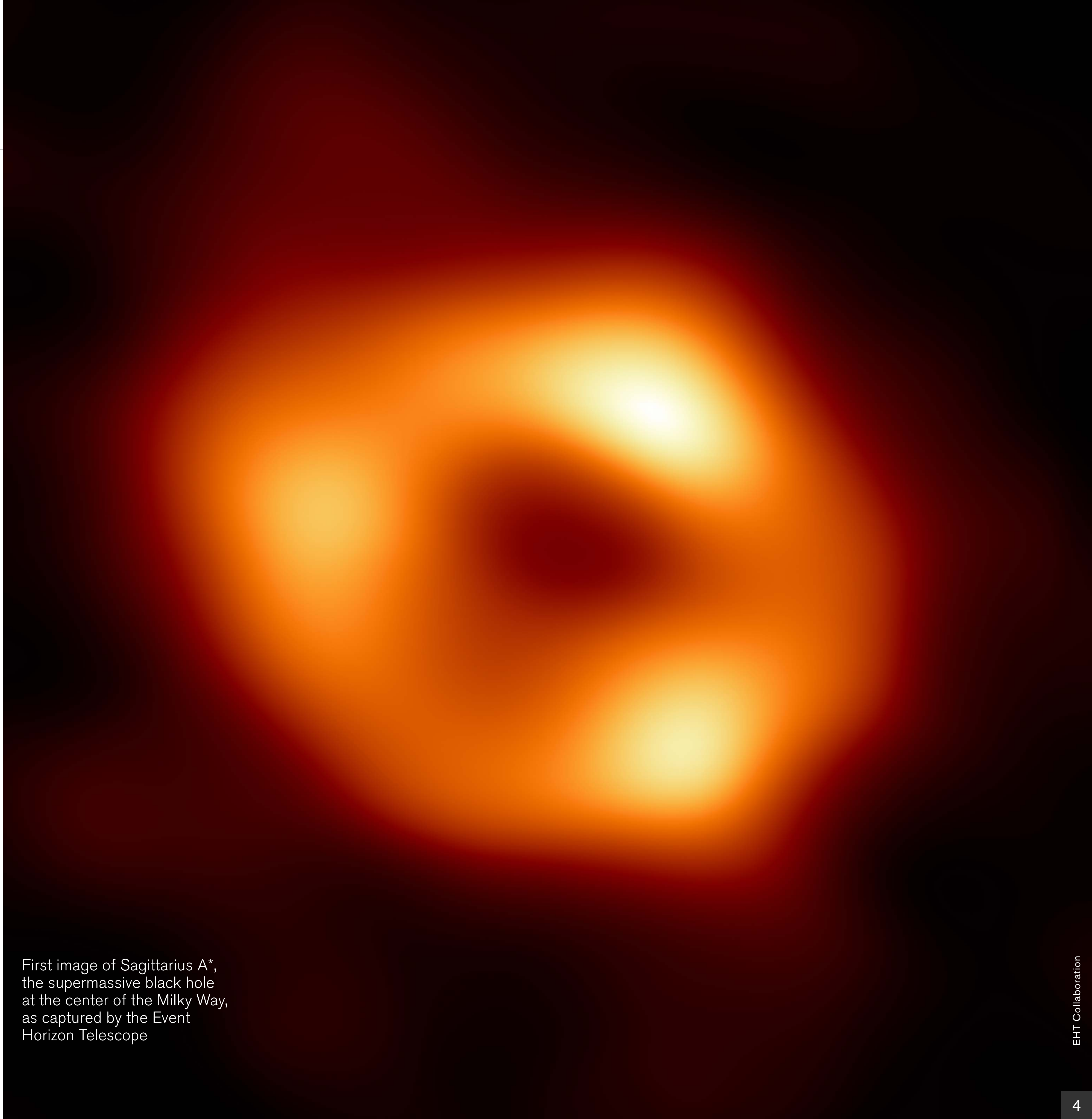
OPINION

NEWS

The First Picture of the Black Hole at the Milky Way's Heart Has Been Revealed

The historic image of Sagittarius A* is the culmination of a decades-long astronomical quest—and a crucial step toward a new understanding of black holes, gravity and spacetime

The mystery at the heart of the Milky Way has finally been solved. On May 12, at simultaneous press conferences around the world, the astronomers of the Event Horizon Telescope (EHT) revealed the first image of Sagittarius A*, the supermassive black hole at the center of the Milky Way. It's not the first picture of a black hole this collaboration has given us—that was the iconic image of M87*, which they revealed on April 10, 2019. But it's the one they wanted most. Sagittarius A* is our own private supermassive black hole, the still point around which our galaxy revolves.



First image of Sagittarius A*, the supermassive black hole at the center of the Milky Way, as captured by the Event Horizon Telescope

EHT Collaboration

Scientists have long thought that a supermassive black hole hidden deep in the chaotic central region of our galaxy was the only possible explanation for the bizarre things that happen there—such as giant stars slingshotting around an invisible something in space at an apprecia-ble fraction of the speed of light. Yet they've been hesitant to say that outright. For example, when astrono-mers Reinhard Genzel and Andrea Ghez shared a portion of the 2020 Nobel Prize in Physics for their work on Sagittarius A*, their citation specified that they were awarded for "the discovery of a supermassive compact object at the centre of our galaxy," not the revelation of a "black hole." The time for that sort of caution has expired.

At the National Press Club in Washington, D.C., Feryal Özel, a professor of astronomy and physics at the University of Arizona and a member of the EHT Science Council, introduced the picture, a dark ring framed by three shining knots of trillion-degree gas. "I met [Sagittari-us A*] 20 years ago and have loved it and tried to understand it since," Özel said. "But until now, we didn't have the direct picture."

Black holes trap everything that falls in, including light, so they are, in a very real sense, unseeable. But they warp spacetime around them so severely that, when they are illuminated by glowing streams of infalling matter shredded in their gravitational grip, they cast a "shadow." The shadow is about two and a half times larger than a black hole's event horizon: its boundary and its defining feature, the line in spacetime through which nothing that passes can ever return.

The EHT captures images of this shadow using a technique called very long baseline interferometry (VLBI), which combines radio observatories on multiple continents to form a virtual Earth-size telescope, an instrument with the highest resolution in all of astronomy. In April 2017 the EHT collaboration spent several nights pointing that virtual instrument at Sagittarius A* and other supermas-sive black holes. We've already seen the first finished product from that effort: M87*. The team also captured the raw data for the Sagittarius A* image in the same campaign, but converting those observations into an actual picture took much longer.

That's because Sagittarius A* is constantly changing. M87*, the black hole at the heart of the galaxy Messier 87, or M87, is so huge that the matter swirling around it takes many hours to complete a full orbit. Practically speaking, that means you can stare at it for a long time, and it will scarcely change. Sagittarius A* is more than 1,000 times less massive, so it changes about 1,000 times faster, as matter moves in tighter, quicker orbits around the black hole. Katie Bouman, a California Institute of Technology computer scientist and astronomer who co-leads the EHT's imaging working group, said that matter orbits Sagittarius A* so quickly that it changes "minute to minute." Imagine taking a time-lapse photograph of a speeding bullet—doing so isn't easy. That's why extracting a clear image of Sagittari-us A* from the data collected in the 2017 observing run has been the work of several years.

If Sagittarius A*'s mercurial nature made it hard to see, it also makes it an exciting laboratory for future studies of black holes and Einstein's general theory of relativity, his hallowed theory of gravity. Through decades of study with all manner of telescopes, astronomers already knew Sagittarius A*'s basic measure-ments (its mass, diameter and distance from Earth) to great accura-cy. Now, at last, they've gained the ability to watch it evolve—to watch as it feeds on flaring, flashing streams of matter—in real time.

LIFTING A MANY-LAYERED VEIL

Scientists started to suspect that a black hole lurked in the heart of the Milky Way in the early 1960s, not long after the discovery of active galactic nuclei—extremely bright regions at the cores of some galaxies illuminated by voraciously feeding supermassive black holes. From our perspective here on Earth, active galactic nuclei are a thing of the past—we only see them in the distant universe. Where did they all go? In 1969 English astrophysicist Donald Lynden-Bell argued that they didn't go anywhere. Instead, he said, they just went to sleep after their heavy meals—dormant supermassive black holes, he predicted, are slum-bering all around us in the hearts of spiral galaxies, including our own.

In 1974 American astronomers Bruce Balick and Robert Brown pointed radio telescopes in Green Bank, W.Va., at the center of the Milky Way and discovered a dim speck they suspected was our galaxy's central black hole. They found the speck in a slice of sky known as Sagittarius A. Radiation from the new source was lighting up—or "exciting"—surrounding clouds of hydrogen. Brown borrowed from the nomenclature of atomic physics, in which excited atoms are marked with an asterisk, and named the newfound speck Sagittarius A*.

For the next two decades, radio astronomers kept gradually improving their view of Sagittarius A*, but they were limited by a lack of suitable telescopes, relatively primitive technology (think reel-to-reel magnetic tape) and the inherent difficulty of looking into the galactic center.

Sagittarius A* is concealed by a multilayered veil. The first layer is the galactic plane—26,000 light-years' worth of gas and dust that blocks visible light. Radio waves sail through the galactic plane unimpeded, but they're obscured by the veil's second layer—the scattering screen, a turbulent patch of space where density variations in the interstellar medium knock radio waves slightly off course. The final layer concealing Sagittarius A* is the obliterated matter surrounding the black hole itself. Peering through that barrier is a bit like peeling off an onion's skins. The outer layers emit longer-wavelength light, so making VLBI work with shorter-wavelength light would enable closer-in views approaching the black hole's event horizon. That, however, was a major technological challenge.

Astronomers using other techniques besides VLBI initially had more success, steadily gathering indirect evidence that Sagittarius A*'s "speck" was actually a seething supermassive black hole. In the 1980s physicist Charles Townes and his colleagues showed that gas clouds in the galactic center were moving in ways that only made sense if they were under the influence of some great, unseen gravitating mass. And in the 1990s Ghez and Genzel independently began tracking the orbits of giant blue stars in the galactic center, mapping their motion around a heavy but hidden pivot point.

Meanwhile the situation for radio astronomers improved. In the late 1990s and early 2000s a new generation of high-frequency radio telescopes started to come online—telescopes that, if augmented with lots of bespoke equipment, could participate in VLBI observations at the microwave frequencies thought to shine from the edge of Sagittarius A*'s shadow. At the same time, the computing revolution that led to solid-state hard drives and smartphones in every pocket vastly increased the amount of data that each observatory in a network of radio telescopes could record and process.

In 2007 a small precursor for the EHT took advantage of these trends and used a trio of telescopes in Hawaii, California and New Mexico to pierce the veil surrounding Sagittarius A*. They were far from making an image, but they saw something.

Scientists had known for a while that a black hole should, in certain circumstances, cast visible shadows. In 1973 physicist James Bardeen predicted that a black hole in front of a bright background would show its silhouette, although he decided that "there seems to be no hope of observing this effect." And in 2000 astrophysicists Heino Falcke, Fulvio Melia and Eric Agol had shown that a microwave-gathering, Earth-size radio telescope should be able to see the shadow of Sagittarius A* against the glow of its surrounding ring of shattered matter.

Half a decade afterward, a few dozen of the astronomers and astrophysicists laboring in this obscure corner of astronomy agreed on the formal goal of building a virtual planet-scale radio telescope to observe that shadow. The first official kickoff meeting for the project occurred in January 2012, and the EHT was born.

Five years later, after growing into a collaboration of more than 200 scientists with eight participating observatories across the globe, the team took its first realistic shot at seeing the shadow of Sagittarius A*. Over the course of 10 days in April 2017, telescopes in North America, South America, Hawaii, Europe and Antarctica collectively zoomed in on the galactic center and other black holes, gathering 65 hours of data on 1,024 eight-terabyte hard drives, which were shipped to supercomputer banks in Massachusetts and Germany for correlation. Five years after that, the elated EHT researchers showed the world that their experiment worked. "We've been working on this for so long that, every once in a while, you have to pinch yourself," Bouman said. "This is the black hole at the center of our galaxy!"

—Seth Fletcher

Time Crystals Made of Light Could Soon Escape the Lab

A new, more robust approach to creating these bizarre constructs brings them one step closer to practical applications


SimoneN/Getty Images

In many respects, scientists are much like detectives, solving mysteries by sifting through evidence in search of cluelike patterns. For example, any crystal, whether a granule of table salt or a diamond necklace, is just a bunch of atoms arranged in a repeating pattern. By glimpsing only a few of the crystal's patterned atoms, a sleuth may surmise where all the others should be.

But what if that pattern was spread across time rather than space, with the pattern's constituents related by "when" instead of "where"? This counterintuitive concept is the basis of "time crystals," quantum systems that exhibit crystal-like predictably repetitive behavior. Massachusetts Institute of Technology physicist and Nobel laureate Frank Wilczek first theorized their existence in 2012. And after years of arduous work, experimentalists only managed to conclusively engineer one into existence in 2021. Now a team of physicists led by engineer Hossein Taheri of the University of California, Riverside, has achieved another advance by making a time crystal out of light. The work, published in *Nature Communications* in February, could help time crystals transform from delicate experimental curiosities into more robust components of practical devices.

Although a time crystal's behavior repeats over time, it cannot be considered a mere ticking clock. Specifically, a clock requires external energy to keep going, but for a time crystal, the "ticking" is its most natural, stable state. This is the opposite of physicists' idea of thermodynamic equilibrium, in which energy flows into a system only to inevitably dissipate: imagine a pot of water that is brought to a rolling boil and then returned to room temperature. In this sense, time crystals are rather like a pot of water that always boils in the exact same way and never cools down. By some definitions, they thus represent a new and unique state of matter that is distinguished by a steadfast persistence in staying out of equilibrium. As such inherent metronomes, time crystals may be a great future asset to precision timekeeping or quantum information processing.

"Time crystals have gone from being a conceptual idea motivated by highly theoretical considerations to something that people are trying to use for technology," says Wilczek, who was not involved in the new work. But researchers have had to follow long and thorny paths in the quest to bring time crystals out of the lab and into the realm of real-world applications. Typically, daunting experimental setups or the unique scrutiny of powerful quantum computers have been required to discern whether any given setup constitutes a time crystal at all.

The team's breakthrough was arguably using a comparatively simpler approach centered on piping twin beams of laser light into a millimeter-wide, disk-shaped crystal cavity. Inside the cavity, the two beams repeatedly ricocheted off of its sides and collided in the process. Crucially, the researchers picked a particular cavity design and precisely controlled the properties of the laser beams so that the salvo of reflected light produced odd patterns that could never emerge from light emitted by, for example, common household light bulbs. Inside its crystalline bounce house, the laser light became a parade of "chunks," each more like a single wave crest that never loses shape rather than a broad, wide ripple on the surface of a perturbed lake. These so-called solitary waves, or solitons, emerged and formed the parade with a predictable periodicity, marching perfectly on beat, consequently building a time crystal. The physicists caught on to this "crystallization" by carefully studying the light that trickled out of the cavity.

If some tiny version of you stood by the cavity's exit while holding a light detector, Taheri explains, initially you would detect periodic variations in the outgoing light's intensity linked to the lasers' properties. Eventually, however, a light intensity pattern would spontaneously emerge with a starkly different periodicity set by the solitons parading through the cavity. This would be a bit like watching a movie on a television that suddenly began playing it in fast-forward, with the specific frame rate set by some hidden mechanics within the display rather than any setting you controlled. "Now we see some features of the [light] wave that are periodic, but their period is actually twice or three times or some other integer multiple of the periodicity imprinted [on the light] by the lasers," Taheri says. This increase revealed a quantum system that now naturally kept its own time—in other words, a light-based time crystal.

Andrey Matsko, a physicist at NASA's Jet Propulsion Laboratory and a co-author of the study, likens it to growing salt crystals by suspending a string in salty liquid. "Tuning our lasers is like controlling the structure of the thread you'd put in the [salt] solution," he says. In either case, the laser or the thread helps crystals form, but their periodicity, their patterning, is fully their own.

Past studies utilized different building blocks for engineering time crystals, yet using light in the new experiment proved to have practical advantages. More important, the team's time crystal operates under relatively normal circumstances. Most quantum phases of matter reveal their special properties only at cryogenic temperatures or other extreme conditions and revert to being very ordinary when they are exposed to the world outside the lab. “From my perspective, this experiment is important because it works at [relatively] high temperatures,” says Berislav Buca, a physicist at the University of Oxford, who did not participate in the study. “This makes it closer to complex processes we see in the real world around us.”

The new time crystal also proved surprisingly resilient against the real world’s notorious messiness. According to Taheri, the system’s random losses of energy, as well as its encroaching noise (a bit like your television heating up and displaying static in the movie-watching analogy), actually boosted its stability. Usually “when these two elements are present, they try to ruin the crystallinity,” he says. To avoid such external perturbations, time crystals typically have to be stringently isolated from their environment. “But our system strikes a balance between these counteracting players,” Taheri says. Igor Lesanovsky, a physicist at the University of Nottingham in England, who was also not involved with the experiment, agrees that keeping a time crystal working without closing it off to its surroundings can be tricky. “You really need a ‘conspiracy’ between different effects,” he says.

Because dissipation and noise conspire to keep each other’s deleterious effects in check, the new light-based time crystal is a promising candidate for integration into practical devices in the future. Making it also requires relatively few components, notes Lute Maleki, CEO of the photonic technology company OEwaves and a co-author of the study. “This is really a simple [device] architecture,” he underscores. “It should be accessible to a lot of [research] groups.” Maleki’s hope is that future research will push this simple but resilient design to the center of both investigations of fundamental physics and applied efforts such as in precision timekeeping.

As a timekeeping device, the light-based time crystal may be slightly less accurate than state-of-the-art atomic clocks. But its stability and unfussy components could make it just right for integration into, for example, communication or computation devices that require very accurate timekeeping while also being rugged enough to function outside a lab’s carefully controlled conditions. Additionally, some common electronics fabrication techniques could possibly enable the time crystal’s implementation on chips, making it easier to add the system to existing consumer gadgets.

Additionally, physicists could study very large time crystals in the same way that more conventional, spatial crystals have been investigated for decades, says study co-author Krzysztof Sacha, a physicist at Jagiellonian University in Poland. Here physicists could exchange space for time to investigate whether time crystals engineered with certain defects or bathed with excess energy display unexpected behaviors. Such behaviors are typically harder to detect in small crystals, so the ability to make its light-based system large potentially sets up the team for a foray into a fully new realm.

"I think that is really opening a new [physics research] horizon,” Sacha underlines. Wilczek agrees. “This is a whole new class of states of matter,” he says. “It is very conceivable to me that, when you examine them, useful devices and other surprises will emerge. It’s virgin territory; we are discovering a new world here.”

—Karmela Padavic-Callaghan

New Revelations Raise Pressure on NASA to Rename the James Webb Space Telescope

E-mailed exchanges show the space agency’s internal struggle to address pleas to change the controversial name of its latest, greatest observatory

Sadness. Disappointment. Frustration. Anger. These are some of the reactions from LGBTQ+ astronomers over the latest revelations regarding NASA’s decision not to rename the James Webb Space Telescope (JWST), given that the agency long had evidence suggesting its Apollo-era administrator James Webb was involved in the persecution of gay and lesbian federal employees during the 1950s and 1960s.

The new information came to light in March, when nearly 400 pages of e-mails were posted online by the journal *Nature,* which obtained the exchanges under a Freedom of Information Act (FOIA) request. Since

early last year, four researchers have been leading the charge for NASA to alter the name of the $10-billion flagship mission, launched in December 2021, which will provide unparalleled views of the universe. The e-mails make clear that, behind the scenes, NASA was well aware of Webb's problematic legacy even as the agency's leadership declined to take his name off the project.

"Reading through the exchanges, it seems that LGBTQ+ scientists and the concern we raised are not really what they care about," says Yao-Yuan Mao of Rutgers University, who maintains the online Astronomy and Astrophysics Outlist of openly LGBTQ+ researchers.

"It's almost amusing how incompetent the whole thing was," says Scott Gaudi, an astronomer at the Ohio State University, "and how little they stopped to think of how important an issue this was to the queer astronomical community and how important NASA is for young queer kids trying to find aspirational reasons to just keep going."

As the successor to the renowned Hubble Space Telescope, JWST's name is likely to one day be known by schoolchildren, suburban parents and senior citizens alike, which is why LGBTQ+ astronomers feel so strongly that the observatory's namesake should not be someone who was allegedly involved in homophobic directives. Many of them see NASA's resistance to renaming JWST as part of a dismaying trend in which the agency's actions speak louder than—and counter to—its stated policy of fostering diversity and inclusion throughout its workforce. In March, for example, NASA officials scrambled to explain their abrupt cancellation of an initiative to allow employees of its Goddard Space Flight Center to more easily display personal pronouns in intra-agency communications.

During a March 30 meeting of NASA's Astrophysics Advisory Committee, officials said that the agency's investigation into Webb's potential involvement with LGBTQ+ persecution is still ongoing and that they expect to present a final report in the coming months. "I'm looking for additional evidence that may conflict with the understanding we currently have of Webb's role in this," said NASA's acting chief historian Brian Odom. At the same meeting, the agency's director of astrophysics Paul Hertz even offered some contrition, acknowledging that "the decision NASA made is painful to some, and it seems wrong to many of us."

"I've worked closely with Paul Hertz for over a decade, and I consider him to be a colleague and a mentor. He knows me. He knows I'm gay. And he didn't ask me. Like, what the hell?"
—Scott Gaudi

To repair its damaged reputation with the LGBTQ+ community, some astronomers say, the agency should now bow to mounting pressure and strike Webb's name from its flagship telescope.

Renaming JWST would be "a simple but very impactful thing that NASA can do, both for astronomers and the wider public," says Johanna Teske, an astronomer at the Carnegie Institution for Science in Washington, D.C. "Why would they not take the opportunity to do that and fulfill one of their core values?"

Originally known as the Next Generation Space Telescope, JWST was rechristened for Webb in 2002, a decision undertaken by Sean O'Keefe, NASA's administrator at the time. Little was known then about Webb's role in a period of mid-20th-century American history known as the Lavender Scare—a McCarthy-like witch hunt in which many gay and lesbian federal employees were seen as national security risks and subsequently surveilled, harassed and fired.

Prior to leading NASA, Webb was second-in-command at the U.S. Department of State. In a September 3, 2021, e-mail *Nature* obtained through FOIA, a redacted writer notes that archival documents paraphrased in a 2004 history book say, "Webb met with President [Harry S.] Truman on June 22, 1950, in order to establish how the White House, the State Department, and the Huey Committee might 'work together on the homosexual investigation.' " A large number of LGBTQ+ workers were fired from the State Department before Webb resigned from his position there in 1952.

Critics say homophobia followed Webb to NASA. During his tenure as the agency's administrator between 1961 and 1968—a critical time in its preparations to land astronauts on the moon—a suspected gay employee, Clifford Norton, was interrogated for hours about his sexual history by NASA's security chief and ultimately fired for "immoral, indecent, and disgraceful conduct." This was part of the basis for calls to rename JWST, which NASA responded to by conducting an internal investigation into Webb's complicity in such actions.

On September 27, 2021, current agency administrator Bill Nelson released a one-sentence statement saying, "We have found no evidence at this time that warrants changing the name of the James Webb Space Telescope." The announcement seems odd, given that, as early as April 2021, one redacted author in the newly released e-mails noted that the official who fired Norton testified that the termination came about because his advisers had told him that dismissal for homosexual conduct was considered a “custom within the agency.”

Prior to Nelson’s statement, the redacted author of the September 3, 2021, e-mail strongly recommended changing the telescope’s name. “That Webb played a leadership position in the Lavender Scare is undeniable,” they wrote.

“It seems like, from the very beginning, the entire research effort was compromised by the fact that the goal was to dismiss the criticism they received,” says Lucianne Walkowicz, an astronomer at the Adler Planetarium in Chicago and one of the scientists leading the push to change JWST’s name.

Especially galling to many LGBTQ+ astronomers is an episode referenced in the e-mails in which Hertz stated he contacted more than 10 members of the astrophysics community—none of whom identified as LGBTQ+ and none of whom expressed disappointment at the prospect of JWST keeping its problematic name.

“I’ve worked closely with Paul Hertz for over a decade, and I consider him to be a colleague and a mentor,” Gaudi says. “He knows me. He knows I’m gay. And he didn’t ask me. Like, what the hell?”

The ad hoc nature of NASA’s response to this controversy highlights the fact that federal agencies rarely follow clear-cut methods for naming or renaming high-profile projects. Such decisions often appear to be taken at the whim of senior officials, with little regard for larger input from other stakeholders, including the public at large. In late 2019, for instance, the National Science Foundation renamed its currently under construction Large Synoptic Survey Telescope in honor of astronomer Vera C. Rubin, who was instrumental in the discovery of dark matter. According to Matt Mountain, president of the Association of Universities for Research in Astronomy, that change emerged from a suggestion made in the U.S. House Committee on Science, Space, and Technology rather than from any large grassroots effort.

NASA’s upcoming Wide-Field Infrared Survey Telescope was similarly renamed after Nancy Grace Roman, another pioneering astronomer and the first female executive at NASA, although in that case, the agency followed a formal policy directive for assigning names to major projects. Most of NASA’s name changes have occurred prior to a project’s completion or launch, but there is precedence for post-launch alterations, too. The Swift Gamma-Ray Burst Explorer was changed to the Neil Gehrels Swift Observatory, after its late principal investigator, and the National Polar-Orbiting Operational Environmental Satellite System Preparatory Project was renamed after meteorologist Verner E. Suomi three months after it launched.

The cost of such undertakings—which involve changing official documents, Web sites and graphic designs—seems to be fairly negligible. The Rubin Observatory’s budget of roughly $40 million per year saw no significant increase during its name change, Mao says, suggesting that such switches carry minimal monetary risks for what could be substantial rewards.

“The change of name, in my opinion, uplifts the Vera Rubin science community,” Mao adds. “The name not only inspires me to do exciting science but also reminds me that there is a responsibility to make this field a more inclusive space.”

Some of the pushback to changing JWST’s name has come from those who insist he was not a hate-monger but merely a complicated figure—a man of his time who, like everyone, did some good and some bad.

“It is alluring to want to search for monsters,” Walkowicz says. “But I think monsters are a myth that we tell ourselves about how prejudice and discrimination is enacted. We’re too focused on a cartoonish idea of what discrimination looks like rather than how discrimination is a multilevel policy decision enacted by many people.” If Webb deserves credit for helping to place astronauts on the moon under his tenure, Walkowicz adds, then he also bears responsibility for homophobic actions conducted by his administration.

Regardless of how NASA proceeds going forward, the harm done to its relationship with the LGBTQ+ community will take time and effort to repair. “I’ve lost faith, and I think a lot of people have,” says Chanda Prescod-Weinstein, a theoretical cosmologist at the University of New Hampshire and another leader of the push for renaming JWST. But change remains possible, she says: “As scientists, we often realize we were in error, and we set a new course.” *—Adam Mann*

The First Rocket Launch from Mars Will Start in Midair

NASA's Mars Ascent Vehicle will attempt a wildly unconventional liftoff to bring Red Planet samples back to Earth

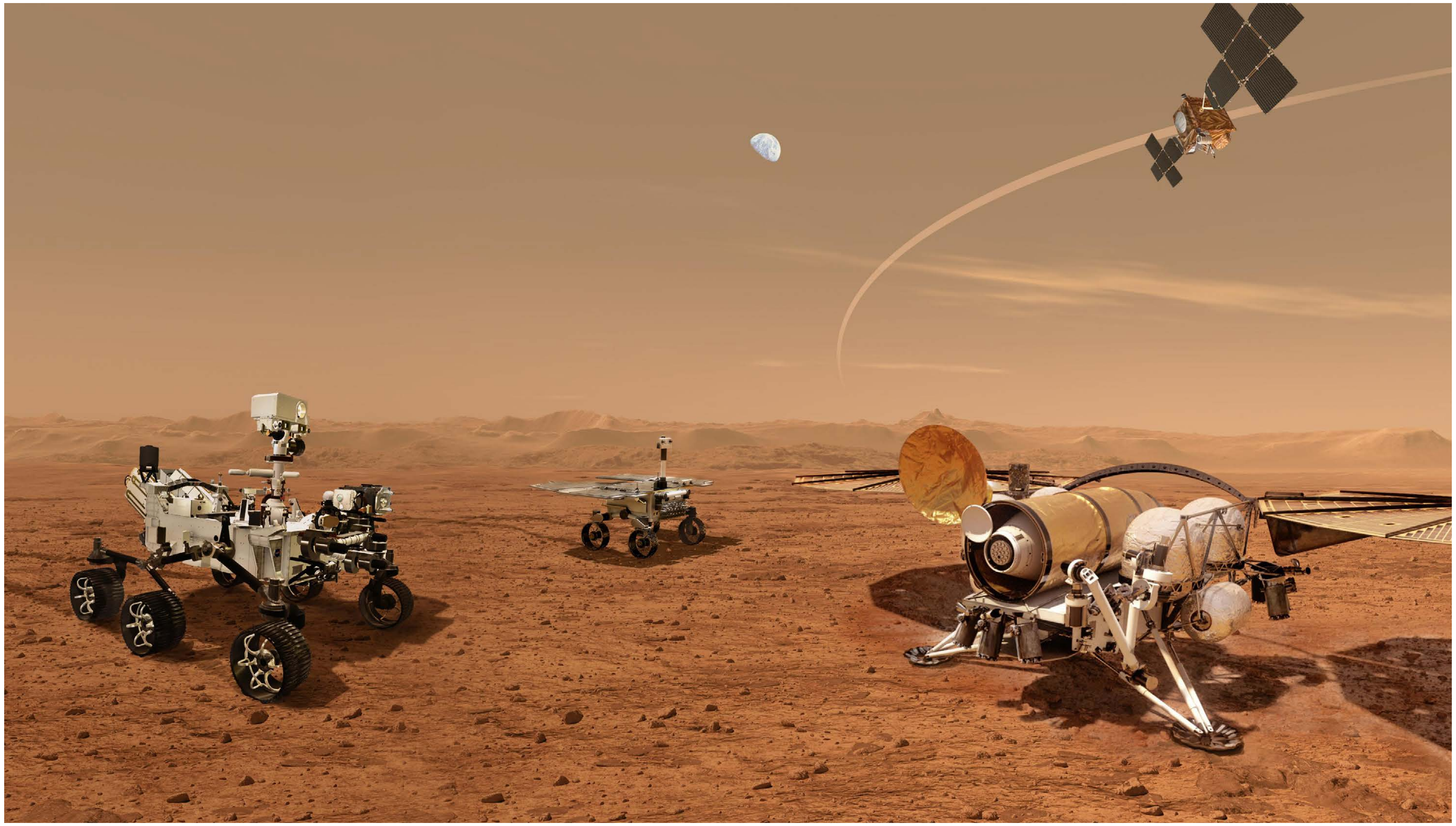


Illustration of the key robotic components of the Mars Sample Return mission, including NASA's Perseverance (*left*), the European Space Agency's Sample Fetch Rover (*center*) and the Sample Retrieval Lander (*right*). The last will carry NASA's Mars Ascent Vehicle.

NASA/ESA/JPL-Caltech

Within a decade a small rover on Mars will pick up samples of rock left by a previous mission. It will then load them into a rocket secured within a small platform on a flat patch of the planet's surface. Once the rocket's hatch has closed, the platform will toss it upward on its side, a bit like a thrown American football. The rocket's engines will ignite, propelling it into Martian orbit—where a waiting spacecraft will grab its invaluable samples for ferrying back to Earth and into the hands of researchers eager to study them for signs of past life on the Red Planet. One might call this wild interplanetary shuffle the most epic game of catch ever conceived, but scientists simply refer to it as Mars Sample Return.

"It's never been done before," says Chris Chatellier of NASA's Jet Propulsion Laboratory (JPL), lead engineer of part of the launch system that will bring the samples back home. But it has been dreamed of—and planned—for decades.

The first step occurred with the landing of NASA's Perseverance rover in Jezero Crater on Mars one year ago to explore the site's eons-old river delta, targeted as one of the most likely locales to harbor any remnants of life from when the planet was a warmer, wetter world. Using an extendable arm and drill inside the crater, Perseverance has started collecting samples that likely date back billions of years. "We believe the samples will tell us whether there used to be life at the surface of Mars," says NASA's

Thomas Zurbuchen, who oversees the space agency's science missions. Ultimately Perseverance will place dozens of samples in small cigarlike tubes, caching them on the surface to await future collection.

The general outline for how this collection will take place is already clear, but key details remain undetermined. For example, where—and in how many locations—will the samples be cached? What will the "fetch rover" that will collect them—to be built by the European Space Agency (ESA)—look like? And perhaps most crucially, how will the samples successfully rocket off the surface of Mars and back to Earth? "This launch off another planet will be history-making," Zurbuchen says. "With it comes answers to our neighboring planet that cannot otherwise be addressed."

The details on that crucial last question have now moved a significant step forward. In February, NASA selected the U.S. aerospace firm Lockheed Martin for a potentially $194-million contract to build the three-meter-long Mars Ascent Vehicle (MAV), a relatively small rocket meant to propel Perseverance's samples into orbit. Already engineers are hard at work designing the MAV's components, which must overcome multiple challenges unique to this first-of-its-kind mission. The Red Planet's gravity, while only a third of Earth's, must be overcome. Mars's thin atmosphere, 100 times as tenuous as Earth's, will make the launch unlike any on our planet—or from the airless moon or asteroids, where previous successful sample-returns have taken place. And the MAV's all-or-nothing launch, millions of kilometers from Earth, must be both autonomous and flawless.

NASA says the MAV will launch to Mars in 2026 or later, and some have forecasted that the likely date will be 2028. It will be stored inside a landing platform not unlike those of predecessors such as NASA's InSight lander. InSight touched down on Mars in 2018, performing a propulsive landing rather than relying on the more complex Sky Crane system required for the heavier Perseverance rover and its kin, Curiosity. The journey to Mars will be slow, 28 months in all, to ensure that the MAV touches down during local summer in or near Jezero. "The spacecraft needs to arrive at the proper season at Mars so that it doesn't encounter dust storms," says Dave Murrow, Lockheed Martin's business development lead for deep-space exploration.

"We nerd out all the time on this. What we're going to do is just amazing."
—Angela Jackman

After safely passing through the atmosphere, the lander will aim to land within a region of the crater that is as benign as possible in order to facilitate an easier subsequent liftoff. "We'll be looking for a nice, flat landing site without many rocks," Murrow says. The actual site will be selected in the coming years. The lander, devoid of scientific instrumentation, will be designed to protect the MAV on the surface, deploy ESA's fetch rover and finally launch the sample-filled MAV back to orbit.

One major challenge will be ensuring that the aluminum-based fuel used by the MAV's propulsion systems, provided by the U.S. aerospace company Northrop Grumman, does not freeze. Temperatures on the Martian surface average about –60 degrees Celsius, so the lander will need to warm the MAV, likely by using solar-powered electric heaters inside an insulated canister aptly called an "igloo." This approach, engineers believe, should allow the MAV to linger on the surface for up to one Earth year, offering, it is hoped, sufficient time for the fetch rover to retrieve Perseverance's samples from one or more surface caches.

Then the real fun begins. Over the past few years Chatellier and his team at JPL have been grappling with the surprisingly hard problem of how, exactly, to launch a small rocket from Mars. "We started with the basic idea of pointing [the MAV] on a rail and launching it off a platform," Chatellier says. But the rail would need to be heavy and almost as long as the lander itself. "The concern was there's not a lot holding the lander down," says Angela Jackman, project manager of the MAV program at NASA's Marshall Space Flight Center. Without the counterweight of a heavy rail, the exhaust plume from the launching MAV could kick the entire platform up into the air to strike the rocket. Earthbound testing of such a system in simulated Mars-like gravity and atmospheric conditions would also be very challenging.

So the team instead settled on another idea: What if the rocket could be tossed several meters above the surface, allowing more clearance for blastoff? "Although it might seem counterintuitive to throw up an unlit rocket, it actually does simplify the design and test process quite a bit," Chatellier says. Such a "cold launch" system is not unprecedented: the U.S. Air Force's Peacekeeper missiles, in service from 1987 to 2005, were lofted out of silos using steam pressure before their engines were ignited. The approach for MAV is also similar to a standard missile launch from a fighter jet, except "we're just throwing it up off the ground," Chatellier says.

The result is a launch system called VECTOR, or Vertically Ejected Controlled Tip-Off Release. For the past two years the JPL team has been testing a mock-up of the MAV with VECTOR, completing 23 "throws" in total so far, with cables catching the rocket in midair. (The system in its entirety, including the ignition of the rocket, will only be fully used for the first time on Mars.)

VECTOR is designed to hurl the MAV skyward from Mars at about five meters per second using a force comparable to a strong human punch. As the MAV ignites its engine, one second post-toss, VECTOR will also help aim the craft, causing a rotation that tilts it up by 45 degrees from a horizontal orientation midair to allow the MAV's two-stage rocket to propel the basketball-sized sample capsule to a 400-kilometer-high orbit above the planet. With any luck, Perseverance will still be operational and watching from a safe distance away, offering everyone back on Earth a virtual front-row seat for this first-ever Martian launch.

If all goes well, shortly thereafter a European-built spacecraft will swoop in to scoop up the sample capsule in Martian orbit, stowing it for the journey home. After departing from Mars, the capsule will purposefully crash land in the Utah desert in the early 2030s with its durable samples intact.

Audacious as it may be, VECTOR appears to be the best way to get the half-kilogram's worth of samples Perseverance will collect back to Earth. "Everyone thought Sky Crane was crazy," Chatellier says. "VECTOR has drawn similarities to that." In the coming years he and his team hope to have completed about 50 tests of system so that it will be ready for launch to Mars in 2028. There are still other details to be worked out, including the finer mechanics of how the rocket will be hurled aloft, but the goal is to have a system that can cope with whatever conditions Mars throws at it. There will be no second chances. "We want to make sure we have a robust design so that, even on the worst possible day on Mars, we know the system is still going to work," Chatellier says.

The dream of Mars Sample Return is now on the cusp of becoming reality, perhaps scarcely a decade away, aided by a deceptively simple idea: land a small rocket on Mars, toss it into the thin, cold air and launch it back to space. Even if the materials it ultimately helps return show no signs of life, the result will be no less historic. "We nerd out all the time on this," Jackman says. "What we're going to do is just amazing." *—Jonathan O'Callaghan*

NASA Criticized for Ending Pronoun Project

More than 100 employees at NASA's Goddard Space Flight Center were surprised when a test project allowing them to add their pronouns to their agency identifiers was abruptly canceled

In a move that has been widely criticized, NASA leaders recently terminated a test project that allowed employees at the agency's Goddard Space Flight Center (GSFC) to display pronouns in their official agency identifiers. The decision affected more than 100 employees who saw their stated pronouns vanish from communication platforms.

The project's termination attracted public attention after it was described in an anonymous post on Reddit. *Scientific American* has since verified many of the details revealed by the post with multiple GSFC employees—all of whom spoke under condition of anonymity for fear of reprisal. In the days following the Reddit post, NASA's pronoun erasure has been called "more than a little disappointing," "pointlessly cruel" and an indication of "queerphobic leadership" by various astronomers.

"Unfortunately, this is very consistent with my experience there," says Beck Strauss, a former National Institute of Standards and Technology research scientist working at GSFC and a current member of the International Society of Nonbinary Scientists. "There are a lot of individuals working at NASA and related organizations who really, genuinely, want things to be better and want to put their pronouns in their display names and want to make these places more welcoming for people from a lot of different backgrounds and identity groups. But those efforts always fail if they do not have administrative support and access to material resources."

> **"I'm the person who leads DEIA [diversity, equity, inclusion and accessibility] across the agency, and so I take responsibility for any poor communication and the mistakes that were made in communicating."**
> *—Steve Shih*

Recently NASA has taken steps to fight bias and increase diversity and equity within the agency, including providing gender-neutral bathrooms, instituting dual-anonymous peer review and removing due dates for some project proposals during the COVID pandemic. But the agency's decision to terminate the GSFC pronoun test also comes on the heels of its refusal to rename the James Webb Space Telescope, a controversy that erupted when astronomers pointed out that the flagship's namesake—a former NASA administrator—had allegedly been complicit in federal homophobic policies toward government workers in the 1950s and 1960s. And it comes amid a volley of legislation and directives in multiple states that are designed to marginalize and restrict the rights of LGBTQ+ people.

"Unfortunately, as a nonbinary person in astronomy, [this decision] doesn't seem bizarre to me at all," says Lucianne Walkowicz, an astronomer at Chicago's Adler Planetarium and co-founder of the JustSpace Alliance. "Because trans and gender nonconforming people experience high rates of harassment, assault and other forms of violence, each moment we have to assert our identities carries risk. At its most benign, this may be a co-worker feeling slighted by our having to correct them in order to be seen as ourselves, and at the more extreme end, it can open the door to bullying, harassment or worse."

A PREPILOT PROJECT

Organized by a handful of management officials within GSFC, the pronoun-inclusive effort was "a tech demo"—a prepilot program, a Goddard employee says, that was a first step toward addressing concerns that included issues with removing deadnames from the agency's IT system. (A deadname is the name a transgender or nonbinary person had before transitioning.) In searching for solutions, the GSFC team spoke with NASA Headquarters, as well as legal departments and employee resource groups at the agency. In other words, "this wasn't a bunch of people going rogue," says a scientist at GSFC.

During that process, the GSFC team identified an option that would let employees add their pronouns to their display names, which are used in electronic communications, including e-mail, contact lists, instant messaging platforms and Microsoft Teams environments. Usually those identifiers include "[Last name]," "[First name]" and "[NASA Center-XXX]," where the "XXX" would be replaced by a three-digit organizational code. But by filling in an optional field that is typically used for nicknames, employees could add pronouns after their names. It was an efficient and inexpensive way to make a necessary change, employees say, and did not require any additional coding or IT investments.

"Having the ability to display pronouns—particularly in visible, prominent places, not tucked away at the bottom of an e-mail signature—removes significant burdens for trans and gender nonconforming

Every year members of the LGBTQ+ Advisory Group at NASA's Ames Research Center participate in the San Francisco Pride parade, as seen here during 2019's festivities.

people," Walkowicz says. "Like all people, trans and gender nonconforming scientists don't want to be constantly self-advocating in order to be themselves in peace. We would actually much prefer to have our pronouns where you can see them so we can all get on with our lives and do some science."

Driven by word of mouth rather than any official encouragement, over a month or so, more than 100 GSFC employees added pronouns to their identifiers. And, a Goddard employee adds, participants were told that the tech demo would pave the way for an official pilot program at GSFC and perhaps even be deployed agency-wide.

"It was cool to see that in people

NASA

and be surprised in a good way," the GSFC scientist recalls. "And that's part of why it was so devastating to be surprised in the opposite way because I felt like we were making progress."

Instead it all came to an abrupt and baffling halt.

NO SATISFACTORY EXPLANATIONS

In late February participants learned they were being called to a meeting on the "Use of IT Systems for Gender Pronouns." Several of them thought, "Great, we will be getting kudos for a system that is working well." But one of the leaders of GSFC's LGBTQ+ employee resource group sent a warning about what was coming.

On February 28 NASA leaders terminated the program during a virtual meeting with GSFC employees. Representing agency leadership were NASA's deputy administrator Pamela Melroy, Goddard's center director Dennis Andrucyk and Steve Shih, NASA's associate administrator for diversity and equal opportunity.

During the hour-long meeting, Melroy and the others made it clear that the test program was over—that the decision was final—although they said they were hoping NASA could formally implement a similar, long-term policy. Yet employees said the presenters offered no satisfactory explanation for the timing of the termination or the rationale behind it. Among the various reasons discussed were concerns about the pronoun field being used for inappropriate identifiers, including nationalities and sports team affiliations; that the program had been implemented without approval by proper personnel; and that this was not what IT systems were designed for.

Shih later elaborated in a conversation with *Scientific American.* "The intention wasn't to trivialize the huge importance of gender pronouns for the LGBTQ+ population," he says. "And unfortunately, communication wasn't obviously as effective as we would like. I think people got the impression that we were trying to trivialize the whole focus on gender pronouns. That was not the intent at all, certainly not trying to equate gender pronouns on the same level as sports teams. In fact, I think the opposite intention was there, which is to say, you know, a sports team identifier wouldn't rise to this level to be included in the system."

The meeting was fraught and contentious, participants say: "People walked away [feeling] all sorts of things—frustrated, pissed off, emotional, hurt," says the GSFC employee. "I can't tell you how much I think this has really harmed the transgender and nonbinary employees in our organization."

At the end of the hour, Melroy and Andrucyk left, but Shih stayed on and continued speaking with employees, some of whom explained how the decision would cause direct harm.

"I'm the person who leads DEIA [diversity, equity, inclusion and accessibility] across the agency, and so I take responsibility for any poor communication and the mistakes that were made in communicating," Shih says. "My door is always open; my phone is always open to any individuals who want to discuss these issues further."

SENDING SIGNALS

But GSFC employees are not giving up. In a recent tweet, astrophysicist Amber Straughn wrote, "There are lots of us trying to do what we can to push back. This is total nonsense."

In the wake of the project's termination becoming public, NASA released an official statement from Shih:

Through an effort to create a more inclusive workplace, NASA recently completed an IT project at Goddard Space Flight Center that allowed approximately 125 employees to test the option of including their gender pronouns in NASA's email display fields—which currently includes each employee's name, center, and an organizational code. The learnings from this test will be used to inform the advancement of diversity, equity, inclusion, and accessibility.

NASA is fully committed to supporting every employee's right to be addressed by their correct name and pronouns. All NASA employees currently have the option and flexibility to include their gender pronouns in their customized email signature blocks. This option remains unchanged and is supported by NASA leadership so that employees can share their gender identities and show allyship to the LGBTQIA+ community.

Shih later told *Scientific American* the agency had terminated the program because the test had achieved its goal—it had demonstrated that existing systems could be used to display pronouns—and NASA was focused on increasing diversity, equity, inclusion and accessibility throughout its workforce.

"We want to look at all of these DEIA advancements in a strategic way and across the entire agency," Shih says. We want to do this more than just at a local level at one organization in NASA."

Strauss, who is also a senior fellow at the Center for Applied Transgender Studies, says that regardless of the reasoning behind the decision, it sends a signal to trans and nonbinary scientists. "A lot of students look to these organizations as indicators of whether they are welcome in the fields where they want to work," they say. "I started and used to run a networking group for nonbinary people in space science, which has more than 70 people in it.... And I look at this group, which is mostly graduate students and undergrads and some postdocs, and I have to really ask myself, 'Do I want to be telling my students to apply for summer internships at an organization that's going to be so cavalier about people's pronouns and names and identities?' "

—Nadia Drake

The Evolving Quest for a Grand Unified Theory of Mathematics

More than 50 years after the seeds of a vast collection of mathematical ideas called the Langlands program began to sprout, surprising new findings are emerging

By Rachel Crowell

Boris SV/Getty Images

Rachel Crowell is a Midwest-based writer covering science and mathematics. Follow Crowell on Twitter @writesRCrowell

Within mathematics, there is a vast and ever expanding web of conjectures, theorems and ideas called the Langlands program. That program links seemingly disconnected subfields. It is such a force that some mathematicians say it—or some aspect of it—belongs in the esteemed ranks of the Millennium Prize Problems, a list of the top open questions in math. Edward Frenkel, a mathematician at the University of California, Berkeley, has even dubbed the Langlands program "a Grand Unified Theory of Mathematics."

The program is named after Robert Langlands, a mathematician at the Institute for Advanced Study in Princeton, N.J. Four years ago he was awarded the Abel Prize, one of the most prestigious awards in mathematics, for his program, which was described as "visionary."

Langlands is retired, but in recent years the project has sprouted into "almost its own mathematical field, with many disparate parts," which are united by "a common wellspring of inspiration," says Steven Rayan, a mathematician and mathematical physicist at the University of Saskatchewan. It has "many avatars, some of which are still open, some of which have been resolved in beautiful ways."

Increasingly, mathematicians are finding links between the original program—and its offshoot, geometric Langlands—and other fields of science. Researchers have already discovered strong links to physics, and Rayan and other scientists continue to explore new ones. He has a hunch that, with time, links will be found between these programs and other areas as well. "I think we're only at the tip of the iceberg there," he says. "I think that some of the most fascinating work that will come out of the next few decades is seeing consequences and manifestations of Langlands within parts of science where the interaction with this kind of pure mathematics may have been marginal up until now." Overall Langlands remains mysterious, Rayan adds, and to know where it is headed, he wants to "see an understanding emerge of where these programs really come from."

A PUZZLING WEB

The Langlands program has always been a tantalizing dance with the unexpected, according to James Arthur, a mathematician at the University of Toronto. Langlands was Arthur's adviser at Yale University, where Arthur earned his Ph.D. in 1970. (Langlands declined to be interviewed for this story.)

"I was essentially his first student, and I was very fortunate to have encountered him at that time," Arthur says. "He was unlike any mathematician I had ever met. Any question I had, especially about the broader side of mathematics, he would answer clearly, often in a way that was more inspiring than anything I could have imagined."

During that time, Langlands laid the foundation for what eventually became his namesake program. In 1969 Langlands famously handwrote a 17-page letter to French mathematician André Weil. In that letter, Langlands shared new ideas that later became known as the "Langlands conjectures."

In 1969 Langlands delivered conference lectures in which he shared the seven conjectures that ultimately grew into the Langlands program, Arthur notes. One day Arthur asked his adviser for a copy of a preprint paper based on those lectures.

"He willingly gave me one, no doubt knowing that it was beyond me," Arthur says. "But it was also beyond everybody else for many years. I could, however, tell that it was based on some truly extraordinary ideas, even if just about everything in it was unfamiliar to me."

THE CONJECTURES AT THE HEART OF IT ALL

Two conjectures are central to the Langlands program. "Just about everything in the Langlands program comes in one way or another from those," Arthur says.

The reciprocity conjecture connects to the work of Alexander Grothendieck, famous for his research in algebraic geometry, including his prediction of "motives." "I think Grothendieck chose the word ['motive'] because he saw it as a mathematical analogue of motifs that you have in art, music or literature: hidden ideas that are not explicitly made clear in the art, but things that are behind it that somehow govern how it all fits together," Arthur says.

The reciprocity conjecture supposes these motives come from a different type of analytical mathematical object discovered by Langlands called automorphic representations, Arthur notes. " 'Automorphic representation' is just a buzzword for the objects that satisfy analogues of the Schrödinger equation" from quantum physics, he adds. The Schrödinger equation predicts the likelihood of finding a particle in a certain state.

The second important conjecture is the functoriality conjecture, also simply called functoriality. It involves classifying number fields. Imagine starting with an equation of one variable whose coefficients are integers—such as $x^2 + 2x + 3 = 0$—and looking for the roots of that equation. The conjecture predicts that the corresponding field will be "the smallest field that you get by taking sums, products and rational number multiples of these roots," Arthur says.

EXPLORING DIFFERENT MATHEMATICAL "WORLDS"

With the original program, Langlands "discovered a whole new world," Arthur says.

The offshoot, geometric Langlands, expanded the territory this mathematics covers. Rayan explains the different perspectives the original and geometric programs provide. "Ordinary Langlands is a package of ideas, correspondences, dualities and observations about the world at a point," he says. "Your world is going to be described by some sequence of relevant numbers. You can measure the temperature where you are; you could measure the strength of gravity at that point," he adds.

With the geometric program, however, your environment becomes more complex, with its own geometry. You are free to move about, collecting data at each point you visit. "You might not be so concerned with the individual numbers but more how they are varying as you move around in your world," Rayan says. The data you gather are "going to be influenced by the geometry," he says. Therefore, the geometric program "is essentially replacing numbers with functions."

"You might not be so concerned with the individual numbers but more how they are varying as you move around in your world."
—Steven Rayan

Number theory and representation theory are connected by the geometric Langlands program. "Broadly speaking, representation theory is the study of symmetries in mathematics," says Chris Elliott, a mathematician at the University of Massachusetts Amherst.

Using geometric tools and ideas, geometric representation theory expands mathematicians' understanding of abstract notions connected to symmetry, Elliot notes. That area of representation theory is where the geometric Langlands program "lives," he says.

INTERSECTIONS WITH PHYSICS

The geometric program has already been linked to physics, foreshadowing possible connections to other scientific fields.

In 2018 Kazuki Ikeda, a postdoctoral researcher in Rayan's group, published a *Journal of Mathematical Physics* study that he says is connected to an electromagnetic duality that is "a long-known concept in physics" and that is seen in error-correcting codes in quantum computers, for instance. Ikeda says his results "were the first in the world to suggest that the Langlands program is an extremely important and powerful concept that can be applied not only to mathematics but also to condensed-matter physics"—the study of substances in their solid state—"and quantum computation."

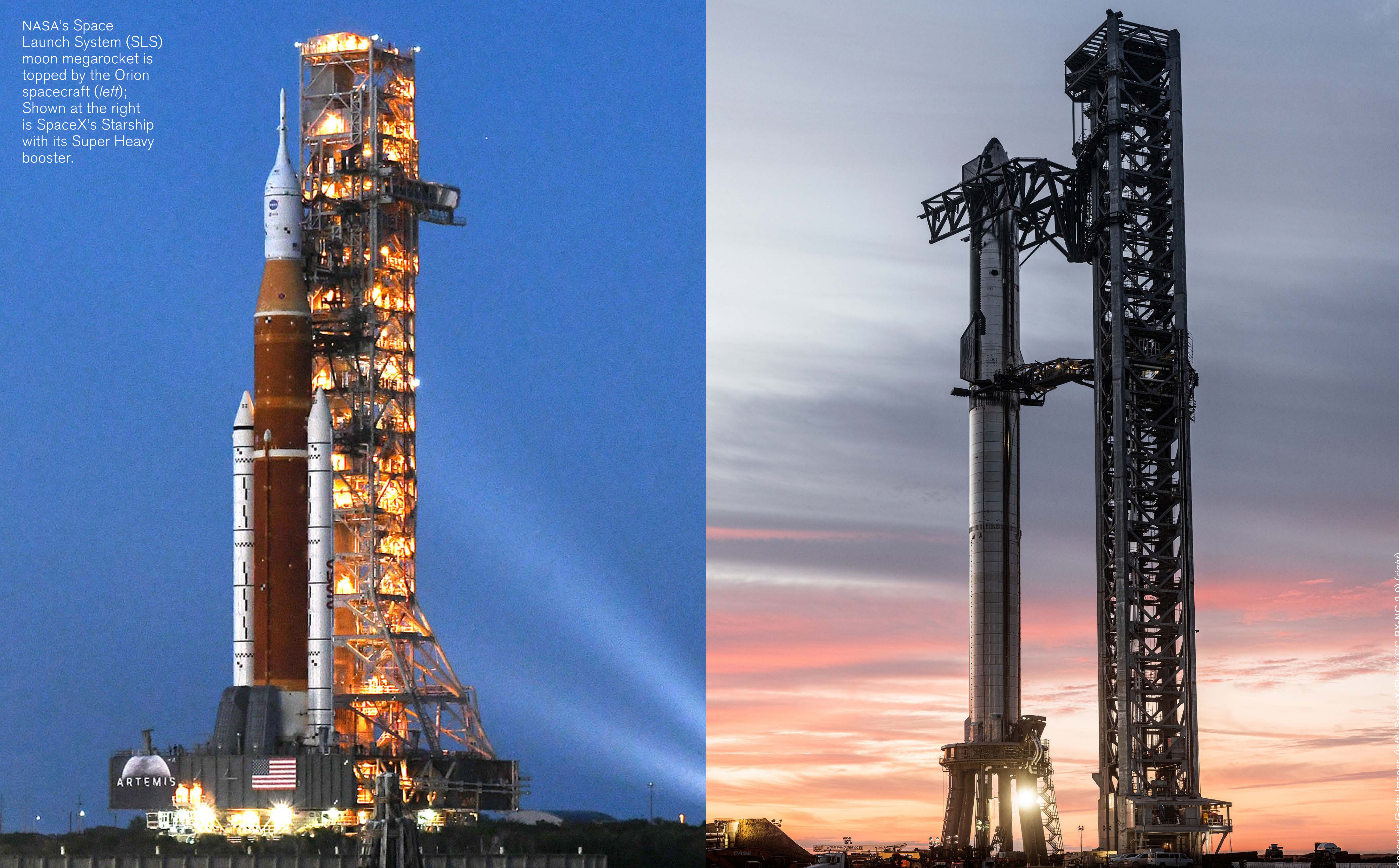
Connections between condensed-matter physics and the geometric program have recently strengthened, according to Rayan. "In the last year the stage has been set with various kinds of investigations," he says, including his own work involving the use of algebraic geometry and number theory in the context of quantum matter.

Other work established links between the geometric program and high-energy physics. In 2007 Anton Kapustin, a theoretical physicist at the California Institute of Technology, and Edward Witten, a mathematical and theoretical physicist at the Institute for Advanced Study, published what Rayan calls "a beautiful landmark paper" that "paved the way for an active life for geometric Langlands in theoretical high-energy physics." In the paper, Kapustin and Witten wrote that they aimed to "show how this program can be understood as a chapter in quantum field theory."

Elliott notes that viewing quantum field theory from a mathematical perspective can help glean new information about the structures that are foundational to it. For instance, Langlands may help physicists devise theories for worlds with different numbers of dimensions than our own.

Besides the geometric program, the original Langlands program is also thought to be fundamental to physics, Arthur says. But exploring that connection "may require first finding an overarching theory that links the original and geometric programs," he says.

The reaches of these programs may not stop at math and physics. "I believe, without a doubt, that [they] have interpretations across science," Rayan says. "The condensed-matter part of the story will lead naturally to forays into chemistry." Furthermore, he adds, "pure mathematics always makes its way into every other area of science. It's only a matter of time."



NASA's Space Launch System (SLS) moon megarocket is topped by the Orion spacecraft (*left*); Shown at the right is SpaceX's Starship with its Super Heavy booster.

Paul Hennessy/Anadolu Agency via Getty Images (*left*); SpaceX/Flickr (CC BY-NC 2.0) (*right*)

SpaceX's Starship and NASA's SLS Could Supercharge Space Science

Scientists are beginning to dream of how a new generation of superheavy-lift rockets might enable revolutionary space telescopes and bigger, bolder interplanetary missions | *By Jonathan O'Callaghan*

Jonathan O'Callaghan is a frequent contributor to *Scientific American*. His work has also appeared in the *New York Times, Science, Nature, Wired* and *LiveScience*, among others. In his spare time, he has traveled to all seven continents.

ASTRONOMERS BREATHED A COLLECTIVE SIGH OF RELIEF AS THE JAMES WEBB Space Telescope (JWST) sprung to life. Getting the $10-billion telescope up and running following its launch on Christmas Day 2021 had been a nerve-racking affair. JWST would not fit into any modern rocket without being folded, and it had to rely on hundreds of moving parts to unfurl to full size once in space. Ultimately those efforts were successful, and the telescope has started returning some of its first calibration images to thrilled audiences back on Earth. Yet the experience left many astronomers wondering if there was a simpler way to build and launch telescopes of this size. "We were worried about the unfolding," says John Blevins of NASA's Marshall Space Flight Center. But with a larger rocket, "you don't have to unfold in space. You can do it on the ground."

As chance would have it, two such rockets are currently sitting on launchpads. Each should ultimately exceed the power of the mighty Saturn V, which sent the Apollo astronauts to the moon. The first, NASA's Space Launch System (SLS), is ready and waiting at Kennedy Space Center in Florida for its inaugural uncrewed voyage around the moon this summer as part of the Artemis I mission—the opening shot in NASA's plan to return humans to the lunar surface in the 2020s. The rocket is meant to be as reliable as possible and is therefore based, in large part, on legacy hardware from NASA's Space Shuttle program. But a reliance on tried-and-true technology could be its Achilles' heel: some estimates currently peg the SLS's cost at an eye-watering $4.1 billion per launch. Presuming it is not scuttled by congressional appropriators feeling buyer's remorse, its massive size could in the end be a boon for scientists seeking to send larger, more ambitious spacecraft and telescopes throughout the solar system—and even beyond.

Over in Texas, Starship, a similarly capable but wildly different rocket being developed by SpaceX, is also in preparation to launch on its first orbital test flight, pending regulatory approval from the Federal Aviation Administration. The cost of the SLS seems so egregious because each multibillion-dollar rocket will be discarded after a single use, its components relegated to junk on the seafloor or adrift in space. Such was the standard for most of the space age, but times have changed. Starship and its giant Super Heavy booster are instead built for endurance, landing back on the ground for rapid reuse similar to SpaceX's current fleet of Falcon rockets, which has already dramatically lowered the cost of reaching space. As big and bold as the SLS may be, experts say it pales in comparison with what Starship could achieve. "Starship holds the promise of transforming the solar system in a way we can't really appreciate," says Alan Stern of the Southwest Research Institute in Texas, who helms NASA's New Horizons mission, which flew by the dwarf planet Pluto in 2015. "It completely changes the game."

Either rocket's shroudlike payload fairing is spacious enough to fit cargo as big or even bigger than JWST, all without the need for folding components into the world's most expensive origami. And both launchers will possess such immense thrust that they can reach remote corners of the solar system on shorter time scales with larger spacecraft than smaller rockets. Starship alone, however, is designed to be refueled in space, meaning that it could transport mind-bogglingly huge payloads to hard-to-reach locales such as Jupiter and Saturn—or pretty much anywhere else around the sun, for that matter.

As this hopeful new era of the super rocket dawns, eager scientists are vying to be along for the ride. "These rockets can enable whole new classes of missions—to all the giant planets and the Kuiper belt objects, to the ocean world satellites and the dwarf planets of the solar system," Stern says. "They're across-the-board useful." Now many are busy drawing up ideas for what might be possible, at the moment focusing more on the SLS because

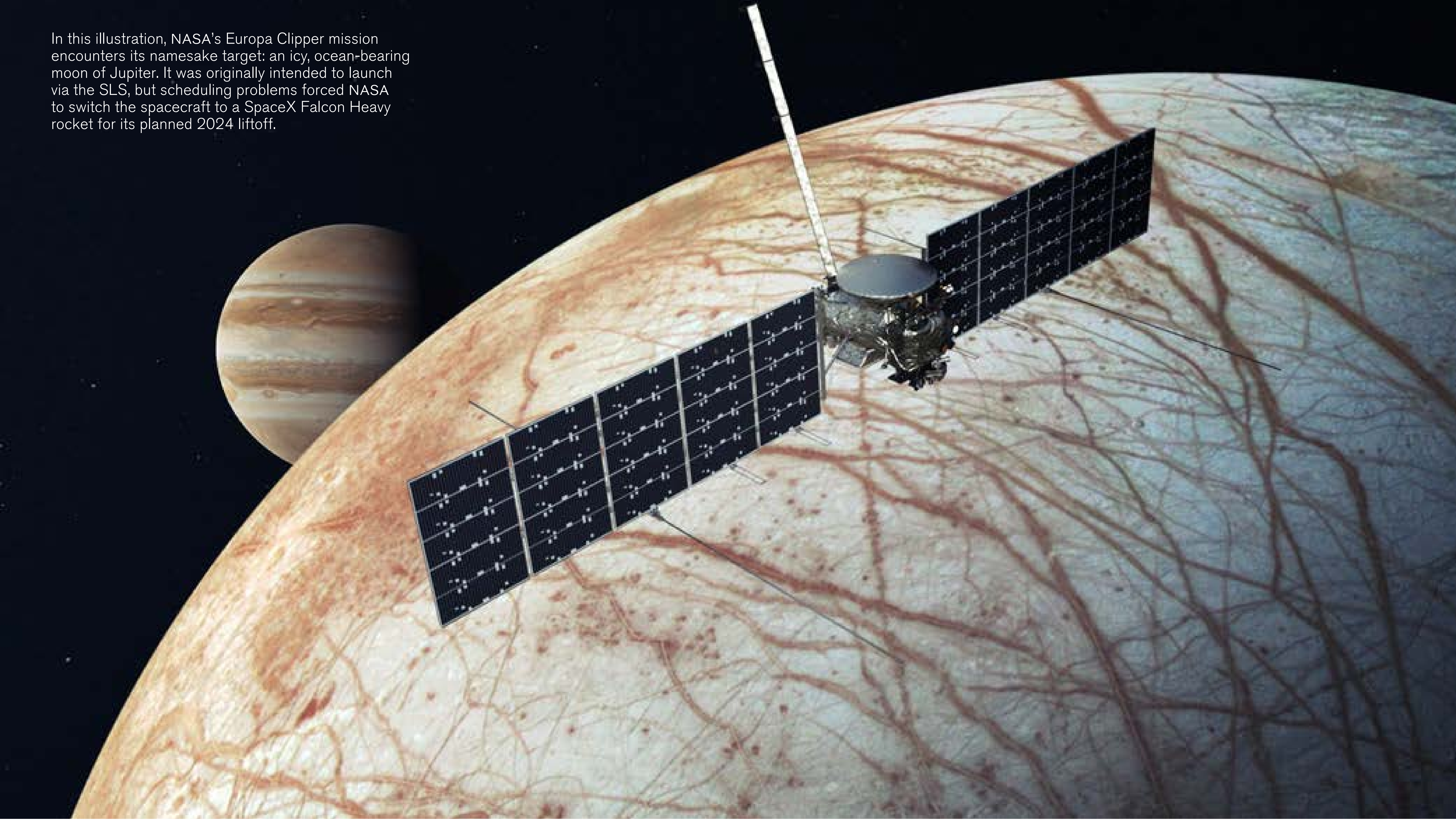
During the Artemis I mission, NASA's SLS rocket will send an uncrewed Orion spacecraft, as illustrated here, soaring away from Earth to the moon.

NASA

of its greater maturity but keeping a beady eye on Starship and its potentially revolutionary capabilities.

THE SCIENCE LAUNCH SYSTEM?

After its initial moonshot, NASA officials say, the SLS will primarily be used to launch the agency's Orion spacecraft with crew onboard. Those launches will work in tandem with NASA-contracted Starship launches, which will serve to land an Artemis crew on the moon as early as 2025—and perhaps one day send astronauts to the surface of Mars. "We expect approximately one human landing per year over a decade or so," NASA's administrator Bill Nelson said in a press conference on March 23. As such, no SLS rocket is likely to be available to solely launch any sort of telescope or scientific probe into the solar system until the 2030s. "Given the demands of the Artemis program between now and the late 2020s, it's going to be very difficult to squeeze a science mission in that time frame," said Robert Stough, payload utilization manager of the SLS at NASA's Marshall Space Flight Center, in a briefing last year.



In this illustration, NASA's Europa Clipper mission encounters its namesake target: an icy, ocean-bearing moon of Jupiter. It was originally intended to launch via the SLS, but scheduling problems forced NASA to switch the spacecraft to a SpaceX Falcon Heavy rocket for its planned 2024 liftoff.

NASA/JPL-Caltech

Consequently, in 2021 NASA switched the planned 2024 launch of its Jupiter-bound flagship mission, Europa Clipper, from the SLS to a SpaceX Falcon Heavy. Even so, agency officials are bullish that the SLS's exorbitant costs and sluggish launch rate can be improved, creating more opportunities for science missions. In his briefing, Stough estimated that $800 million or lower was an achievable target by the 2030s. According to a paper presented at a November 2020 American Institute of Aeronautics and Astronautics (AIAA) meeting, the SLS's final, most powerful planned configuration could be supercharged with the addition of a new "kick stage" that would add propulsion to the top of the rocket. Such an upgrade would allow the SLS to send some 16 metric tons to Jupiter, about six metric tons to Neptune and one metric ton to interstellar space. The New Horizons mission to Pluto, by comparison, had a mass of half a metric ton. "There's no rocket right now that can carry anywhere near this payload," says Blevins, who is chief engineer of the SLS at Marshall.

On April 19 the National Academies of Sciences, Engi-

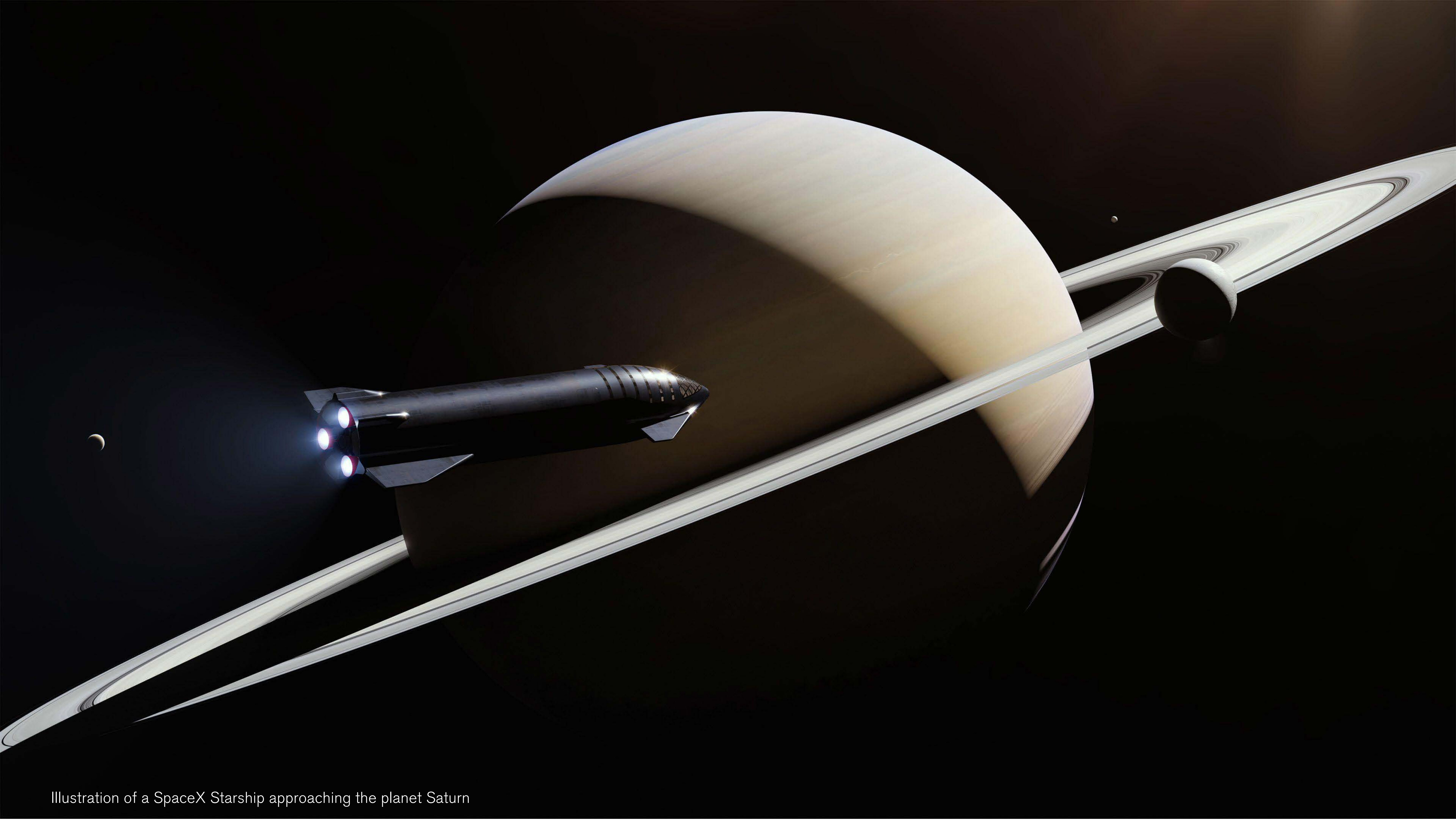


Illustration of a SpaceX Starship approaching the planet Saturn

Geopix/Alamy Stock Photo

neering, and Medicine was set to release its much awaited Planetary Science and Astrobiology Decadal Survey which will recommend NASA's otherworldly science priorities well into the 2030s. As part of the survey, NASA solicited studies from scientists on mission concepts that the agency might consider for targets in the outer solar system. Three of those suggested using the SLS to allow faster, bulkier missions: a Pluto orbiter, an orbiter and lander to Saturn's moon Enceladus, and an orbiter and atmospheric probe to Neptune.

"We wanted to use existing or very near-term technology," says Kirby Runyon of the Johns Hopkins University Applied Physics Laboratory (JHUAPL), who is part of the proposed Neptune mission. "The SLS is the furthest along in its design and maturation of any of the very large vehicles."

Runyon's group's proposal, Neptune Odyssey, would launch as soon as 2031 on an SLS rocket to enter orbit around Neptune in the 2040s. The mission would provide unprecedented insight into a planet that has only been visited once, a fleeting flyby from the Voyager 2

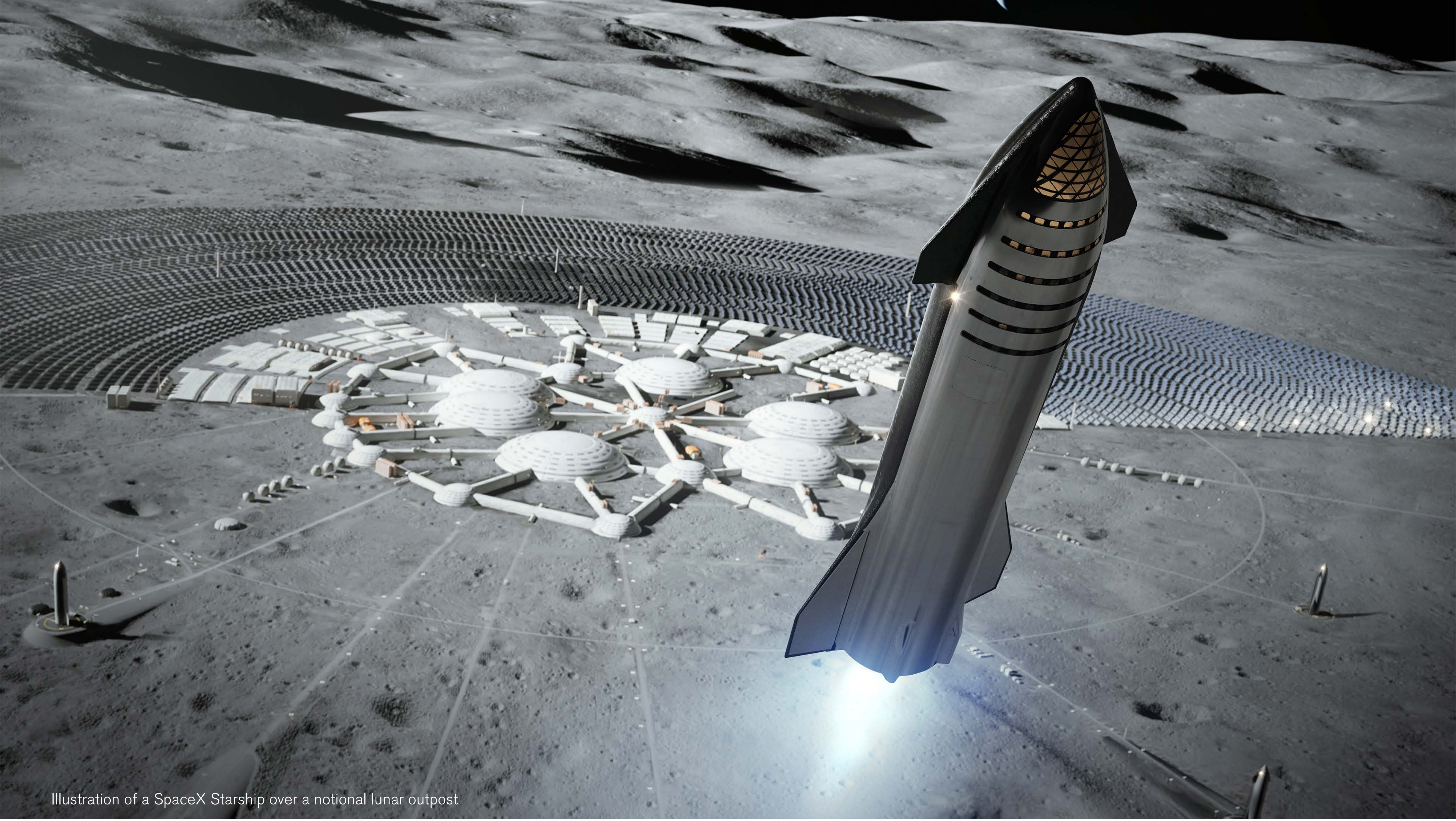


Illustration of a SpaceX Starship over a notional lunar outpost

spacecraft in 1989 on its journey out of the solar system. Odyssey would study Neptune and its largest moon Triton for four years while also deploying a probe into the planet's stormy atmosphere. Slightly smaller rockets such as the Falcon Heavy could also get Odyssey to Neptune but only via various add-ons that would raise the mission's cost and complexity while reducing its tolerance for error. That approach "is definitely more risky," Runyon says.

The Enceladus Orbilander, meanwhile, would be a mission to seek out signs of life within the Saturnian moon's ocean, which is ejecting plumes of water vapor and organic molecules through cracks in its overlying icy crust. The spacecraft could fly through and sample the plumes before landing on the moon's surface to perform in situ studies. The SLS, again, makes a mission like this easier than it would be with a smaller rocket, which would require gravitational boosts from planetary flybys in the inner solar system. "This means we don't have to design the spacecraft to survive both the warm conditions of the inner solar system and the frigid conditions out at Saturn," says Shannon MacKenzie, the concept's lead at JHUAPL.

Even the SLS has its limitations, though. Assuming a launch in 2031, the giant rocket would still take nearly three decades to propel a proposed orbiter, called Persephone, to Pluto. And despite its immense size, the SLS will be limited by its inability for on-orbit refueling to boost its carrying capacity once in space. In their more audacious dreams of cosmic exploration, scientists have eyes for only one rocket: Starship. "Starship is not just an incremental change," says Jennifer Heldmann of NASA's Ames Research Center. "This is a significant paradigm shift."

> **"You can put a 100-foot [30-meter] drill on the vehicle and then just deploy it. You don't have to try and fold it up. That's exciting because you can drill down into ice on Mars, which is very important for sustaining human exploration and also the search for life."**
> ***—Jennifer Heldmann***

INTO THE UNKNOWN

Starship, by its design, can be refueled by other Starship vehicles in Earth orbit. This means it could, hypothetically, carry a huge amount of mass around the solar system. "You could get a 100-ton object to the surface of Europa," SpaceX's CEO Elon Musk said in a public meeting of the National Academies in November 2021. That is a five times greater performance than the very best the SLS can offer, even in its final configuration with a kick stage. Starship is also forecast to be significantly cheaper, although whether it can hit Musk's optimistic projection of less than $10 million per launch remains to be seen. "If they get anywhere near that cost, it's kind of an analogue to a 747 and a shipping container all in one," says Robin Hague, former head of launch at the U.K. launch company Skyrora. "That's going to be used throughout the solar system."

With 1,000 cubic meters of usable volume, Starship is also big enough to fit the entire Eiffel Tower, disassembled (though not powerful enough to lift it into orbit). This gargantuan capability led Heldmann and her colleagues to publish a paper on what sort of equipment Starship could carry to the lunar or Martian surface. "Refilling Starship in orbit effectively resets the rocket equation, allowing for large payloads to be transported to the Moon and Mars," they wrote, a reference to the fact that the more mass you want to launch, traditionally the more thrust you need on an exponential scale. Starship is not limited to these destinations, though. "It is not fine-tuned to either the moon or Mars," says Margarita Marinova, a former senior Mars development engineer at SpaceX. "The goal for Starship is to create this more generic, larger-scale exploration capability."

Ideas include launching full-size drills rather than pint-size versions. "You can put a 100-foot [30-meter] drill on the vehicle and then just deploy it," Heldmann says. "You don't have to try and fold it up. That's exciting because you can drill down into ice on Mars, which is very important for sustaining human exploration and also the search for life." Starship could conceivably also offer a two-way delivery service, returning vast quantities of material to Earth from these and other worlds. "We've always been very cautious about the samples we return because we've been limited by the amount of mass," Heldmann says. "With Starship, you can just load up that vehicle with rocks and ice and whatever else you find."

Meanwhile Martin Elvis of the Harvard-Smithsonian Center for Astrophysics and his colleagues have written a white paper on how Starship's unique capabilities could be used to launch a wide variety of next-generation space telescopes to revolutionize astrophysics. One idea is an extension of the Event Horizon Telescope, a "virtual" observatory on Earth used in 2019 to capture the first-ever image of a supermassive black hole. In a single launch, Starship could send a stack of six-meter telescopes into space, allowing for the creation of a much larger virtual telescope. That could provide views of "thousands of supermassive black holes" found at the centers of galaxies like our own, Elvis says.

Starship—and the SLS—could also launch a large telescope custom-built to image Earth-like exoplanets around other stars, as recommended to NASA by the National Academies' Astronomy and Astrophysics Decadal Survey in November 2021. "The diameter of mirror the Decadal report suggested was six meters, which is about the same as the JWST," Elvis says. But with a super rocket's large payload fairing, such a mirror could be monolithic, without any need to unfold and deploy in space, likely resulting in major cost savings and a speedier path to the launchpad. "That would simplify the design dramatically," Elvis says.

A CAVALCADE OF ROCKETS

The SLS and Starship are not the only options for future heavy exploration of the solar system. The Washington State–based company Blue Origin, founded by Jeff Bezos, is working on a reusable rocket called New Glenn that it says could loft 45 metric tons into Earth orbit. And New Glenn's successor New Armstrong is expected to be even more powerful. Both Blue Origin rockets could play a role in the scientific exploration of the solar system, although their true capabilities are unknown. China, meanwhile, is working on its own superheavy rocket called the Long March 9 to transport humans and machinery to the moon and Mars as early as the 2030s. It is touted as being able to lift as much as 140 metric tons to Earth orbit, says Andrew Jones, a space journalist who closely follows the Chinese space program.

"They're set on a super rocket," Jones says. "We're seeing China become more and more interested in planetary exploration—and even looking beyond the boundaries of the solar system." That latter notion is also something the U.S. is considering with a proposed mission called Interstellar Probe, which may need to rely on the SLS or a similarly sized rocket to reach its full scientific potential if it is selected by the upcoming Heliophysics Decadal Survey from the National Academies. "Without the SLS or larger launch vehicles, you could not do the Interstellar Probe as intended," says Runyon, who is planetary science lead for the proposal.

Some have wondered if this new generation of super-heavy-lift vehicles is needed at all and whether multiple smaller launchers could send spacecraft components into orbit for subsequent assembly by astronauts or robots. That same modular approach could also be used to launch rocket fuel to fill orbital depots, potentially offering similar enhancements to in-space capabilities without the need for a giant rocket. This fuel-depot idea is rumored to have been much maligned by NASA in the early days of the SLS's development because it undercut the rationale for the program in the first place.

George Sowers, former chief scientist at the United Launch Alliance (ULA) and now at the Colorado School of Mines, says he had worked on such ideas at ULA a decade ago but was asked to stop. "It got really political," he says. "We were basically told to sit down and shut up." NASA would later change its tune, and the agency has since selected ULA and others to demonstrate in-space refueling and depot technology.

Daniel Dumbacher, who is now executive director of AIAA and previously part of the leadership at NASA that selected the SLS for development in 2010, says other options were considered. The agency looked at a variant of the SLS that used kerosene rather than the liquid-hydrogen and liquid-oxygen version that was eventually chosen. That system also used smaller rockets launched in tandem such as ULA's Atlas V or SpaceX's Falcon Heavy. Ultimately, however, such an option was deemed too complex and expensive. "We did look at an option of what it would take if we utilized Atlas V and Falcon Heavy vehicles," Dumbacher says. "It was down selected out because it had negative effects on mission reliability, and it was more costly because of the number of launches required to execute the mission." More than 10 launches would have been needed to replicate a single SLS launch, he says.

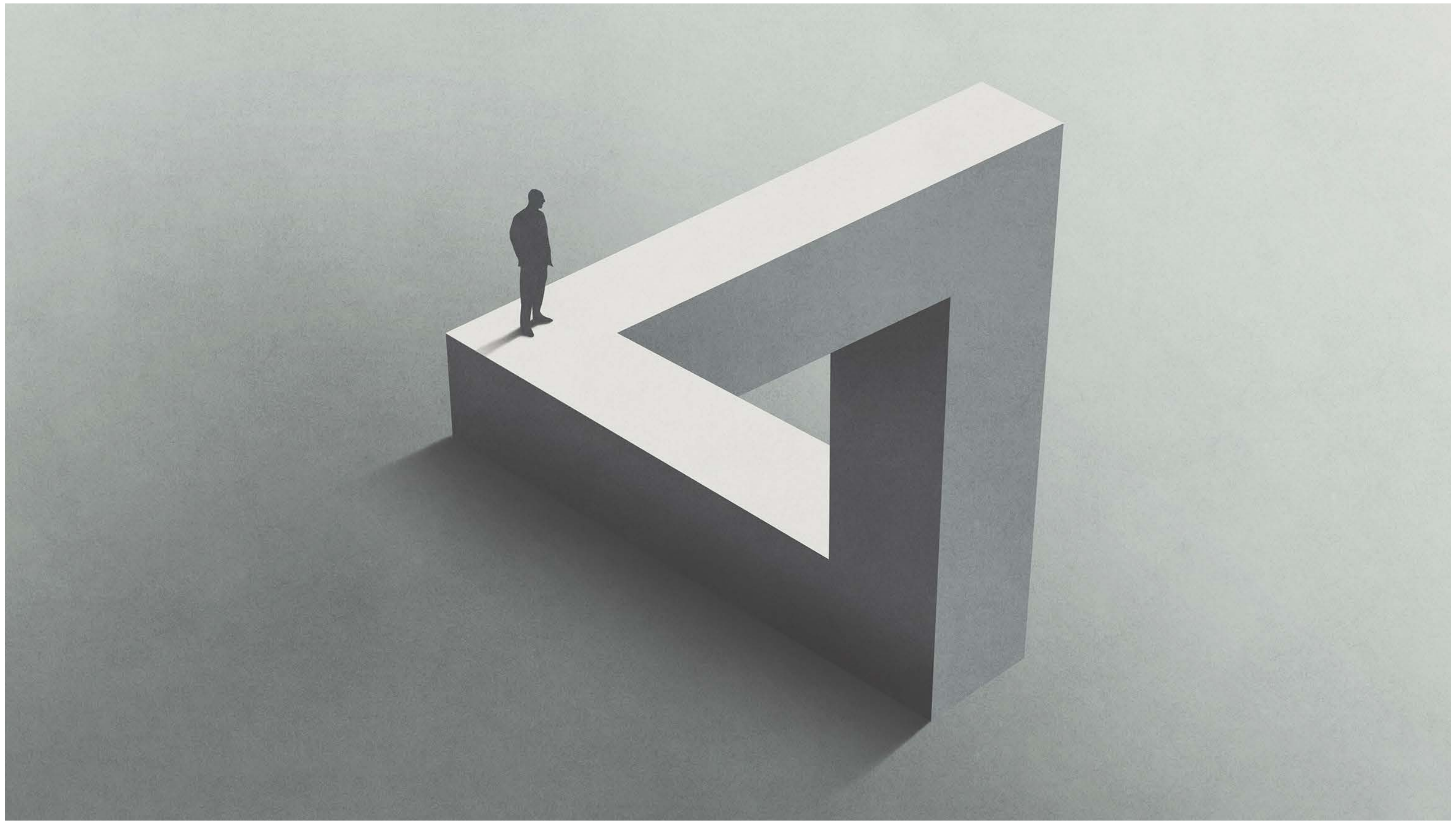
There is no denying that the SLS is an expensive machine. Yet given its technological maturity, if costs can be brought down, it remains a promising option for future scientific missions. Starship, meanwhile, represents something entirely new in space exploration. There is much that has yet to be proved, including the launch and landing of the giant rocket and its ability to refuel in space. But if those hurdles can be overcome, future exploration of the solar system and the cosmos may no longer be limited mostly by rockets but rather by human imagination.

"There's a ton of excitement about what really high-performance rockets will enable," Runyon says. "The solar system really opens up in a way that's never been done before."

John Horgan directs the Center for Science Writings at the Stevens Institute of Technology. His books include *The End of Science, The End of War* and *Mind-Body Problems,* available for free at mindbodyproblems.com. For many years he wrote the popular blog Cross Check for *Scientific American.*

Does Quantum Mechanics Rule Out Free Will?

Superdeterminism, a radical quantum hypothesis, says our "choices" are illusory



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A conjecture called superdeterminism, outlined decades ago, is a response to several peculiarities of quantum mechanics: the apparent randomness of quantum events; their apparent dependence on human observation or measurement; and the apparent ability of a measurement in one place to determine, instantly, the outcome of a measurement elsewhere, an effect called nonlocality.

Albert Einstein, who derided nonlocality as "spooky action at a distance," insisted that quantum mechanics must be incomplete; there must be hidden variables that the theory overlooks. Superdeterminism is a radical hidden-variables theory proposed by physicist John Bell. He is renowned for a 1964 theorem, now named after him, that dramatically exposes the nonlocality of quantum mechanics.

Bell said in a BBC interview in 1985 that the puzzle of nonlocality vanishes if you assume that "the world is superdeterministic, with not just inanimate nature running on behind-the-scenes clockwork but with our behavior, including our belief that we are free to choose to do one experiment rather than another, absolutely predetermined."

In a recent video, physicist Sabine Hossenfelder, whose work I admire, notes that superdeterminism eliminates the apparent randomness of quantum mechanics. "In quantum mechanics," she explains, "we can only predict probabilities for measurement outcomes rather than the measurement outcomes themselves. The outcomes are not determined, so quantum mechanics is indeterministic. Superdeterminism returns us to determinism."

"The reason we can't predict the outcome of a quantum measurement," she explains, "is that we are missing information," that is, hidden variables. Superdeterminism, she notes, gets rid of the measurement problem and nonlocality as well as randomness. Hidden variables determine in advance how physicists carry out the experiments;

physicists might think they are choosing one option over another, but they aren't. Hossenfelder calls free will "logically incoherent nonsense."

Hossenfelder predicts that physicists might be able to confirm superdeterminism experimentally. "At some point," she says, "it'll just become obvious that measurement outcomes are actually much more predictable than quantum mechanics says. Indeed, maybe someone already has the data, they just haven't analyzed it the right way." Hossenfelder defends superdeterminism in more detail in a technical paper written with physicist Tim Palmer.

Hossenfelder's commitment to determinism puts her in good company. Einstein, too, believed that specific causes must have specific, nonrandom effects, and he doubted the existence of free will. He once wrote, "If the moon, in the act of completing its eternal way around the earth, were gifted with self-consciousness, it would feel thoroughly convinced that it was traveling its way of its own accord."

I'm nonetheless baffled by superdeterminism, whether explicated by Hossenfelder or another prominent proponent, Nobel laureate Gerard 't Hooft. When I read their arguments, I feel like I'm missing something. The arguments seem circular: the world is deterministic, hence quantum mechanics must be deterministic. Superdeterminism doesn't specify what the hidden variables of quantum mechanics are; it just decrees that they exist and that they specify everything that happens, including my decision to write these words and your decision to read them.

Hossenfelder and I argued about free will in a conversation last summer. I pointed out that we both made the choice to speak to each other; our choices stem from "higher-level" psychological factors, such as our values and desires, which are underpinned by but not reducible to physics. Physics can't account for choices and hence free will. So I said.

Invoking psychological causes "doesn't make the laws of physics go away," Hossenfelder sternly informed me. "Everything is physics. You're made of particles." I felt like we were talking past each other. To her, a nondeterministic world makes no sense. To me, a world without choice makes no sense.

Other physicists insist that physics provides ample room for free will. George Ellis argues for "downward causation," which means that physical processes can lead to "emergent" phenomena, notably human desires and intentions, that can in turn exert an influence over our physical selves. Mathematicians John Conway and Simon Kochen go even further in their 2009 paper "The Strong Free Will Theorem." They present a mathematical argument, which resembles Bell's theorem on quantum nonlocality, that we have free will because particles have free will.

To my mind, the debate over whether physics rules out or enables free will is moot. It's like citing quantum theory in a debate over whether the Beatles are the best rock band ever (which they clearly are). Philosophers speak of an "explanatory gap" between physical theories about consciousness and consciousness itself. First of all, the gap is so vast that you might call it a chasm. Second, the chasm applies not just to consciousness but to the entire realm of human affairs.

Physics, which tracks changes in matter and energy, has nothing to say about love, desire, fear, hatred, justice, beauty, morality, meaning. All these things, viewed in the light of physics, could be described as "logically incoherent nonsense," as Hossenfelder puts it. But they have consequences; they alter the world.

Physics as a whole, not just quantum mechanics, is obviously incomplete. As philosopher Christian List told me recently, humans are "not just heaps of interacting particles." We are "intentional agents, with psychological features and mental states" and the capacity to make choices. Physicists have acknowledged the limits of their discipline. Philip Anderson, a Nobel laureate, contends in his 1972 essay "More Is Different" that as phenomena become more complicated, they require new modes of explanation; not even chemistry is reducible to physics, let alone psychology.

Bell, the inventor of superdeterminism, apparently didn't like it. He seems to have viewed superdeterminism as a reductio ad absurdum proposition, which highlights the strangeness of quantum mechanics. He wasn't crazy about any interpretations of quantum mechanics, once describing them as "like literary fiction."

Why does the debate over free will and superdeterminism matter? Because ideas matter. At this time in human history, many of us already feel helpless, at the mercy of forces beyond our control. The last thing we need is a theory that reinforces our fatalism.

Pamela Burdman is executive director of Just Equations, a policy institute focused on the role of math in education equity.

To Keep Students in STEM Fields, Let's Weed Out the Weed-Out Math Classes

Reimagining calculus has changed several schools' success rates. Here's how

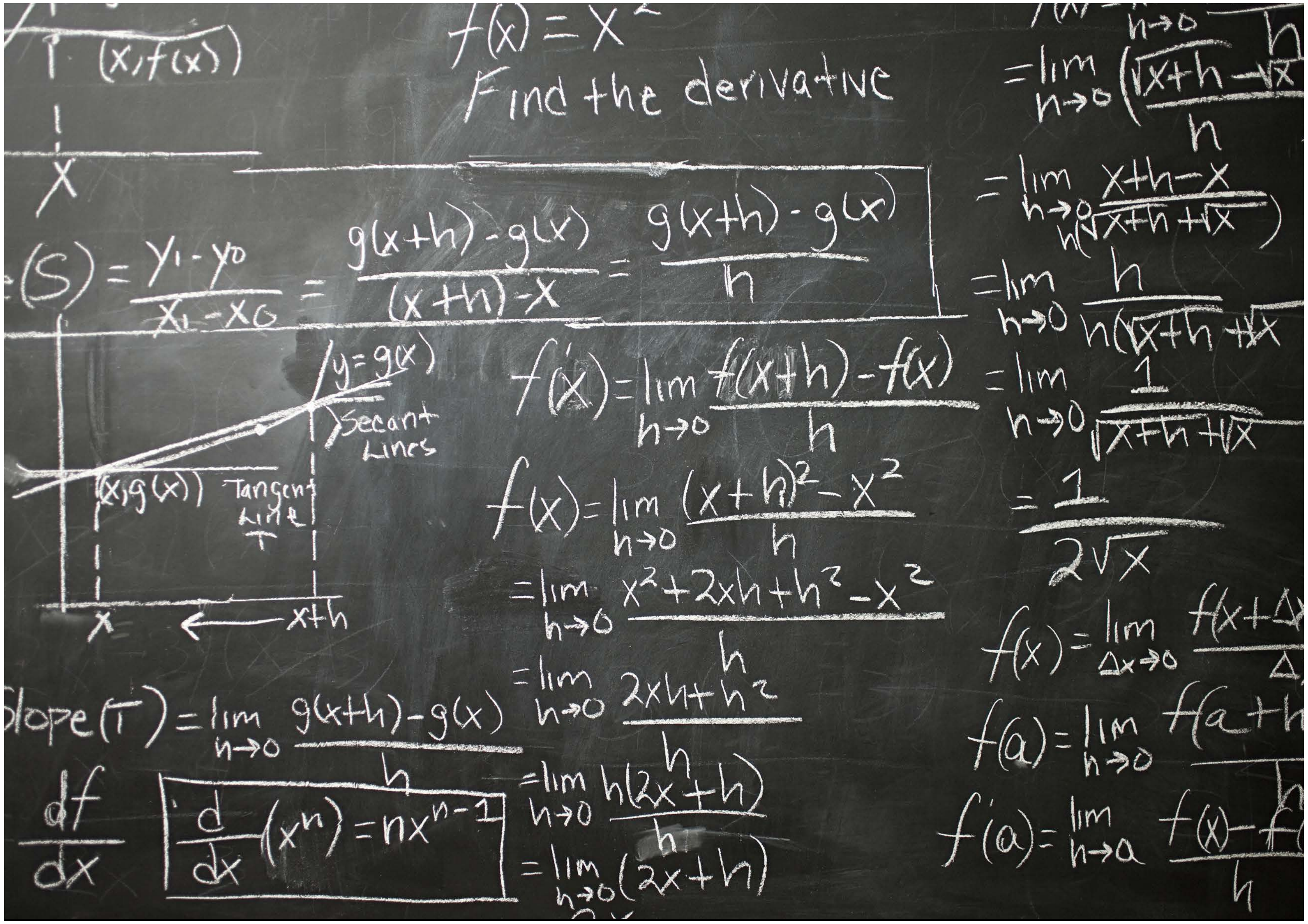

Image Source/Getty Images

All routes to STEM (science, technology, engineering and mathematics) degrees run through calculus classes. Every year hundreds of thousands of college students take introductory calculus. But only a small fraction ultimately complete a STEM degree, and research about why students abandon such degrees suggests that traditional calculus courses are one of the reasons. With scientific understanding and innovation increasingly central to solving 21st-century problems, this loss of talent is something society can ill afford.

Math departments alone are unlikely to solve this dilemma. Several of the promising calculus reforms highlighted in our report *Charting a New Course: Investigating Barriers on the Calculus Pathway to STEM,* published with the California Education Learning Lab, were spearheaded by professors outside of math departments. It's time for STEM faculty to prioritize collaboration across disciplines to transform math classes from weed-out mechanisms to fertile terrain for cultivating a diverse generation of STEM researchers and professionals.

This is not uncharted territory.

In 2013 life sciences faculty at the University of

California, Los Angeles, developed a two-course sequence that covers classic calculus topics such as the derivative and the integral but emphasizes their application in a biological context. The professors used modeling of complex systems such as biological and physiological processes as a framework for teaching linear algebra and a starting point for teaching the basics of computer programming to support students' use of systems of differential equations.

Creating this course, Mathematics for Life Scientists, wasn't easy. The life sciences faculty involved, none of whom had a joint appointment with the math department, said they resorted to designing the course themselves after math faculty rebuffed their overture. The math faculty feared creating a "watered-down" course with no textbook (although after the course was developed, one math instructor taught some sections of the class). Besides math, the life sciences faculty said that they experienced "significant pushback" from the chemistry and physics departments over concerns that the course wouldn't adequately prepare students for required courses in those disciplines.

But the U.C.L.A. course seems to be successful, and a textbook based on it now exists.

According to recently published research led by U.C.L.A. education researchers, students in the new classes ended up with "significantly higher grades" in subsequent physics, chemistry and life sciences courses than students in the traditional calculus course, even when controlling for factors such as demographics, prior preparation and math grades. Students' interest in the subject doubled, according to surveys.

The U.C.L.A. example highlights long-standing concerns about the relevance of traditional calculus for biology students. Traditionally college math departments have overseen general education math courses for students in other majors. A little over two decades ago biology faculty convened by the Mathematical Association of America (MAA) advocated that, for biology majors, "statistics, modeling, and graphical representation should take priority" over calculus. But change has been slow, until life sciences departments got involved.

Math education researchers consider a more relevant and engaging curriculum to be an important strategy for increasing persistence rates, particularly among students traditionally excluded from STEM fields, such as Black, Latinx and Indigenous students, as well as women.

Engineering departments also worry about calculus sequences driving attrition. In Ohio, Wright State University's solution also involved revising math offerings. But rather than changing the content of the calculus course, they focused on preparing students for calculus by emphasizing "engineering motivation for math." In lieu of traditional calculus prerequisites such as precalculus or college algebra, the engineering faculty launched a contextualized math course in 2004. Emphasizing problem-based learning, the course covers topics students need in sophomore engineering classes, including linear equations, quadratic equations, 2-D vectors and complex numbers. A modest redesign of the engineering curriculum allows students to delay taking a traditional calculus sequence until later in their programs.

The approach enhanced opportunities for students with weaker math backgrounds to succeed in engineering and doubled the average graduation rate of engineering students without reducing the average grade of graduates. Students from groups historically underrepresented in STEM (female, Black and Latinx) experienced the greatest gains, with those in the new problem-based course completing engineering degrees at three times the rate of engineering majors who did not take it. At least 15 other universities are replicating the strategy.

Increasingly leading math and science organizations are recognizing the importance of interdisciplinary collaboration; the MAA has a history of convening faculty from partner disciplines, and a National Academies' 2013 publication called for reassessing math education in a cross-disciplinary context. The National Science Foundation, which funded both the U.C.L.A. and Wright State innovations, recognizes the value of cross-disciplinary or "convergence" research, which is driven by a compelling scientific or societal problem. Low persistence in STEM majors and lack of diversity in the STEM fields are themselves pressing societal problems.

Yet math departments without jointly appointed professors seem to be less interested in evidence-based contributions from other disciplines to enhance the effectiveness of math instruction—or even aware of successes to date. The shift toward more practical applications of calculus is missing one key academic endorsement: publication in widely read journals, if the success of the courses is examined academically at all.

The U.C.L.A. research appears in a life sciences education journal, and presentations on Wright State's innovation reach an American Society for Engineering Education audience. Faculty responsible for undergraduate math education are not likely to see these journals.

Ten years ago, at the University of California Berkeley, Lior Pachter used his joint appointments in math and biology to create a new course with the help of his fellow mathematicians and biologists. Methods of Mathematics: Calculus, Statistics, and Combinatorics (Math 10A and 10B) expands on the standard calculus curriculum to reflect how data and technology have transformed the field of biology. Today most U.C. Berkeley life sciences majors take the sequence, and the campus is offering 15 sections of 10B beginning this spring. (Pachter now teaches at the California Institute of Technology and says U.C. Berkeley's math department has yet to publish any research on the calculus sequence, despite having institutionalized it.)

Math learning is fundamental to all STEM fields, but the opposite also appears to be true: the STEM fields may be central to making math learning effective for more students. Involving other STEM disciplines in redesigning math classes is a key way to ensure those classes offer engaging and inclusive on-ramps to STEM.

OPINION

Amir Siraj is an undergraduate in the Harvard University–New England Conservatory of Music dual-degree program, studying astrophysics and piano performance. He is the youngest laureate of the 2021 *Forbes* 30 Under 30 list in Science.

janiecbros/Getty Images

Spy Satellites Confirmed Our Discovery of the First Meteor from Beyond the Solar System

A high-speed fireball that struck Earth in 2014 looked to be interstellar in origin, but verifying this extraordinary claim required extraordinary cooperation from secretive defense programs

On January 8, 2014, at 17:05:34 UT, an approximately meter-sized rock from space streaked through the sky off the coast of Manus Island, Papua New Guinea, burning up with an energy equivalent to about 110 metric tons of TNT and raining debris into the depths of the Pacific Ocean. Similar-sized fireballs are not uncommon occurrences in Earth's skies; in fact, a few dozen of them occur each year. But what was unusual about this particular meteor was the very high speed and unusual direction at which it encountered our planet, which collectively suggested it came from interstellar space.

Sensors on a classified U.S. government satellite designed to detect foreign missile launches were the sole known witnesses to the fireball. Thanks to a partnership between the Department of Defense and NASA, the data describing the event eventually were shared on a public database hosted by the Center for Near Earth Object Studies (CNEOS) within the space agency's Jet Propulsion Laboratory, along with data for more than 900 other fireballs recorded by U.S. government sensors between 1988 and the present day.

The data for these events include dates, times, latitudes, longitudes, altitudes, speeds, three-dimensional velocity components and energies for each. Notably omitted from the database are the uncertainties for most of these measurements—presumably to ensure the precision thresholds for U.S. global sensing capabilities are not divulged, because this information could potentially be exploited by adversaries.

My involvement with this meteor traces back to April 2019, when my academic adviser at Harvard, astrophysicist Avi Loeb, brought the CNEOS fireballs catalog to my attention. At the time, he and I were about eight months into our studies of data related to 'Oumuamua, the object identified in October 2017 as the first-known interstellar visitor to the solar system. Since 'Oumuamua originated from outside of the solar system, each of its properties, including its very detection, conveyed previously inaccessible information about our cosmic neighborhood.

The holy grail of interstellar object studies would be to obtain a physical sample of an object that originated from outside of the solar system—a goal as audacious as it is scientifically groundbreaking.

With the wealth of knowledge carried by interstellar visitors foremost in our minds, Loeb and I had been pondering the possibility of finding others to study, and the CNEOS data seemed promising. Within days I had identified the 2014 Manus Island fireball as a potential interstellar meteor candidate. Loeb then suggested that I use the speed of impact, combined with knowledge of the kinematics of small-body populations in the solar system, to estimate the probability that it originated from elsewhere, beyond our solar system. Contemplating this approach, I then proposed a more precise method to derive the object's trajectory that accounted for the gravitational influences of our sun and its planets. Loeb agreed with my proposal, and I swiftly got to work.

At Earth's distance from the sun, any object moving faster than about 42 kilometers per second is in an unbounded, hyperbolic orbit relative to our star, meaning that it is too speedy to be captured by the sun's gravity. Anything traveling over this local celestial speed limit, then, may come from (and if unimpeded should return to) interstellar space. The CNEOS entry for the 2014 Manus Island fireball indicated the meteor hit Earth's atmosphere at about 45 kilometers per second—very promising. But some of this speed came from the object's motion relative to Earth and Earth's motion around the sun. Teasing apart these effects with the help of computer programs that I wrote, I found that the object had overtaken Earth from behind before striking our atmosphere and likely had a sun-relative speed closer to 60 kilometers per second. The corresponding orbit that I calculated was clearly unbound from the sun—even if there had been large uncertainty errors. If the data were correct, this event would be the first interstellar meteor ever discovered. And it was hiding in plain sight.

Extraordinary claims, of course, require extraordinary evidence. So Loeb and I reverse engineered estimates of the classified satellites' measurement errors, using independently verified data on other fireballs in the CNEOS database and elsewhere in the scientific literature. After this arduous reality check, we were left with the same astonishing conclusion: the 2014 fireball had clearly originated from interstellar space. We soon drafted a paper reporting our discovery for peer-reviewed publication.

Journal referees balked at the unknown nature of the error bars, so we enlisted the help of Alan Hurd and Matt Heavner, scientists at Los Alamos National Laboratory with high-level security clearances as well as an interest in promoting collaboration with the public sector to enable blue-sky science. In short order, Heavner made contact with the anonymous analyst who had derived the meteor's velocity components from the classified satellite observations and who confirmed that the relevant uncertainties for each value were no higher than 10 percent. Plugged into our error analysis, this implied an interstellar origin with 99.999 percent certainty, but the paper was again turned down by referees, who raised objections about the fact that the statement about uncertainties was a private communication with an anonymous U.S. government employee and not an official statement from the U.S. government, which Heavner had difficulty in procuring. After several further failed attempts to pierce the veil of secrecy to the satisfaction of journal reviewers, we regretfully moved on to other research, leaving the true nature of the 2014 meteor unconfirmed.

A year later, however, we were approached by Pete Worden, the chair of the Breakthrough Prize Foundation, with an introduction to Matt Daniels, who at the time was working for the Office of the Secretary of Defense. Daniels had read our preprint about the 2014 meteor and wished to help to confirm its origin from within the U.S. government. After a year of laboriously navigating multiple layers of government bureaucracy, in March/April 2022 Daniels was able to procure official confirmation from Lt. Gen. John Shaw, deputy commander of U.S. Space Force, and Joel Mozer, chief scientist of the branch's Space Operations Command, of the relevant uncertainties—and thus effective confirmation that the meteor was of true interstellar origin.

Three years after our original discovery, the first object originating from outside of the solar system observed to strike Earth—the first-known interstellar meteor—has officially been recognized. The 2014 meteor is also the first recorded interstellar object to be detected in the solar system, predating ‘Oumuamua by more than three years, and is one of three interstellar objects confirmed to date, alongside ‘Oumuamua and the interstellar comet Borisov.

The 2014 object's interstellar nature carries fascinating consequences. Its size implies that each star needs to contribute a significant mass of similar objects over its lifetime to make the 2014 detection likely—suggesting there are many more interstellar meteors to be found. And its high speed relative to the average speeds of our neighboring stars suggests that it could have been ejected from deep within another planetary system, relatively close to its star. This is surprising, as one would naively expect most interstellar objects to instead originate from far more distant circumstellar regions where escape velocities are lower, namely, the clouds of comets that exist at the outskirts of many star systems.

This new field, the study of interstellar meteors, certainly has much to tell us about our place in the cosmos. Further investigations of the observed properties of the 2014 meteor could provide insights about our local interstellar environment, especially when compared with the characteristics of its successors, ‘Oumuamua and Borisov. Meteor databases are ripe for follow-on searches, and fresh motivations exist for building new sensing networks, with a focus on detecting future interstellar meteors. Observing an interstellar meteor burn up in real time would allow for the study of its composition, yielding novel insights into the chemistry of other planetary systems.

The holy grail of interstellar object studies would be to obtain a physical sample of an object that originated from outside of the solar system—a goal as audacious as it is scientifically groundbreaking. We are currently investigating whether a mission to the bottom of the Pacific Ocean off the coast of Manus Island, in the hopes of finding fragments of the 2014 meteor, could be fruitful or even possible. Any sufficiently large interstellar meteor discovered in the future should also produce a shower of debris, which we could potentially track down and analyze. There is, of course, another approach for getting samples, which, as director of interstellar object studies for the Galileo Project, I am excited to also be pursuing: a spacecraft rendezvous. In collaboration with Alan Stern, the principal investigator of NASA's New Horizons mission, we have now received funding to develop a concept for a space mission to some future interstellar object.

Like exotic seashells, these messengers from the stars have been washing ashore on our planetary beach for billions of years, each carrying secrets of their—and our—cosmic origins. Now, at last, we are starting to comb the shoreline.

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