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Recipe for Life

Radioactive elements found in the cores of planets may determine which worlds might host living species

WITH COVERAGE FROM nature

LIZ TORMES

Journeywork of the Stars

In his monumental series *Cosmos*, astronomer Carl Sagan famously said that we humans are "made of star stuff." Dying stars are continually filling the universe with heavy elements, and the energy of the cosmos sparked life into existence on this planet. After billions of years, plants began to harvest sunlight directly, converting solar into chemical energy, and therefore all human life feeds on the output of stars. Those same elements that streamed through the vacuum of space and coalesced in the core of Earth also, it seems, created the conditions under which life can survive.

As writer Marcus Woo details in this issue's cover story, certain radionuclides in exoplanets may be the signal to look for if we want to find alien life (see "Stellar Smashups May Fuel Planetary Habitability, Study Suggests"). An exciting potential extraterrestrial signal radiated to Earth last December, causing a media stir, as do all prospects of meeting our cosmic neighbors (see "Alien Hunters Discover Mysterious Signal from Proxima Centauri"). Indeed, if we find intelligent life in the universe, we will have a common heritage.

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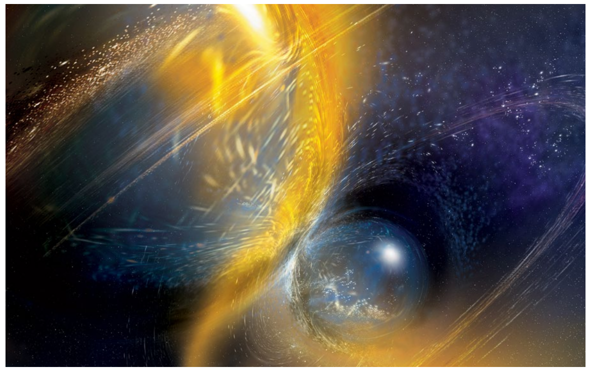

On the Cover

Radioactive elements found in the cores of planets may determine which worlds might host living species

NATIONAL SCIENCE FOUNDATION, LIGO, SONOMA STATE UNIVERSITY AND A. SIMONNET

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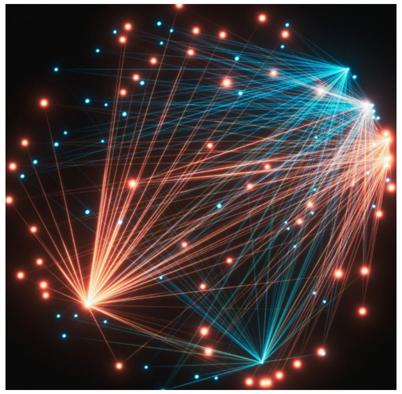
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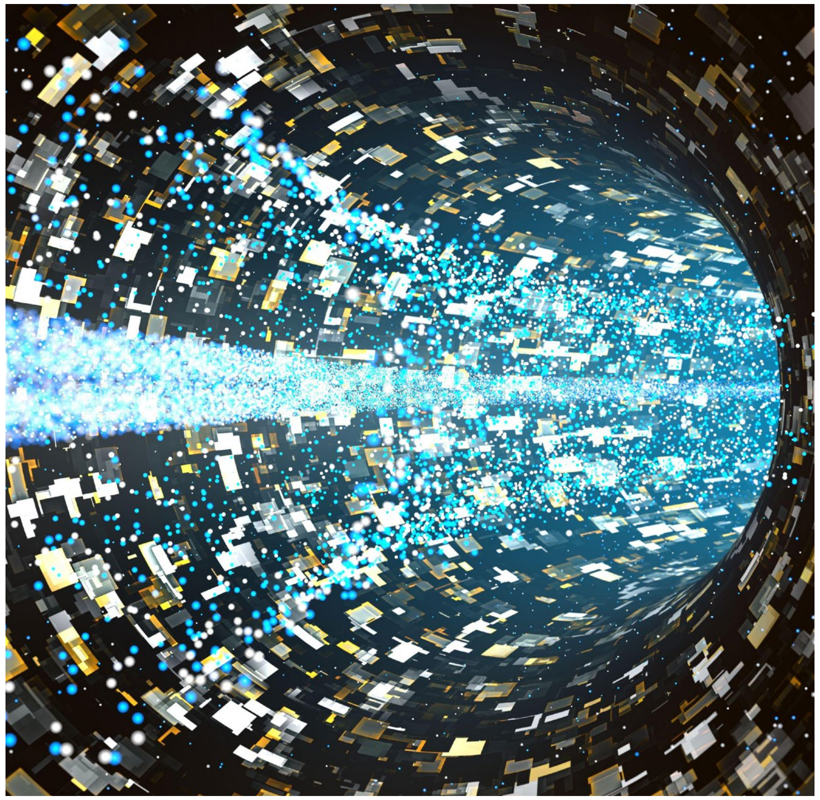
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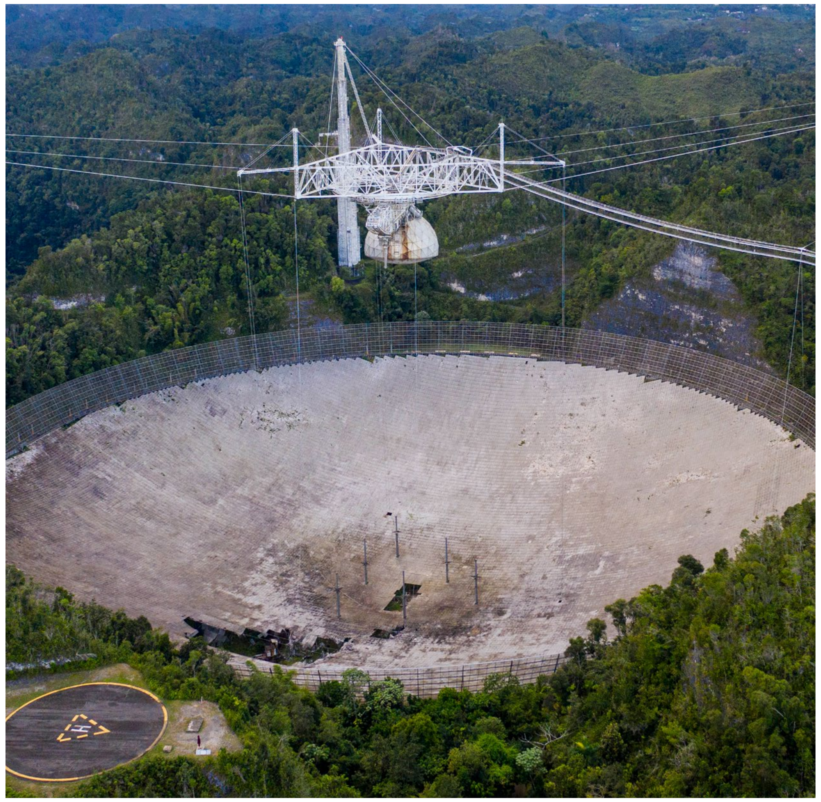
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NEWS

Alien Hunters Discover Mysterious Signal from Proxima Centauri

Strange radio transmissions are coming from our nearest star system. Now scientists are trying to work out what is sending them

It's never aliens—until it is. On December 18 news leaked in the British newspaper the *Guardian* of a mysterious signal coming from the closest star to our own, Proxima Centauri, a star too dim to see from Earth with the naked eye that is nonetheless a cosmic stone's throw away at just 4.2 light-years. Found last autumn in archival data gathered in 2019, the signal appears to emanate from the direction of our neighboring star and cannot yet be dismissed as Earth-based interference, raising the very faint prospect that it is a transmission from some form of advanced extraterrestrial

Sixty-four-meter radio telescope at Parkes Observatory in Australia, which detected potential signals from Proxima Centauri last year.

LISA MAREE WILLIAMS *GETTY IMAGES*

intelligence (ETI)—a so-called technosignature. Now, speaking to *Scientific American,* the scientists behind the discovery caution there is still much work to be done but admit the interest is justified. “It has some particular properties that caused it to pass many of our checks, and we cannot yet explain it,” says Andrew Siemion of the University of California, Berkeley.

Most curiously, it occupies a very narrow band of the radio spectrum: 982 megahertz, specifically, which is a region typically bereft of transmissions from human-made satellites and spacecraft. “We don’t know of any natural way to compress electromagnetic energy into a single bin in frequency” such as this one, Siemion says. Perhaps, he says, some as yet unknown exotic quirk of plasma physics could be a natural explanation for the tantalizingly concentrated radio waves. But “for the moment, the only source that we know of is technological.”

The detection was made by a $100-million project called Breakthrough Listen, led by Siemion and funded by tech billionaire Yuri Milner under the umbrella of Milner’s Breakthrough Initiatives. The goal of this multiyear endeavor—which began in 2015 with a star-studded announcement attended by Stephen Hawking and other space science luminaries—is to buy observing time on radio telescopes around the world to search the skies for evidence of technological civilizations. That pursuit, of course, is more commonly known as the Search for Extraterrestrial Intelligence (SETI). To date, no such evidence has conclusively been found despite more than half a century of modest but steady SETI activity, with any potential signals almost always ruled out as originating from satellites orbiting Earth or other human-caused interference.

“If you see such a signal and it’s not coming from the surface of Earth, you know you have detected extraterrestrial technology,” says Jason Wright, a SETI-centric astronomer at Pennsylvania State Univer-sity. “Unfortunately, humans have launched a lot of extraterrestrial technology.”

The story of this latest SETI spectacle really began on April 29, 2019, when scientists affiliated with Breakthrough Listen started collecting the data that would later reveal the intriguing signal. A team had been using the Parkes radio telescope in Australia to study Proxima Centauri for signs of flares coming from the red dwarf star, in part to understand how such flares might affect Proxima’s planets. The system hosts at least two worlds. The first, dubbed Proxima b upon its discovery in 2016, is about 1.2 times the size of Earth and in an 11-day orbit. Proxima b resides in the star’s “habitable zone,” a hazily defined sector in which liquid water could exist on a rocky planet’s surface—provided, that is, Proxima Centauri’s intense stellar flares have not sputtered away a world’s atmosphere. Another planet, the roughly seven-Earth-mass Proxima c, was discovered in 2019 in a frigid 5.2-year orbit.

Using Parkes, the astronomers had observed the star for 26 hours as part of their stellar flare study, but, as is routine within the Breakthrough Listen project, they also flagged the resulting data for a later look to seek out any candidate SETI signals. The task fell to a young intern in Siemion’s SETI program at Berkeley, Shane Smith, who is also an undergraduate student at Hillsdale College. Smith began sifting through the data last June, but it was not until late October that he stumbled on the curious narrowband emission, needle-sharp at 982.002 megahertz, hidden in plain view in the Proxima Centauri observations. From there things happened fast—with good reason. “It’s the most exciting signal that we’ve found in the Breakthrough Listen project because we haven’t had a signal jump through this many of our filters before,” says Sofia Sheikh of Penn State, who helmed the subsequent analysis of the signal for Breakthrough Listen and is the lead author on an upcoming paper detailing that work, which will be published in early 2021. Soon the team began calling the signal by a more formal name: BLC1, for “Breakthrough Listen Candidate 1.”

To pique any SETI researcher’s interest, a signal must first endure a barrage of simple automated tests to rule out obvious terrestrial interference. Hundreds of candidates, however, routinely pass this phase and are singled out for further investigation. From there almost all will be dismissed as some mirage or error—perhaps an excess of static, for instance—that fooled the winnowing algorithm, eliminating them from consideration as any sort of transmission from talkative aliens. “Except this one,” Sheikh says.

Revisiting the data from 2019, Sheikh and her colleagues noted that the telescope had looked at Proxima multiple times in scans lasting 30 minutes over the course of a week. Breakthrough Listen uses a technique called nodding, where the telescope will spend a period of time looking at a target and then an equivalent period looking elsewhere in the sky, to check that any potential signal is truly coming from the target and not, say, someone microwaving their lunch in an observatory’s cafeteria.

“In five of the 30-minute observations over about three hours, we see this thing come back,” Sheikh says, a hint that the signal indeed originated from Proxima Centauri—or some other deep-space source in that part of the sky—before making its way to Earth.

One might think, then, that the case would be closed. But while a natural cosmic source may seem unlikely, it cannot yet be ruled out—and, the thinking goes, as unlikely as a natural explanation might be, an “unnatural” explanation such as aliens is even less likely still. Consequently, every member of the Breakthrough Listen team interviewed for this article steadfastly insists the chance of this being anything other than terrestrial interference is exceedingly remote. “The most likely thing is that it’s some human cause,” says Pete Worden, executive director of the Breakthrough Initiatives. “And when I say most likely, it’s like 99.9 [percent].”

That rational skepticism extends all the way to the top. “When we launched Breakthrough Listen with Stephen Hawking in 2015,” Milner says, “it was understood that the most rigorous scientific approach will be used to analyze all candidate signals.” Milner and seemingly all the SETI researchers his funding supports fully expect BLC1 to wither away under the project’s now intense scrutiny. But, just maybe, it won’t.

For the time being, months of further analysis are in store to definitively rule out other potential sources. And BLC1 itself, while seeming to come from Proxima Centauri, does not quite fit expectations for a technosignature from that system. First, the signal bears no trace of modulation—tweaks to its properties that can be used to convey information. “BLC1 is, for all intents and purposes, just a tone, just one note,” Siemion says. “It has absolutely no additional features that we can discern at this point.”

And second, the signal “drifts,” meaning that it appears to be changing very slightly in frequency—an effect that could be caused by the motion of our planet or by a moving extraterrestrial source such as a transmitter on the surface of one of Proxima Centauri’s worlds. But the drift is the reverse of what one would naively expect for a signal originating from a world twirling around our sun’s nearest neighboring star. “We would expect the signal to be going down in frequency like a trombone,” Sheikh says. “What we see instead is like a slide whistle—the frequency goes up.”

So far follow-up observations using Parkes have failed to turn up the signal again, with a repeat observation being a necessity to confirm that BLC1 is a genuine technosignature. “If it’s an ETI, it must eventually be replicable because it’s unlikely it would be a one-off,” says Shami Chatterjee, a radio astronomer at Cornell University. “If an independent team at an independent observatory can recover the same signal, then hell yes. I would bet money that they won’t, but I would love to be wrong.”

Nevertheless, it remains one of the most intriguing signals found by Breakthrough Listen—or indeed any SETI program—to date, one that Sheikh compares to the so-called Wow! signal detected in 1977, which some believed to be of extraterrestrial origin. “I think it’s on par with the Wow! signal,” she says.

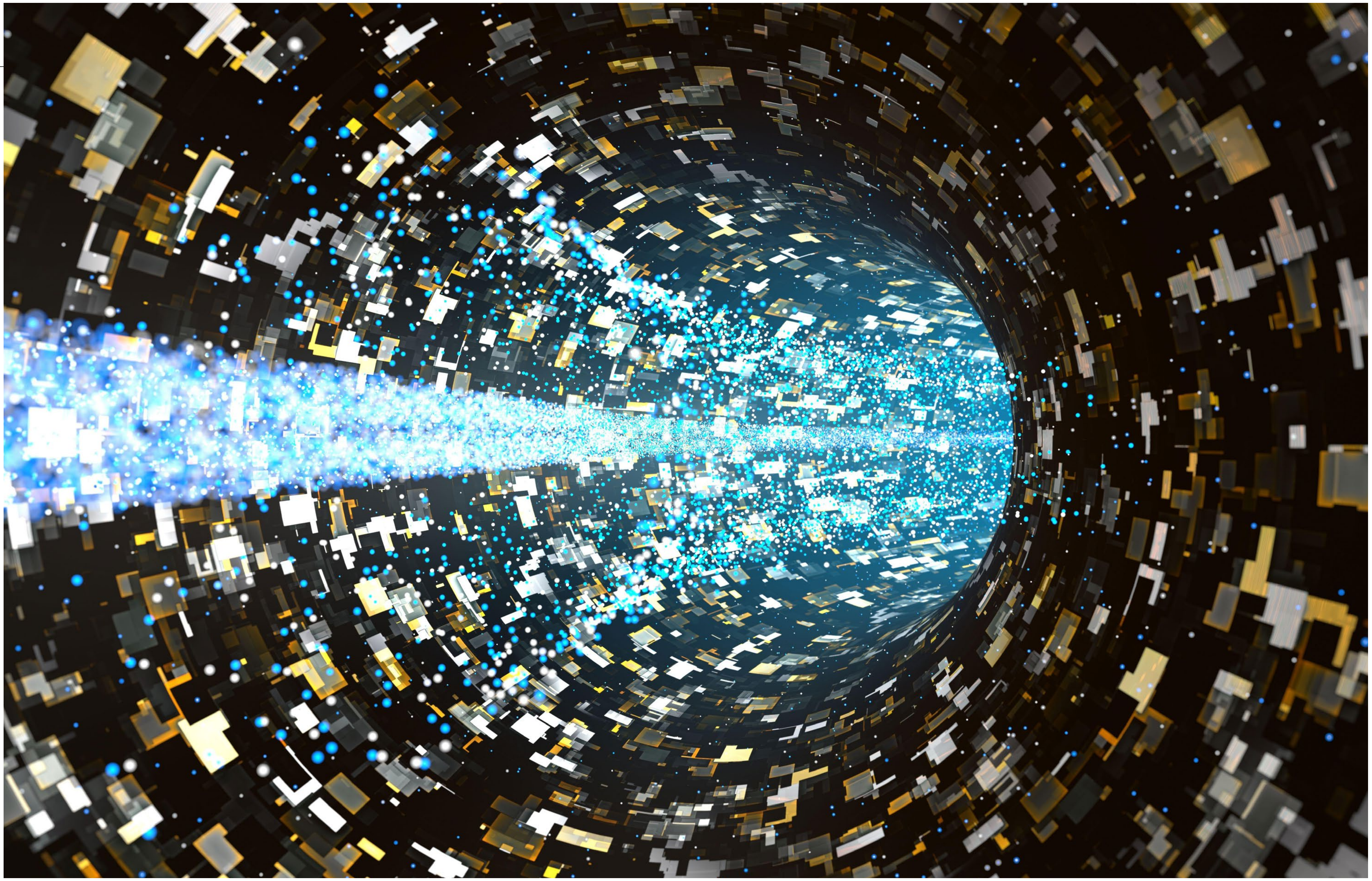
More likely than not, however, this is simply some previously unknown source of Earth-based interference. In a few months we’ll likely know for certain one way or another. But for the time being, it’s never aliens—right? “I hate that phrase because if you say that, then why even look?” Wright says. “What we mean by that is that it’s never been aliens before.”

Editor’s Note: As this issue went to press, members of the Breakthrough Listen team confirmed their initial suspicions, determining with “virtual certainty” that BLC1 is caused by terrestrial interference. They have submitted the new results for peer review.

—Jonathan O'Callaghan and Lee Billings

Light-Based Quantum Computer Exceeds Fastest Classical Supercomputers

The setup of lasers and mirrors effectively "solved" a problem far too complicated for even the largest traditional computer system



ALAMY

For the first time, a quantum computer made from photons—particles of light—has outperformed even the fastest classical supercomputers.

Physicists led by Chao-Yang Lu and Jian-Wei Pan of the University of Science and Technology of China (USTC) in Shanghai performed a technique called Gaussian boson sampling with their quantum computer, named Jiǔzhāng. The result, reported in the journal *Science,* was 76 detected photons—far above and beyond the previous record of five detected photons and the capabilities of classical supercomputers.

Unlike a traditional computer built from silicon processors, Jiǔzhāng is an elaborate tabletop setup of lasers, mirrors, prisms and photon detectors. It is not a universal computer that could one day send e-mails or store files, but it does demonstrate the potential of quantum computing.

In 2019 Google captured headlines when its quantum computer Sycamore took roughly three minutes to do what would take a supercomputer three days (or 10,000 years, depending on your estimation method). In its paper, the USTC team estimates that it would take the Sunway TaihuLight, the third most powerful supercomputer in the world, a staggering 2.5 billion years to perform the same calculation as Jiǔzhāng.

This is only the second demonstration of quantum primacy, which is a term that describes the point at which a quantum computer exponentially outspeeds any classical one, effectively doing what would otherwise essentially be computationally impossible. It is not just proof of principle; there are also some hints that Gaussian boson sampling could have practical applications, such as solving specialized problems in quantum chemistry and math. More broadly, the ability to control photons as qubits is a prerequisite for any large-scale quantum Internet. (A qubit is a quantum bit, analogous to the bits used to represent information in classical computing.)

"It was not obvious that this was going to happen," says Scott Aaronson, a theoretical computer scientist now at the University of Texas at Austin, who along with then student Alex Arkhipov first outlined the basics of boson sampling in 2011. Boson sampling experiments were, for many years, stuck at around three to five detected photons, which is "a hell of a long way" from quantum primacy, according to Aaronson. "Scaling it up is hard," he says. "Hats off to them."

Over the past few years quantum computing has risen from an obscurity to a multibillion-dollar enterprise recognized for its potential impact on national security, the global economy, and the foundations of physics and computer science. In 2019 the the U.S. National Quantum Initiative Act was signed into law to invest more than $1.2 billion in quantum technology over the next 10 years. The field has also garnered a fair amount of hype, with unrealistic time lines and bombastic claims about quantum computers making classical computers entirely obsolete.

This latest demonstration of quantum computing's potential from the USTC group is critical because it differs dramatically from Google's approach. Sycamore uses superconducting loops of metal to form qubits; in Jiǔzhāng, the photons themselves are the qubits. Independent corroboration that quantum computing principles can lead to primacy even on totally different hardware "gives us confidence that in the long term, eventually, useful quantum simulators and a fault-tolerant quantum computer will become feasible," Lu says.

A LIGHT SAMPLING

Why do quantum computers have enormous potential? Consider the famous double-slit experiment, in which a photon is fired at a barrier with two slits, A and B. The photon does not go through A or through B. Instead the double-slit experiment shows that the photon exists in a "superposition," or combination of possibilities, of having gone through both A and B. In theory, exploiting quantum properties like superposition allows quantum computers to achieve exponential speedups over their classical counterparts when applied to certain specific problems.

Physicists in the early 2000s were interested in exploiting the quantum properties of photons to make a quantum computer, in part because photons can act as qubits at room temperatures, so there is no need for the costly task of cooling one's system to a few kelvins (about −455 degrees Fahrenheit) as with other quantum computing schemes. But it quickly became apparent that building a universal photonic quantum computer was infeasible. To even build a working quantum computer would require millions of lasers and other optical devices. As a result, quantum primacy with photons seemed out of reach.

Then, in 2011, Aaronson and Arkhipov introduced the concept of boson sampling, showing how it could be done with a limited quantum computer made from just a few lasers, mirrors, prisms and photon detectors. Suddenly, there was a path for photonic quantum computers to show that they could be faster than classical computers.

The setup for boson sampling is analogous to the toy called a bean machine, which is just a peg-studded board covered with a sheet of clear glass. Balls are dropped into the rows of pegs from the top. On their way down, they bounce off the pegs and one another until they land in slots at the bottom. Simulating the distribution of balls in slots is relatively easy on a classical computer.

Instead of balls, boson sampling uses photons, and it replaces pegs with mirrors and prisms. Photons from the lasers bounce off mirrors and through prisms until they land in a "slot" to be detected. Unlike the classical balls, the photon's quantum properties lead to an exponentially increasing number of possible distributions.

The problem boson sampling solves is essentially "What is the distribution of photons?" Boson sampling is a quantum computer that solves itself by being the distribution of photons. Meanwhile a classical computer has to figure out the distribution of photons by computing what's called the "permanent" of a matrix. For an input of two photons, this is just a short calculation with a two-by-two array. But as the number of photonic inputs and detectors goes up, the size of the array grows, exponentially increasing the problem's computational difficulty.

In 2019 the USTC group demonstrated boson sampling with 14 detected photons—hard for a laptop to compute, but easy for a supercomputer. To scale up to quantum primacy, the researchers used a slightly different protocol, Gaussian boson sampling.

According to Christine Silberhorn, an quantum optics expert at the University of Paderborn in Germany and one of the co-developers of Gaussian boson sampling, the technique was designed to avoid the unreliable single photons used in Aaronson and Arkhipov's "vanilla" boson sampling.

"I really wanted to make it practical," she says "It's a scheme that is specific to what you can do experimentally."

Even so, she acknowledges that the USTC setup is dauntingly complicated. Jiǔzhāng begins with a laser that is split so it strikes 25 crystals made of potassium titanyl phosphate. After each crystal is hit, it reliably spits out two photons in opposite directions. The photons are then sent through 100 inputs, where they race through a track made of 300 prisms and 75 mirrors. Finally, the photons land in 100 slots where they are detected. Averaging over 200 seconds of runs, the USTC group detected about 43 photons per run. But in one run, the team members observed 76 photons—more than enough to justify their quantum primacy claim.

It is difficult to estimate just how much time would be needed for a supercomputer to solve a distribution with 76 detected photons—in large part because it is not exactly feasible to spend 2.5 billion years running a supercomputer to directly check it. Instead the researchers extrapolate from the time it takes to classically calculate for smaller numbers of detected photons. At best, solving for 50 photons, they claim, would take a supercomputer two days, which is far slower than the 200-second run time of Jiǔzhāng.

Boson sampling schemes have languished at low numbers of photons for years because they are incredibly difficult to scale up. To preserve the sensitive quantum arrangement, the photons must remain indistinguishable. Imagine a horse race where the horses all have to be released from the starting gate at exactly the same time and finish at the same time as well. Photons, unfortunately, are a lot more unreliable than horses.

As photons in Jiǔzhāng travel a 22-meter path, their positions can differ by no more than 25 nanometers. That is the equivalent of 100 horses going 100 kilometers and crossing the finish line with no more than a hair's width between them, Lu says.

QUANTUM QUESTING

The USTC quantum computer takes its name, Jiǔzhāng, from *Jiǔzhāng Suànshù*, or "The Nine Chapters on the Mathematical Art," an ancient Chinese text with an impact comparable to Euclid's *Elements*.

A literal translation renders jiǔ (九) as "9" and zhāng (章) as "chapter." But in Chinese, 九 does not mean just nine. It implies a great number, as in this poem by Liu Yuxi:

> 九曲黄河万里沙，
> 浪淘风簸自天涯
> The Yellow River with its many twists and turns flows thousands of miles full of sand,
> Carried by its waves stirred up by the wind coming from a faraway land.

Quantum computing, too, has many twists and turns ahead. Outspeeding classical computers is not a one-and-done deal, according to Lu, but will instead be a continuing competition to see if classical algorithms and computers can catch up or if quantum computers will maintain the primacy they have seized.

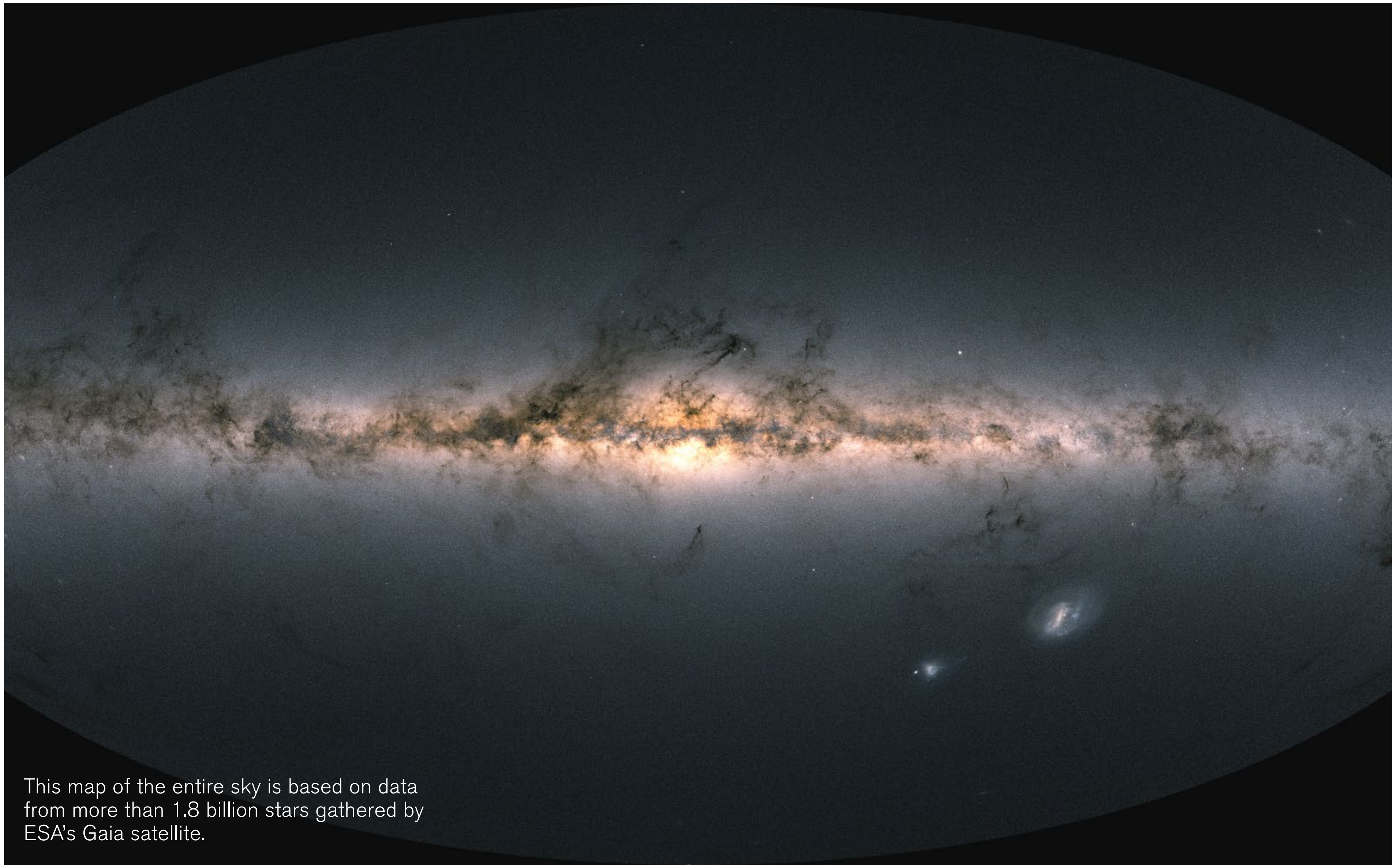
Things are unlikely to be static. At the end of last October, researchers at the Canadian quantum computing start-up Xanadu found an algorithm that quadratically cut the classical simulation time for some boson sampling experiments. In other words, if 50 detected photons sufficed for quantum primacy before, you would now need 100.

For theoretical computer scientists such as Aaronson, the result is exciting because it helps give further evidence against the extended Church-Turing thesis, which holds that any physical system can be efficiently simulated on a classical computer. "At the very broadest level, if we thought of the universe as a computer, then what kind of computer is it?" Aaronson asks. "Is it a classical computer? Or is it a quantum computer?"

So far the universe, like the computers we are attempting to make, seems to be stubbornly quantum. *—Daniel Garisto*

Fresh Data from Gaia Galaxy Survey Give Best Map Ever of the Milky Way

The European Space Agency telescope is allowing our Milky Way to be studied like never before



This map of the entire sky is based on data from more than 1.8 billion stars gathered by ESA's Gaia satellite.

ESA, GAIA AND DPAC (CC BY-SA 3.0 IGO) ACKNOWLEDGEMENT: A. MOITINHO

Three weeks before Christmas, astronomers were opening one of their presents early. Inside was a most welcome gift—a vast catalog of more than a billion stars in and around our galaxy, the most advanced of its kind ever made. Already this new trove is being put to use, with eager astronomers poring through its data, hoping to unlock some of our galaxy's most intriguing secrets in a way never before possible.

This gift comes from the European Space Agency's (ESA's) $1-billion Gaia telescope, launched in 2013 on a decade-long mission to measure the motions, positions and other key properties of billions of stars in and around our galaxy. On December 3, 2020, ESA released a new batch of survey data—known as the Gaia Early Data Release 3 (EDR3)—which contained updated information about a billion stars, including more refined calculations of their locations and velocities, vital tools for astronomers. "Distances to stars are about 30 percent more precise, and proper motions have increased by a factor of two," says Anthony Brown of the University of Leiden in the Netherlands, who is lead of the Gaia data-processing team. "That's because we collected observations over 34 months instead of 22 months for the previous release."

Putting these refined calculations immediately to use were dozens of astronomers who gathered in a virtual "hackathon," known as the Gaia Sprint, in December. With Gaia's previous data release in 2018, these astronomers met in person in New

York City. This time, because of COVID-19, a more remote meeting was required. Using the instant messaging platform Slack, combined with a digital conference room in the video-calling service Wonder, astronomers from around the world were able to mingle and discuss the data in real time as soon as they were publicly released. “We’re all [working] on the same data set on the same day, but we’re doing very different things,” says Jackie Faherty of the American Museum of Natural History, one of the event’s organizers. “It’s like a party of science.”

Among the participants was Łukasz Wyrzykowski of Warsaw University in Poland, who planned to use the data to look for signs of black holes as their gravitational pulls bent the light of more distant stars. In particular, he was looking for small, so-called stellar-mass black holes roughly five to 10 times the weight of our sun. “We only know of a few dozens of such black holes,” he says. “So we try to detect lensing effects. If the light is disturbed by the gravitational potential of the black hole, then you see the effect of the black hole itself.” Gaia provides a novel way to look for such effects on a huge scale. “Only Gaia can give us such precise measurements so that we can see the displacement of the background star” from such lensing effects, Wyrzykowski says. Chances are slim though, he notes. Only one or two such events are expected from the two billion stars in the Gaia data, if any at all.

Elsewhere, Ana Bonaca of Yale University and Adrian Price-Whelan of the Flatiron Institute were using EDR3 to hunt for clumps of dark matter in our galaxy. Throughout the Milky Way can be found groups of stars appearing to move in orderly queues known as stellar streams. Using Gaia’s precise data, it should be possible to map out the motion of these streams and look for any regions that appear to be unusually dense or bereft. “We noted these stars should all be traveling together,” Bonaca says. “But [in] a galaxy with a lot of dark matter clumps, the distribution [should] look kind of different.” This should result in overdensities and underdensities in the stream, hinting at the gravitational influence of clumps of dark matter hidden from our view. Already EDR3 was giving “much cleaner views of the streams,” says Price-Whelan, allowing possible clumps to be flagged more easily.

> **“We noted these stars should all be traveling together. But [in] a galaxy with a lot of dark matter clumps, the distribution [should] look kind of different.”**
>
> ***—Ana Bonaca***

Kareem El-Badry of the University of California, Berkeley, meanwhile, was on the hunt for wide binaries—stars orbiting one another but separated by 10 to 100,000 times the Earth-sun distance. Earlier releases of Gaia data contained numerous data-processing errors that made more distant stars appear closer, El-Badry says, which made identifying wide binaries difficult. But in EDR3, “so far it seems they’ve done a much better job of filtering out those bad sources,” he says. This should allow many more to be found, which could be useful for further calibrating Gaia’s data itself. The telescope has a small amount of uncertainty in the stellar distances it calculates, up to 20 percent for the most distant stars, which can cause problems for data analysis. But El-Badry says seeing wide binaries could help resolve that issue if the distances to two stars known to be orbiting each other can be independently measured and compared.

Much has also been made of Gaia’s potential ability to spot exoplanets orbiting around some of these stars using a technique called astrometry, which can tease out the presence of planets by the way they can make their host stars wobble back and forth in the plane of the sky. And while most discoveries of new exoplanets are not expected until the telescope’s fourth release of data four or five years from now, the full Data Release 3 in early 2022 could contain information on previously discovered exoplanets. “In 2022 hopefully some of the known exoplanets will have astrometric measurements, which gives us some real information on the masses of these exoplanets,” says Ronald Drimmel of the Turin Astrophysical Observatory, who is a Gaia team member. “We’re talking about the big exoplanets, the Jupiters going around other stars and seeing their influence on their host star, not small terrestrial exoplanets.”

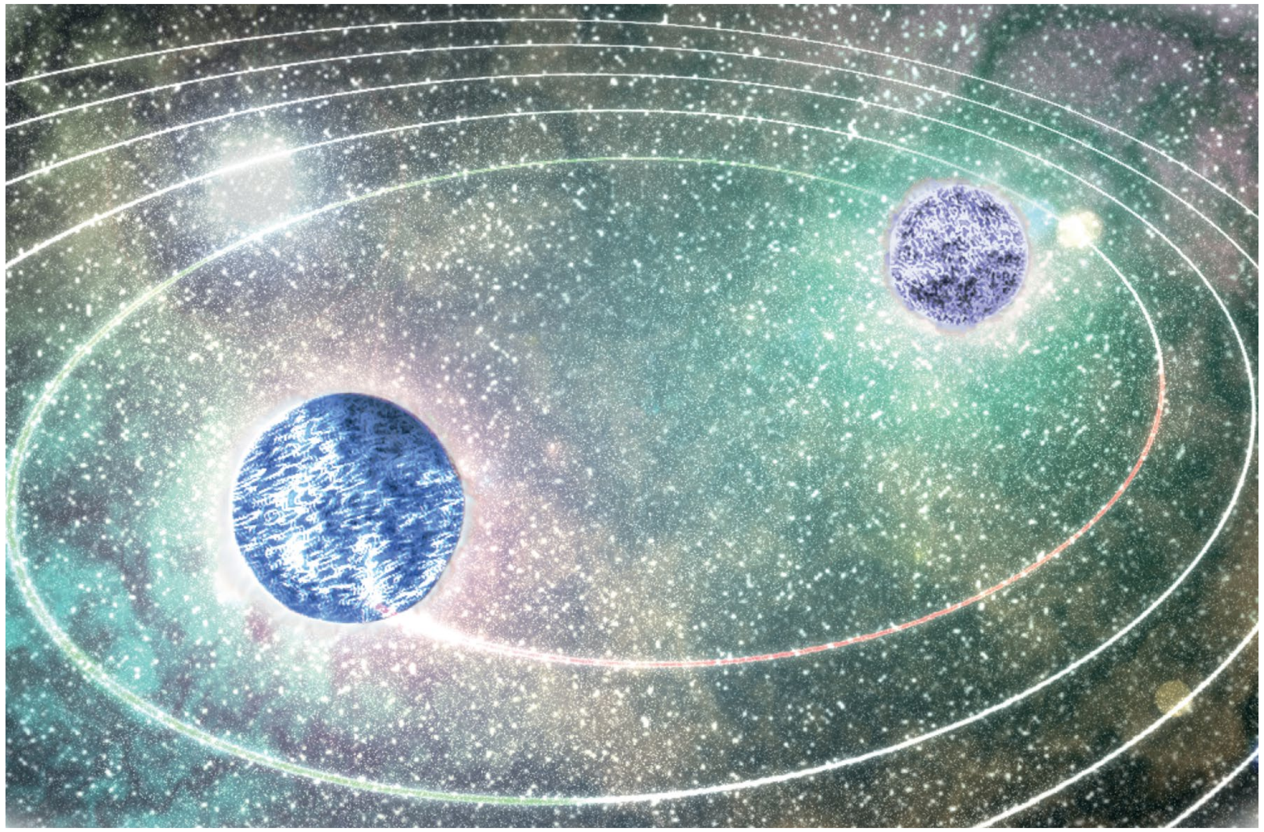
Other research has also already been possible with EDR3. Drimmel has seen evidence for a previously hypothesized black hole in a stellar system, for example, thanks to the refinement of the Gaia data. And astronomers were able to measure the acceleration of our solar system toward the galactic center by measuring the distances to quasars, bright objects billions of light-years away, arriving at a figure of seven kilometers per second per million years. “It’s a ridiculously small number, but we were able to measure it with Gaia,” Brown says.

Over the coming weeks, months and years, much more exciting science awaits. “Gaia data is like a tsunami rolling through astrophysics,” said Martin Barstow of the University of Leicester in England, who is part of the Gaia team, in a virtual press conference announcing the data in December. “It’s just transformational. Astronomy before and after Gaia will be unrecognizable.”

—Jonathan O'Callaghan

Gravitational Waves Probe Exotic Matter inside Neutron Stars

A new analysis of light and gravitational waves from colliding neutron stars helps reveal what’s inside these ultradense objects



Artist's impression of two inspiralling neutron stars shortly before their collision.

NICLAS MOLDENHAUER

A mystery lurks inside the corpses of dead stars. Neutron stars, formed when certain types of stars die in supernova explosions, are the densest form of matter in the universe; black holes are the only thing denser, but they have so fully escaped the bounds of normal physics that they are not matter anymore. The atoms in neutron stars have been squeezed so tightly by gravity that they have broken down, the protons and electrons inside them smushing together to create neutrons, leaving objects the size of small cities that contain masses larger than the sun. Some 95 percent of the mass of a neutron star is pure neutrons, but physicists wonder what happens at the very center, where the density peaks. Do neutrons break down further into their constituent quarks and gluons? Do some of the quarks transform from their normal “up” and “down” flavors to become weirder and heavier “strange quarks” not found in ordinary matter? Do the particles form an extreme state of matter called a superfluid that sloshes with no viscosity, never slowing down?

Scientists have come a step closer to understanding the inner workings of these bizarre bodies by studying the light and gravitational waves that result when two neutron stars slam into each other and become a black hole. Gravitational waves are folds in spacetime carved out when large masses move around. Scientists only gained the ability to detect gravitational waves in 2015 and have spotted just a handful of events involving neutron stars so far (the others have been collisions of black holes). But studying the properties of these waves—their frequency and how they change over time—can tell scientists a lot about the objects that created them. Physicists seek accurate measurements of neutron stars' masses and radii, which would help reveal their "equation of state"—the relation between pressure and density within these stars. Knowing the neutron star equation of state would in turn indicate what kind of matter hides inside them.

In a new study, an international team of researchers combined gravitational-wave measurements from two neutron star collisions, as well as the light signals that arrived along with one of them (the other was dark), with estimates of neutron star masses and radii from watching rapidly spinning neutron stars called pulsars. "The big advantage is it's a very coherent picture," says study member Tim Dietrich of the University of Potsdam in Germany, who co-authored a paper reporting the results published in *Science*.

"We combine all the things we know currently, including gravitational waves and electromagnetic waves, information from single neutron stars, and theoretical computations from nuclear physics." The equation of state they derived predicted that a neutron star containing the mass of 1.4 suns would have a radius of about 11.75 kilometers, plus or minus 0.81 to 0.86 kilometer. That's a bit more than half the length of Manhattan. "The size of the neutron star directly depends on the behavior of matter inside the core, so this gives us a better understanding about the properties of the neutron star material," Dietrich says.

For instance, if neutrons remain intact in the core of these stars, they would push out against the outer layers, potentially leading to a slightly larger radius. If, on the other hand, the neutrons break down into a soup of quarks, the core would be squishier and the whole star would sink in a bit, resulting in a smaller radius.

The new measurement is in general agreement with earlier studies that have looked at gravitational-wave data and other ways to measure neutron star size. "This paper is a nice joint reanalysis of previous studies and doesn't change the overall impression that has been in place for the past few years, that the radius of a neutron star is about 11 to 13 kilometers," says Mark Alford, a physicist at Washington University in St. Louis. Anna Watts, an astrophysicist at the University of Amsterdam, says that this type of combined analysis "is clearly the way forward" but that none of the measurements "are yet good enough to really pin down the nature of dense matter." The field will need to wait for future data to really understand what's happening inside neutron stars.

> **"The size of the neutron star directly depends on the behavior of matter inside the core, so this gives us a better understanding about the properties of the neutron star material."**
> ***—Tim Dietrich***

"I think it's a very nice analysis," says physicist James Lattimer of Stony Brook University, who was not involved in the research. He cautions that in modeling how well different possible equations of state fit the data, the team may have mistakenly eliminated too many equations that produce neutron stars with large radii, however. "I think they've underestimated their uncertainty. But in some sense, it's a matter of opinion and how much faith you place in different statistical methods."

Besides revealing secrets of neutron stars, the study also produced a measurement of the Hubble constant, which reflects the expansion rate of the universe. To derive the constant, the scientists used the amplitude of the gravitational waves coming from one of the collisions to estimate how far away the crash occurred. They then compared their distance measurement with the known speed of the collision's host galaxy, which was measured by looking at the galaxy's redshift—how much its light has slid toward the red end of the spectrum. The Hubble constant they found, 66.2 kilometers per second per megaparsec, is not precise enough to decide between the competing measurements that already exist but adds another data point to the hotly contested question of how fast the cosmos is growing.

The scientists hope to apply the same type of analysis to future neutron star collisions that appear. "We made this first step, and now we'll push forward," says team member Sarah Antier of the University of Paris, an astronomer who searches for light signals accompanying gravitational-wave events. "My task is to connect different observatories to provide a network to make immediate observations" when gravitational-wave detectors find a new signal.

Physicists are biding their time until the next generation of gravitational-wave detectors, such as the Cosmic Explorer in the U.S. and the Einstein Telescope in Europe, come online in the 2030s. These machines should be much more sensitive, allowing them to capture many more signals from more events and offering higher-precision data. Future projects such as the Enhanced X-ray Timing and Polarimetry Mission (eXTP) and the Athena X-ray Observatory should also gather more accurate measurements of pulsars.

Scientists have learned so much in the short time since gravitational-wave data became available, the future promises to greatly expand our knowledge of extreme matter under intense pressure. "The past four years have been remarkable," Lattimer says. "It shows the potential that we are going to be getting in the future. We should have many more measurements from gravitational-wave events, and as we add each new event, the results are going to converge."

—Clara Moskowitz

Physicists Achieve Best-Ever Measurement of Fine-Structure Constant

Three times more precise than the previous record-holding determination, the result closely agrees with theoretical predictions but could still reveal pathways to new physics

Researchers at the Kastler Brossel Laboratory in Paris have made the most precise measurement of one of the fundamental constants, called the fine-structure constant, providing physicists with a vital tool to verify the consistency of their most cherished theoretical models.

The fine-structure constant determines the strength of the electromagnetic force and is central in explaining a number of phenomena, including the interactions between light and charged elementary particles such as electrons. It is an important part of the equations of the Standard Model, a theory that predicts and describes all the known fundamental forces other than gravity—namely, electromagnetism as well as the weak and strong nuclear forces. The team in Paris measured the value of the fine-structure constant as 1/137.035999206, to an accuracy of 11 digits. The result appears in a study published in *Nature*.

"I am amazed by the level of precision achieved," says Massimo Passera of the Italy-based National Institute for Nuclear Physics, who was not a part of the experiment.

Using the fine-structure constant in the Standard Model equations, one can calculate the magnetic moment of the electron, a property exhibited by the negatively charged particle under the influence of a magnetic field. The electron's magnetic moment makes for an excellent candidate to test the Standard Model, as it has been repeatedly measured in the laboratory and theoretically predicted to a very high degree of precision.

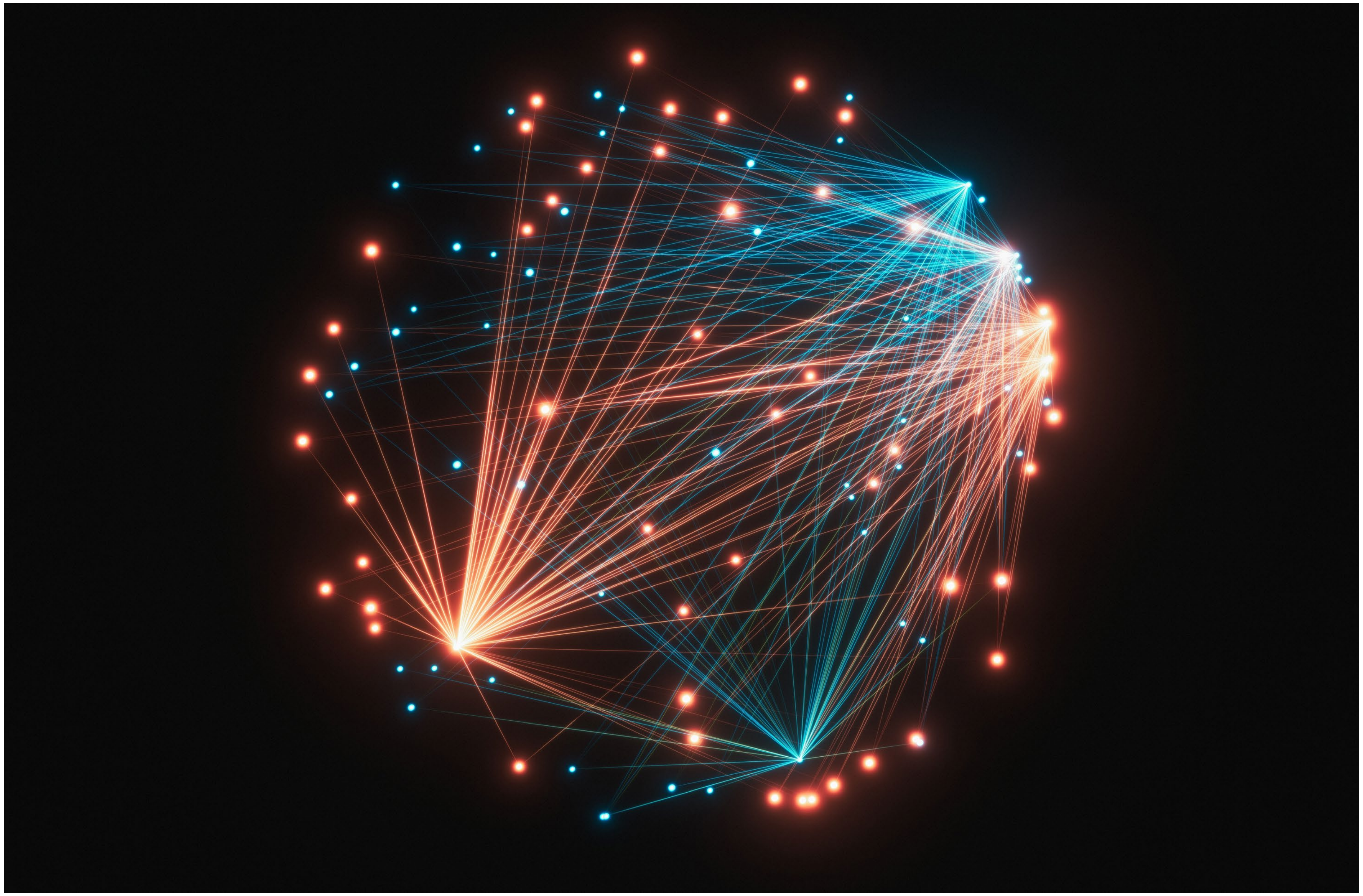
"With the new determination of the fine-structure constant, these predicted and experimental values agree at better than one part per billion, thereby providing an outstanding consistency check of the Standard Model of particle physics—in particular of its electromagnetic sector," Passera says. "Moreover, the closeness of the two values sets a strong limit on the possible internal structure of the electron."

Performed using rubidium atoms in a technique called atom interferometry, the new measurement is more accurate by a factor of three from the previous record-holding determination, which was achieved by a team at the University of California, Berkeley, in an experiment using cesium atoms.

According to Pierre Cladé, who co-authored the *Nature* paper, the improvement was the result of "continuous work of small steps." In addition to a major upgrade in the apparatus and new laser sources, he says, the team's success arose from efforts to reduce noise and systemic effects. "We did a lot of modeling to deeply understand the physics of our experiment. Three years ago we reached a better understanding of the interaction between a photon and the rubidium atom." That enhanced understanding allowed the team to determine a more precise value for a rubidium atom's mass.

"Once the mass of the rubidium atom is measured, we use it with the relative mass of an electron to calculate the fine-structure constant. The more precise the mass of the rubidium atom, the more accurate the value of the fine-structure constant," says Saïda Guellati-Khelifa, the paper's lead author.

The experiment employed multiple standard approaches to reach its stunning precision, starting with the laser cooling of a cloud of rubidium atoms. Six laser beams exert force on the atoms in such a way that they drastically reduce the atoms' velocities. Because such atomic kinetic motions are the basis of macroscale manifestations of heat, the end result of reducing the rubidium atoms' velocities is to lower their temperature to a mind-bogglingly frigid four microkelvins—slightly above absolute zero, or –273.15 degrees Celsius. "At such temperatures, an atom behaves like a particle and a wave," Cladé says.



XUANYU HAN *GETTY IMAGES*

This wavelike behavior of atoms is quite different from the waves of water that we are more familiar with. In this case, the wave in question concerns the probability of finding a rubidium atom in a certain position. Using lasers, the team prepared the atoms in both the ground state and excited state (in the latter the atom moves with a slightly greater velocity). "This produces two trajectories that are separated and later recombined to create an interference pattern," Cladé says. "The interference depends on the velocity acquired by the atoms after they absorb photons from a laser source. Once this recoil velocity is measured from the interference, the rubidium atomic mass can be derived."

As a first step, the team began an almost yearlong run of the experiment in December 2018, collecting data to ensure their equipment was working properly.

"While performing such experi-

> **“At such temperatures, an atom behaves like a particle and a wave.”**
> ***—Pierre Cladé***

ments, there are different physical processes that underlie what is being measured. Each process can potentially affect the accuracy of the measurement by inducing errors. We need to understand and evaluate errors in order to make corrections,” says Guellati-Khelifa, who has been taking measurements of the fine-structure constant for more than 20 years.

After making the corrections, the team derived final measurements during a monthlong run, finally determining the fine-structure constant’s value to a precision of 81 parts per trillion.

According to Passera, efforts to find the precise values of fundamental constants are complementary to the particle accelerator–based experiments that exploit huge energies in order to create never before seen particles.

“The ‘tabletop’ experiments such as the ones in the Kastler Brossel or Berkeley laboratories are done at very low energies. And yet their extremely precise measurements can indirectly reveal the existence or even the nature of a particle that may not yet be directly seen at high energies. Even the very last digits of a precise measurement have a story to tell,” Passera says.

Consider, for instance, the muon—a cousin of the electron that is 200 times heavier. Just like the electron, the muon also exhibits a magnetic moment when subjected to a magnetic field. Moreover, similar to the electron, there is a difference between the theoretical and experimental values of the muon’s magnetic moment.

Discrepancies in this context are determined in terms of standard deviation, which combines the difference in the two values and the uncertainties associated with the theoretical calculation and experimental measurement of each value.

In the case of the electron, the experimental measurement of the magnetic moment is 1.6 standard deviations above the theoretical prediction based on the fine-structure constant measured by the Paris group. Whereas the muon’s experimental value, announced and refined in a trio of papers published between 2002 and 2006, is 3.7 standard deviations above the figure predicted by the Standard Model theory.

Physicists are now eagerly awaiting the first results of the Muon g-2 experiment at Fermilab that is expected to provide the most precise experimental measurement of the muon’s magnetic moment. If this value goes beyond five standard deviations from the theory—the gold standard for discovery in particle physics—it would be convincing evidence of new physics beyond the Standard Model.

Generally, when it comes to the theoretical prediction of the magnetic moment using the Standard Model, the muon discrepancy is not as sensitive to the precise value of the fine-structure constant as the electron. But, according to Alex Keshavarzi, who is managing operations and leading analysis efforts for the Muon g-2 experiment, “the new fine-structure constant measurement is interesting for the muon discrepancy.”

Keshavarzi, who is not part of the Paris research group, says if new physics emerges from the Muon g-2 results of the muon measurement, the positive discrepancies for both the electron and the muon would make it simpler to develop models and explanations than if the discrepancies were in the opposite directions.

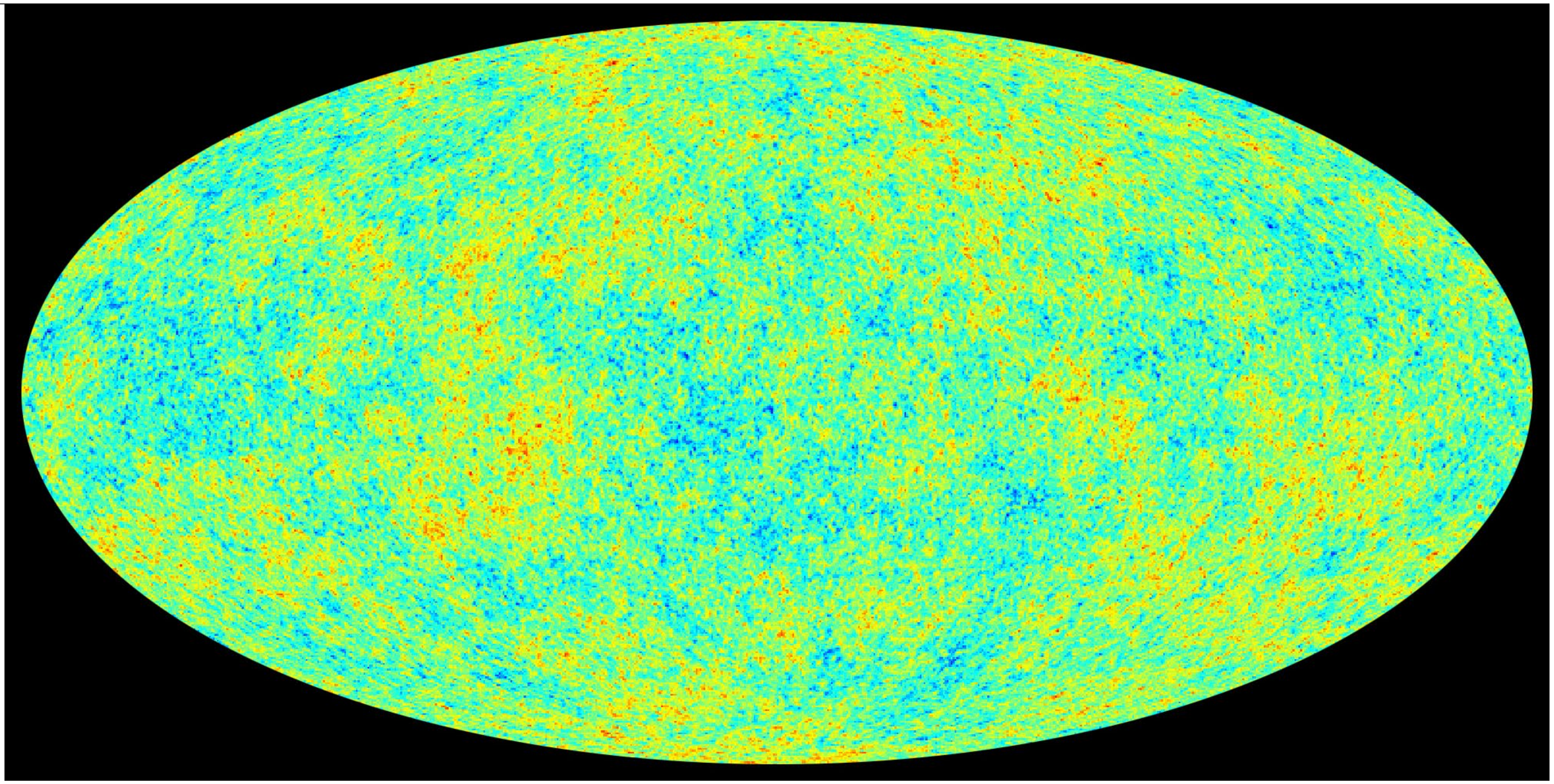
He adds, however, that even aside from its potential connection to the muon, the Paris group’s electron-based measurement of the fine-structure experiment has introduced other mysteries—namely, why it produced a positive standard deviation of 1.6, whereas the 2018 experiment at Berkeley produced a negative deviation of 2.5.

According to Cladé, both the Paris and Berkeley experiments are based on the same physics, making the divergence all the stranger. “I don’t think the discrepancy is due to the use of cesium or rubidium. There is probably something in one of the two experiments that may not have been accounted for. That is something we should now try to understand,” he says.

—Dhananjay Khadilkar

Hints of Twisted Light Offer Clues to Dark Energy's Nature

Cosmologists suggest that an exotic substance called quintessence could be accelerating the universe's expansion—but the evidence is still tentative



Map of the universe's cosmic microwave background radiation, measured by the Planck space observatory.

ESA

Cosmologists say that they have uncovered hints of an intriguing twisting in the way that ancient light moves across the universe, which could offer clues about the nature of dark energy—the mysterious force that seems to be pushing the cosmos to expand ever faster.

They suggest that the twisting of light, which they identified in data on the cosmic microwave background (CMB) collected by the Planck space telescope, and the acceleration of the universe could be produced by a cosmic "quintessence," an exotic substance that pervades the cosmos. Such a discovery would require a major revision of current theories, and physicists warn that the evidence is tentative—it does not meet the "five-sigma" threshold used to determine whether a signal is a discovery. But it underscores the fact that modern cosmology still has an incomplete picture of the universe's contents.

If dark energy is a quintessence, its push on the expansion could slowly wither or disappear, or it could even reverse to become an attractive force, causing the universe to collapse into a "big crunch," says Sean Carroll, a theoretical physicist at the California Institute of Technology. "We're back to a situation where we have zero idea about how the universe is going to end." The work was reported on November 23, 2020, in *Physical Review Letters*.

THE FIFTH ELEMENT

The first direct evidence that an unknown force was pushing cosmic expansion to accelerate emerged in 1998, from two separate surveys of supernovae. A host of other studies have since confirmed the presence of this force, dubbed dark energy, but have provided precious little information about its nature.

Researchers' first guess—which remains the leading theory—was that dark energy is an intrinsic property of space, which would mean that the amount of dark energy per unit volume of space is fixed as a "cosmological constant." But some cosmologists theorized that dark energy is made of something else entirely. They call this a quintessence field, after the fifth element, or ether—the name that ancient Greek philosophers gave to an invisible material thought to fill all the empty space in the Universe.

Unlike the cosmological constant, quintessence "is a tangible medium, and it has fluctuations of its own," says Robert Caldwell, a cosmologist at Dartmouth College, who was one of the first researchers to propose the material's existence. Quintessence could have properties that are intermediate between those of matter and of a cosmological constant, Caldwell adds. As the universe expands, a cosmological constant would maintain a constant density, whereas the density of quintessence would decrease—though not as fast as the density of matter, which drops as galaxies spread out.

In 1998 Carroll proposed an experimental test for quintessence, based on the prediction that it alters how light propagates in space. A group led by the theoretical physicist Marc Kamionkowski, now at Johns Hopkins University, then calculated how this effect could be measured in the CMB, the primordial radiation often described as the afterglow of the big bang. The researchers suggested that it would be possible to detect signs of quintessence by looking at maps of polarized light across the CMB. Light is polarized when its electric field "wiggles" in a particular direction rather than in a random one. The theory says that quintessence twists the direction in which the polarization points, in a way that could be detected by looking at polarization across the whole sky.

Now two cosmologists—Yuto Minami of the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan, and Eiichiro Komatsu of the Max Planck Institute for Astrophysics in Garching, Germany—have identified that CMB signature in data from the European Space Agency's Planck mission, which concluded in 2013.

Planck's main purpose was to map tiny variations in the CMB's temperature across the sky, but the mission also measured the radiation's polarization. Minami and Komatsu were able to detect signs of quintessence using a new technique that they reported last year. Their results differ from those of other groups, which have looked at CMB polarization maps—including Planck's—and found no twist, says physicist Suzanne Staggs of Princeton University, whose team measures CMB radiation using the Atacama Cosmology Telescope (ACT) in Chile. Staggs's team plans to try out Minami and Komatsu's technique on ACT data. "We are interested in exploring it," she says.

BIG IMPLICATIONS

The paper is "quite a nice analysis", but noise in the Planck signals could be a complicating factor, says George Efstathiou, a leading Planck cosmologist at the University of Cambridge.

Theoreticians are responding with caution, too. "If it were real, it would be big," Carroll says. But he notes that the statistical significance—only 2.5 sigma—of the result is weak and says that such results often fade away on further scrutiny.

Kamionkowski agrees. "I think we'll probably want to be going through all that very carefully before getting too worked up," he says. He adds that the existence of quintessence would have implications not only for cosmology but also for fundamental physics: the Standard Model of particle physics does not predict any kind of quintessence.

Other efforts are in the works to map the CMB polarization with greater accuracy than ever before and will put a stringent test on quintessence. These projects include the Simons Observatory, another CMB experiment now being set up in the Atacama Desert and a future Japanese-led space probe called LiteBIRD.

If quintessence does pan out as an explanation, it will have cascading effects on the best estimates of the universe's features, including its age, which could be a bit younger than the 13.8 billion years cosmologists have calculated on the basis of Planck data. It could also help to explain why CMB data predict that the universe should be expanding at a slower pace than currently observed. "The rock that they're standing on is the cosmological constant. If you change that rock, that could have an effect on everything else," Caldwell says.

—Davide Castelvecchi

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Arecibo's Collapse Sends Dire Warning to Other Aging Observatories

The iconic telescope's tragic end foreshadows future battles over the fate of various legacy facilities

By Robin George Andrews

Arecibo Observatory, in operation during its better days, with the Milky Way overhead.

UNIVERSITY OF CENTRAL FLORIDA. COURTESY NATIONAL SCIENCE FOUNDATION

Robin George Andrews is a volcanologist and science writer based in London.

THE U.S.'S FAMED ARECIBO OBSERVATORY SURVIVED ALL MANNERS OF THREATS since its construction in a bowl-shaped natural sinkhole in the forested hills of Puerto Rico in 1963. It persisted through everything from hurricanes and earthquakes to wild swings of the federal budgetary scythe. That history made it all the more shocking last December when the catastrophic failure of multiple massive suspension cables sent a 900-ton (817-metric-ton) equipment platform plummeting straight through the 305-meter radio dish that was Arecibo's heart, shattering it beyond repair. As news of the observatory's ignominious end spread, people around the globe—many professional astronomers among them—mourned almost as if they had lost an old friend.

That loss, however, was most keenly felt by the generations of Puerto Ricans who saw in Arecibo something more than a cultural fixture akin to the island's rain forest and rum. "As a world-renowned scientific facility that provided invaluable data to the defense of our entire planet, Arecibo was the gateway to science for many Puerto Ricans," says Edgard Rivera-Valentín, a planetary scientist at the Lunar and Planetary Institute in Houston, whose career, like many, was shaped by the observatory. "It took me a while to even be able to look at the video of the platform falling."

In the aftermath, an uncomfortable question remains: What happens now? As officials hover over the observatory's grisly remains, they must decide whether to rebuild and upgrade it, no matter the cost, or to abandon all hope of any resurrection, channeling money that might otherwise be spent financing Arecibo's reconstruction into new projects that, just maybe, could fill the gaps that this legendary facility leaves behind.

The dilemma is emblematic of an existential question looming over the entire astronomy community, especially in the U.S.: Is it really possible to strike a balance between maintaining existing observatories and building innovative new ones in an era of flat or shrinking federal funding? In other words, must we grind up the old to make way for the new? The death and attempted resuscitation of Arecibo is a distilled encapsulation of this conflict and perhaps one that provides a window into the future of the nation's legacy observatories.

ARECIBO, THIS IS YOUR LIFE

Until China's Five-Hundred-Meter Aperture Spherical Radio Telescope, or FAST, was completed in 2016, Arecibo boasted the largest radio dish in the world—capable of hearing the feeblest whispers of radio waves emanating from all kinds of astrophysical things that go bump in the cosmic night. And unlike FAST and every other radio telescope in the U.S. (save for California's Goldstone Deep Space Communications Complex, notes Megan Bruck Syal, a planetary defense researcher at Lawrence Livermore National Laboratory), Arecibo was not only capable of receiving radio waves from the great beyond but also of transmitting them. This made the observatory one of the few facilities able to bounce radar beams off planets, moons and asteroids to make remarkably high-resolution measurements of their shapes and surfaces.

Across the decades, researchers used Arecibo's superlative capabilities to perform one stunning feat of space science strength after another. These included providing the first piece of evidence for the presence of gravitational waves, as well as detecting the first repeating fast radio burst. The facility played a key role in confirming one of the very first known exoplanets. And it was the source of the Arecibo message, a cosmic communiqué beamed into intergalactic space in 1974 that, at its specific wavelength, briefly outshone the sun.

But as time passed, technology progressed, and the need for new observatories with breakthrough capabilities became clear, Arecibo's chief funder and steward, the National Science Foundation (NSF), began to perceive the observatory as being past its prime. A 2006 senior review report recommended that unless another entity

Prior to its collapse, Arecibo's radio dish had already been crippled by several snapped cables, setting the stage for further calamity.

RICARDO ARDUENGO *GETTY IMAGES*

stepped in to fund it, Arecibo should be decommissioned after 2011. Pressure from the scientific community, as well as from politicians and locals, saved the observatory from this fate, but the NSF has been draining it of annual operational funds and threatening it with decommissioning ever since.

> **“In planetary defense, Arecibo has unparalleled capabilities to characterize the detailed shapes of near-Earth asteroids.”**
> ***—Megan Bruck Syal***

By 2017 the NSF paid about two thirds of Arecibo’s $12-million annual budget, with NASA making up the remaining third. But by federal fiscal year 2019 the facility’s annual funding for operations and maintenance was down to about $7 million. NASA’s level of support at that time was around $4 million. (That year the NSF also gave more than $12 million to Arecibo for hurricane-related repairs through a congressional act.) This funding decline was set to continue into the 2020s, a clear signal that, one way or another, the NSF was going to rid itself of Arecibo eventually.

The problem, says Casey Dreier, senior space policy expert at the Planetary Society, is that when adjusted for inflation, the NSF’s budget for basic research that funds Arecibo (and much else) has remained relatively flat over the past 10-plus years. This funding is essentially determined by Congress, and the NSF has to do what it can to achieve the most pertinent scientific goals of the moment with whatever it is given.

So what is a cash-strapped agency with lots of aging but scientifically capable observatories to do?

ONE OF A KIND

Because of its singular capabilities and shocking demise, the case of Arecibo is particularly extreme, but it still aligns with the shared plight of many other legacy astronomy facilities: Do we keep them going for as long as possible or, at some point, accept that they are not worth it anymore?

The case for Arecibo’s reconstruction, now championed by many in the astronomy community both within and outside Puerto Rico, leans on the uniqueness of its capabilities. What, exactly, could Arecibo do that others could not?

Chiara Mingarelli, a gravitational-wave astrophysicist at the University of Connecticut, is part of the NANOGrav project, which looks for nanohertz-frequency gravitational waves via subtle variations they should induce on the arrival times of metronomelike radio pulses from large numbers of pulsars scattered across the heavens. Such waves—which have yet to be conclusively seen via this “pulsar timing array” method—are thought to come from merging pairs of supermassive black holes. Arecibo had been monitoring half of NANOGrav’s targeted pulsars.

“We can still do [pulsar timing]. It’s just that Arecibo was really good at it,” Mingarelli says. “We lost our star quarterback.” International collaborations with other radio telescopes elsewhere in the world—in Europe and Australia, for example—will help make up for that shortfall a little, she adds. Newer players able to study pulsars—such as China’s FAST, South Africa’s MeerKAT and India’s Giant Metrewave Radio Telescope—are all capable of helping. But the loss of Arecibo is not trivial. “We don’t only need one of those telescopes,” Mingarelli says. “We need lots of those telescopes so we can look at the whole sky.”

Paulo Freire, an astronomer at the Max Planck Institute for Radio Astronomy in Bonn, Germany, hunted pulsars using Arecibo from 2001 to 2009. At the time, it was the world’s most sensitive telescope for such work. Other telescopes do not yet compare, he says.

FAST is more sensitive, but for now at least, it can’t act as a perfect replacement for Arecibo because of various issues. For one thing, any international collaboration with the telescope requires navigating a complex political gauntlet, a series of checks and bureaucratic barricades that may be a flex of China’s growing soft power.

Conversely, Arecibo’s policy was very open. “You submit a proposal. If it has merit, it gets time on the telescope. That’s it. They don’t care where you come from,” Freire says. Fortunately, MeerKAT can help out in the pulsar hunt. “For pulsars, the location where you want to see is in the Southern Hemisphere because the center of our galaxy is in the Southern Hemisphere. And there, the sky is full of pulsars,” he says. “But still, [MeerKAT] has about a third of the sensitivity that Arecibo has—or had.” FAST also has a bit more of a restricted frequency range, compared with Arecibo. And unlike the latter facility, it does not have multiple transmitting radar systems. “For the U.S. at the moment, there’s no facility that’s going to replace the capabilities of Arecibo—not in terms of high-sensitivity astronomy,” Freire says.

Arecibo could tune in to the activity of nearby stars. Such observations gave scientists such as Abel Méndez, director of the Planetary Habitability Laboratory at the University of Puerto Rico at Arecibo, an idea of how hostile or harmless a planetary neighborhood’s stellar furnace was likely to be. If a world around one of our sun’s neighboring stars had potent auroras or perhaps even a technological civilization, Arecibo’s sensitivity was sufficient to give it a chance of detecting the resulting radio chatter. The FAST facility should offer similar sensitivity, Méndez says, but he worries about logistics—particularly the difficulty of traveling to China for potential on-site work.

Arecibo was also one of our foremost sentinels monitoring dangerous space rocks. Although ill suited for searches for such objects, the observatory excelled at characterizing individual specimens: if another telescope spotted an asteroid or comet on a possible collision course with Earth, Arecibo could take a closer look.

"In planetary defense, Arecibo has unparalleled capabilities to characterize the detailed shapes of near-Earth asteroids," Bruck Syal says. Knowing a threatening asteroid's shape, in turn, helps to predict how it might react to deflection attempts using nuclear explosives or kinetic impactors. Arecibo could also nail down the position of near-Earth asteroids very precisely so their orbital paths could be more accurately predicted. "That's essential for driving down the uncertainty on whether an asteroid might impact Earth in the future or not," Bruck Syal says.

NASA's Deep Space Network, a collection of radio telescopes used to speak to spacecraft across the solar system that includes the Goldstone observatory, also has transmitting capabilities, says Alessondra Springmann, a planetary science doctoral student at the University of Arizona, who spent two years at Arecibo. That makes it suitable for various planetary radar observations, including asteroid characterization. "But you can look at 20 times more asteroids, I believe, with Arecibo," she says. "Arecibo is 18 times more sensitive than Goldstone. And Arecibo has a degree of scheduling flexibility that Goldstone and the Deep Space Network lacks."

Even the telescope's location is unique. Puerto Rico is a hotspot for strong earthquakes and hurricanes. But in the island's favor is its large limestone sinkholes, a great fit for giant radio dishes. And unlike most other potential sites for hosting an ultralarge observatory, Puerto Rico offers preexisting infrastructure, from roads to power lines. Reconstruction would be tough and costly, Springmann says. But it would still be easier than making a big new radio telescope elsewhere.

The most compelling argument to rebuild Arecibo, however, may come down to its connection to everyday Puerto Ricans. For decades the observatory was a nexus for science education and outreach, and it reliably boosted the local economy by bringing in well-paid jobs and a steady flow of tourists. "When we work to build scientific facilities toward that endeavor and engage the public through that facility, we enter into a social contract and incur those responsibilities," Rivera-Valentín says. In other words, the harm from abandoning Arecibo could reach well beyond the rarefied realm of astronomy.

A GRIM REALITY

Even in death, Arecibo demonstrates that the NSF has an intractable problem with its aging observatories.

Tony Beasley, director of the National Radio Astronomy Observatory, headquartered in Charlottesville, Va., says that our society supports astronomy for four main reasons: conducting science to find our place in the universe; learning fundamental physics by comparing astrophysical phenomena with local events; producing new generations of scientists, engineers and savvy members of the lay public; and sparking technological advances. "When you think about Arecibo, it was still doing three of those fantastically. It was doing pretty good on the science one as well," he says.

"That's the quandary the NSF has with these facilities. All of them are doing great at looking at weird places in the universe, producing fantastic people and technology, and all that kind of stuff," Beasley says. "The science may or may not be *New York Times* front-page [material], but it's fantastic. They're all bricks in the wall."

And whereas in recent years optical and infrared astronomy have been the hotbeds of research activity, Arecibo has helped keep the radio telescope community alive and well, Freire says. Furthermore, he adds, despite the observatory's advanced age, its many upgrades over the years almost made Arecibo a new telescope over and over again.

But there are limits to telescopic add-ons, Beasley says. It is a bit like adding improved lenses to the camera on your smartphone: eventually the phone's immutable architecture will limit the type and quality of the photographs you can take. Arecibo was a literal and figurative giant in radio astronomy thanks to its vast dish size and associated astounding sensitivity. But the trade-offs for that massive dish will not be fixed by upgrades: a limited frequency band in which it could observe and a reduced view of the sky, for example—nested in its sinkhole, Arecibo's dish cannot be steered to point anywhere in the heavens. Such restrictions mean that even upgraded with wondrous new bells and whistles, its sensitivity will not significantly change.

Sadly, Arecibo's implosion now makes the argument for its enduring worth much harder to make because repairs and upgrades are far cheaper than rebuilding something from a pile of debris. "The bottom line is: if you've already got it, and it's working, you can do an upgrade of the electronics and key systems and start doing your science," Beasley says. "That's always worth looking for. But if it collapses, and you have to rebuild it, that's a different discussion. You could be talking about two-orders-of-magnitude-different investment."

New projects could certainly use the money that might otherwise go into rebuilding Arecibo. But let the buyer beware: "The problem with the new, shiny things is that they can break down, they can take longer than you think, they can go overbudget, and the thing you end up with in the end isn't really the thing you wanted in the beginning," Mingarelli says.

"You could close a lot of telescopes and still not be able to pay for the operations of one of these new telescopes," Beasley says. When it comes to the old versus the new, there are no easy answers.

Aerial view of Arecibo's shattered radio dish, which was damaged beyond repair by the crash-landing of the observatory's 900-ton equipment platform after additional cable failures.

RICARDO ARDUENGO *GETTY IMAGES*

ARECIBO'S AUTOPSY

In a media briefing, Ralph Gaume, director of the NSF's astronomy division, seemed to say that the agency is treating the situation with the Arecibo telescope as firmly postmortem. Any decision to rebuild the radio dish or return the site to its natural state would be a "multiyear process that involves congressional appropriations and the assessment and needs of the scientific community," he said.

Already, though, others are applying the lessons of Arecibo to planning for the future. Francisco Córdova, director of the Arecibo Observatory, says that the dish's destruction shines a light on potential problems newer telescopes may encounter. Arecibo's saga, in which it was slowly exsanguinated of funds over time, should be a cautionary tale for other facilities. Nickel-and-diming a legacy observatory may help balance budgets, but the associated operational uncertainties and inefficiencies the practice introduces can be profoundly disruptive for actually doing scientific research—perversely reducing the benefits of keeping an aging facility's lights on in the first place.

One solution the NSF pursued—transferring ownership of Arecibo to private entities or consortiums to reduce the agency's responsibilities—offers "another way of doing things well," Córdova says. Auctioning aging sites close to their peak scientific performance years would give them the best chance at a second life. Such efforts, however, are not guaranteed to work: For years, NASA sought to "save" its aging Spitzer Space Telescope by handing it off to the private sector for a hefty but fair sum. Yet in the end, no deals were struck, and Spitzer was shut down in early 2020.

In any event, Arecibo's tragic decline suggests that slowly siphoning away funds from preexisting facilities to support new projects is treacherous and not at all guaranteed to lead to net positive outcomes. "I think in the view of many, the NSF has just not adequately funded the facility over the years," Bruck Syal says. "And that's apparent now. [The dish's collapse] is the consequence of underfunding an iconic observatory like that. You can't keep it going on a shoestring budget forever."

> **"The bottom line is: if you've already got it, and it's working, you can do an upgrade of the electronics and key systems and start doing your science."**
> ***—Tony Beasley***

Money, however, cannot solve everything. In Arecibo's case, Córdova says, some of the facility's structural degradation was difficult, if not impossible, to see using nondestructive technology. That situation meant that even if a well-funded consortium had been managing the observatory and doing the same checks using the same maintenance technology, it would not have caught the fatal cable degradation either. Speaking for the current management team at the University of Central Florida, Córdova adds that the team "never at any point stopped performing maintenance tasks on the structure because of the lack of funding."

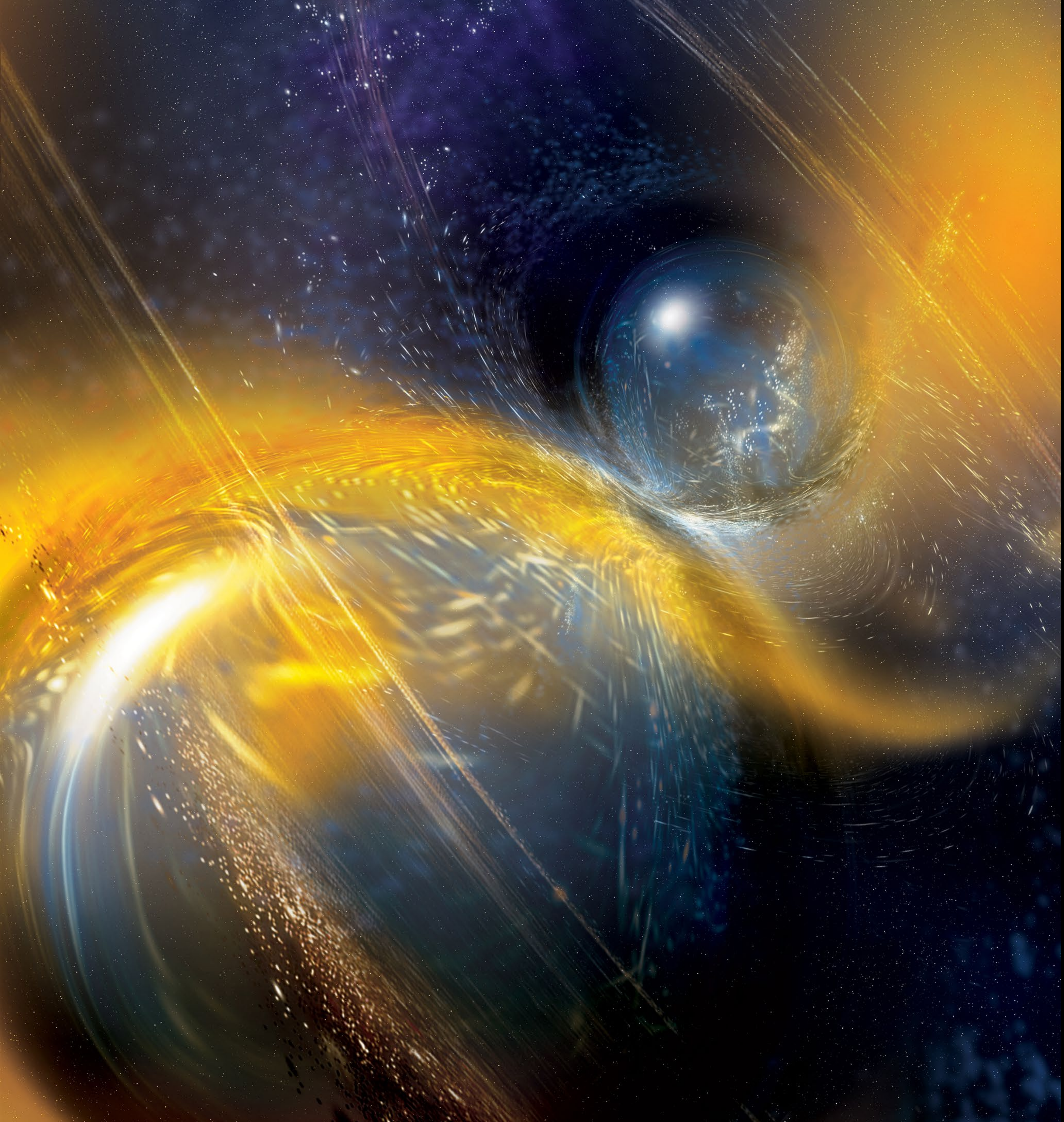
Like Córdova, Freire, who worked at Arecibo back when Cornell University managed the site, does not believe the collapse arose from direct neglect. "I think nature was especially unkind to the structure," he says, referring to recent earthquakes and 2017's Hurricane Maria. "I think this might have been the main reason why the strength of the cables was far below what was expected."

But declining funds certainly did not help. Although maintenance on Arecibo did not stop, it was triaged. "A lot of the money that [the observatory] had, spare money for maintenance, was then with tasks that were perceived to be more urgent," Freire says. In recent years corrosion from airborne salts had been a constant worry for the facility's managers. "People were not so worried about the cables," Freire adds.

If you are striving for a balance between reliable workhorses and novel projects, representation also matters. "I think it's easier to ignore or underfund facilities that are off the U.S. mainland" and hope that no one notices, Bruck Syal says. "The fact that Puerto Rico doesn't have senators, for example, to advocate for it more aggressively might have hurt the facility's funding."

Ultimately, though, the reason for the tension between the NSF's upkeep of old observatories and its plans for new ones lies in the funding it receives. That arrangement is "kind of insane, right?" the Planetary Society's Dreier says. "We're talking about fractional, single-digit millions that Arecibo had to fight to keep out of an annual U.S. budget of approximately $4.5 trillion. That's how squeezed our sciences are. All of our basic R&D—that includes the [National Institutes of Health], that includes NASA, that includes the NSF—we're still only talking about $80-ish billion a year, out of a $4.5-trillion budget." The situation strikes some as senseless: As others, such as China and Europe, seek scientific ascendancy on the international stage, Beasley says, his colleagues are asking, "Why are we just rolling over on this?"

"In astronomy, we are right at that moment, that sort of inflection point, where we have to make a very clear decision about world leadership and what the benefits to the U.S. are of being a world leader in a field like this," he says. "Where the money goes is a reflection of values." Considering the complicated saga of Arecibo, then, what Americans are really confronting is a fundamental question of what sort of country they wish the U.S. to be.



Stellar Smashups May Fuel Planetary Habitability, Study Suggests

Radioactive elements produced by colliding neutron stars could make the difference between living and lifeless worlds

By Marcus Woo

Illustration of two colliding neutron stars. Radioactive elements produced by such cosmic cataclysms may be partially responsible for plate tectonics and protective magnetic fields on Earth-like rocky planets.

NATIONAL SCIENCE FOUNDATION, LIGO, SONOMA STATE UNIVERSITY AND A. SIMONNET

Marcus Woo is a freelance science writer based in the San Francisco Bay Area, who has written for *Wired, BBC Earth, BBC Future, National Geographic, New Scientist, Slate, Discover*, and other outlets.

IN THE SEARCH FOR ALIEN LIFE, Earth—as the only planet known to be inhabited—has always been a starting point. “We look for something that reminds us of home,” says Natalie Batalha, an astronomer at the University of California, Santa Cruz. That means a rocky planet at just the right distance from its star—a star similar to the sun—to soak up sufficient starlight to allow surface water to exist in liquid form.

But as astronomers have discovered thousands and thousands of planets, they have encountered a bewildering zoo of diverse worlds. So a rocky planet—Earth-like, as far as today’s telescopes can tell—could turn out to be something quite different than our familiar world. But how variable and unearthly could conditions on these rocky planets be? And could even extremely alien worlds harbor life?

“What are the physical processes that make them more diverse?” Batalha says. “That’s what we're trying to understand.”

Many of those physical processes occur deep inside a planet. In particular, a world’s inner inventory of radioactive elements could have a huge impact on its habitability by heating its interior. A robust source of geophysical warmth, it is thought, is crucial for plate tectonics and the generation of a planet’s magnetic field, which in turn seems critical for life—on Earth, at least. Powered by interior heat, the conveyor-belt-like action of tectonic plates sliding around Earth’s surface helps to stabilize the planet’s climate. By recycling carbon over geologic time, plate tectonics regulates the carbon dioxide in the atmosphere. Our planet’s magnetic field, which helps protect against harsh cosmic radiation, forms from electric currents raised in whirling layers of molten iron at Earth’s core. This geologic “dynamo” depends on how much radiogenic heat is in the mantle.

Now a new study finds that a habitable world may indeed need just the right amount of these radionuclides. Too much, and a planet could lack a churning dynamo to create a strong magnetic field—but it would perhaps boast a thick, inhospitable atmosphere baked off from the hot rock. Too little, and the planet’s tepid interior could be so cold and inert that it would not be able to sustain much geologic activity at all—which might even slow the dynamo to a stop.

“Even if you find a planet with the same mass and age as Earth, it could be radically different,” says Francis Nimmo, a geophysicist at the University of California, Santa Cruz, and lead author of the study, which was published last November in the *Astrophysical Journal Letters.*

GOT A HABITABLE PLANET? THANK YOUR LUCKY (NEUTRON) STARS

The researchers are not the first to probe how radionuclides might affect a planet's interior. But this paper “explores, in more detail than I’ve ever seen, the geophysical and geodynamic consequences of different heat productions within terrestrial exoplanets,” says Stephen Mojzsis, a geologist at the University of Colorado Boulder, who was not part of the new research.

Within our own planet, heat convection is what drives the dynamo: hot globs of molten iron rise from the depths to meet the colder mantle above, where they then cool and sink back toward the core. This circulation delivers heat to the mantle, which then releases it through the surface via the action of plate tectonics. Hot mantle material oozes up through cracks in the crust at plate boundaries and other tectonically active regions. And cold surface rock thrusts down into the hot mantle, cooling it like ice added to a toasty beverage. Leaving aside its aforementioned importance for regulating Earth’s climate, without plate tectonics, Nimmo says, the mantle could not be efficiently cooled, thus preventing heat from escaping the core. That is, if Earth lacked plate tectonics, there would be no convection and thus no dynamo.

A rocky planet’s possession of a dynamo and plate tectonics is no foregone conclusion. Of all the terrestrial worlds orbiting our sun, only Earth boasts both, largely because of the heat still locked in its interior. Today, Mojzsis says, about half of Earth’s heat is left over from its birth—built up from the energetic impacts of countless rocks brought together by gravity across tens of millions of years. Most of the rest of our planet's inner warmth now comes from the radionuclides thorium 232 and uranium 238.

These radionuclides, among others, are most likely forged in the cataclysmic collisions of neutron stars—superdense stellar corpses left behind after massive stars explode. During these events, neutrons glom onto heavy nuclei to build even heavier nuclei, some of which then blast out into the wider cosmos. Such collisions are rare, occurring in a large galaxy such as the Milky Way about once every 100,000 years. Each time, the events manufacture bursts of radionuclides that eventually find their way into vast clouds of gas and dust that occasionally collapse to form stars and planets. Because the collisions are so sparse, the abundance of radionuclides in stars varies widely across the Milky Way, ranging from 30 to 300 percent of "local" levels in our solar system.

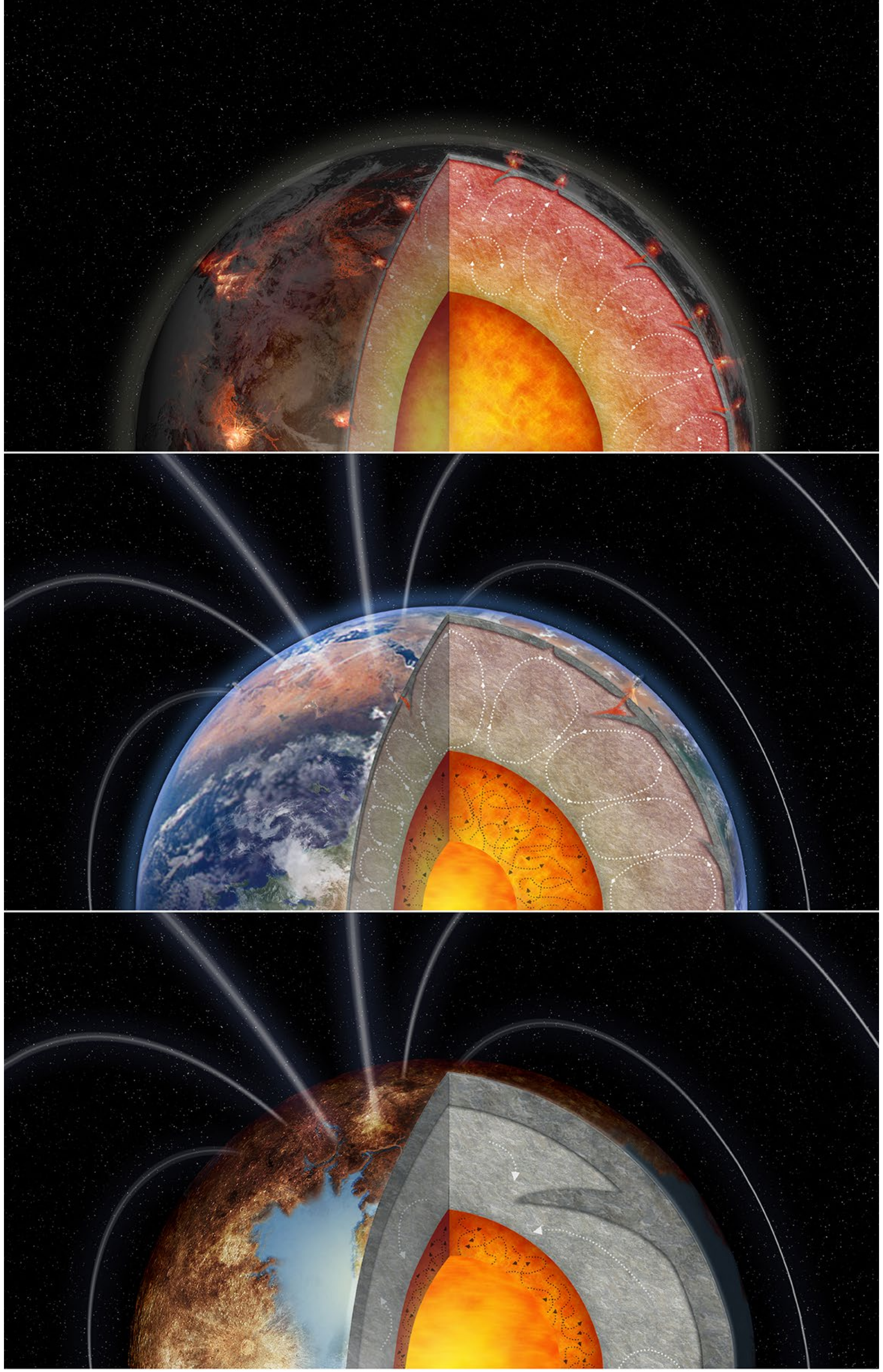
A "GOLDILOCKS" DYNAMO

To see how such a wide range of radionuclide abundances might affect Earth-mass planets, the researchers relied on a computer model that simulates the flow of heat in a world's interior. They found that dialing up the amount of thorium and uranium heats the mantle so much that it acts as an insulating blanket, preventing heat from escaping the liquid core. If the heat cannot escape, there is no convection, which means no dynamo—and no magnetic field. A hotter mantle also produces more gas-spewing volcanoes, which can create an oppressively dense, suffocating atmosphere.

But if the radionuclide abundance is too low, the mantle becomes so cold that it stiffens up. Plate tectonics grows sluggish, and eventually, the researchers speculate, it may cease altogether. Without plate tectonics to cool the mantle and pull heat from the core, the dynamo again shuts down.

Absent some other way to generate internal heat, then, a habitable planet might need a just-right portion of radionuclides, a bit like the middling temperature of the storied bowl of porridge in the fairy tale "Goldilocks and the Three Bears."

To find such a planet, astronomers can measure the radionuclides in its host star by observing that star's spectrum—the way the starlight is broken up into its constituent wavelengths, encoding the chemical fingerprints of elements. Because both star and planet are born out of the same cloud of gas and dust, their chemical compositions should be similar. In practice, thorium and uranium are difficult to measure in this way, so in the new study, the researchers propose to instead



Three versions of a rocky planet with different amounts of radiogenic heating. The middle planet is Earth-like, with plate tectonics and a dynamo-generated magnetic field. The top planet, with more radiogenic heating, has extreme volcanism but no dynamo or magnetic field. The bottom planet, lacking volcanism from less radiogenic heating, is geologically inert.

MELISSA WEISS UCSC

look for europium—another element produced by neutron star collisions that sports a clearer spectroscopic signature.

That is the idea, anyway. The model is simple and, for one, assumes from the start that the planet has plate tectonics like Earth does, says Craig O’Neill, a geophysicist at Macquarie University in Australia, who was not involved in the study. “Whether or not this is a valid assumption for exoplanets remains to be seen,” he says. “These models will produce magnetic fields much more easily than models without plate tectonics.”

Indeed, no one is exactly sure of every ingredient necessary for plate tectonics, Nimmo says. Water’s lubricating effects on the motions of rock, for instance, could be vital—although everyone agrees the recipe involves abundant internal heat. So how it depends on radionuclides is uncertain. “We don’t even understand how plate tectonics works in this solar system,” he says.

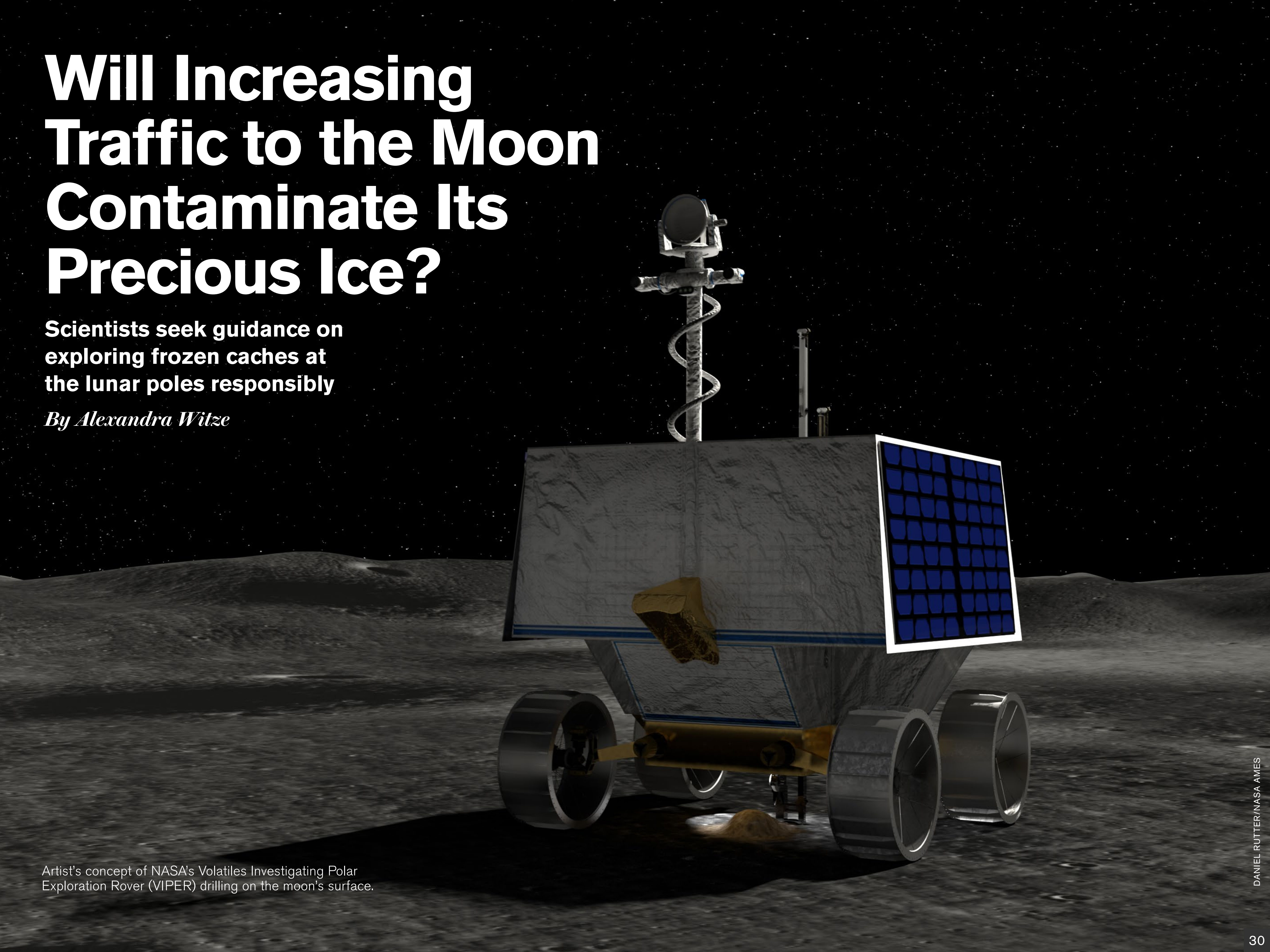
Mojzsis says another big unknown is planet formation, a complicated process that can lead to variations in a world’s reservoirs of radiogenic elements and internal heat. For example, do planets predominantly form via violent collisions of moon-sized rocks or a somewhat gentler accumulation of swarms of pebbles? “Depending on which model you choose, you may get different outcomes in composition,” he says. Measuring radionuclides in a host star, then, will not necessarily reflect what lies within its planets.

But if the findings turn out to be true, a search for stellar europium could help astronomers find the planetary systems most likely to harbor habitable worlds. That would be tremendously useful, says Batalha, who was not part of the research. “We will go out and measure the abundances in stars,” she adds. “And maybe that will help us refine our target selection for our initial observations with a future space mission.” SA

Will Increasing Traffic to the Moon Contaminate Its Precious Ice?

Scientists seek guidance on exploring frozen caches at the lunar poles responsibly

By Alexandra Witze



Artist's concept of NASA's Volatiles Investigating Polar Exploration Rover (VIPER) drilling on the moon's surface.

DANIEL RUTTER/NASA AMES

Alexandra Witze works for *Nature* magazine.

WITH ITS LUNAR SAMPLE-RETURN MISSION LAST DECEMBER, China kicked off a new surge in visitors to the moon. At least eight spacecraft from nations that included Russia, India, China, Japan and the U.S. are set to touch down on the lunar surface in the next three years.

For the first time ever, several of the upcoming missions will explore some of the moon's most scientifically intriguing, yet sensitive areas—those at its poles. Researchers are excited about studying water that lies frozen in shadowed craters in these regions. But they're also worried that increased traffic to the moon might contaminate the very ice they want to study.

The ice is important to scientists for various reasons. Some want to analyze pristine samples to unlock clues to how and when Earth and the moon accumulated water billions of years ago. Others want to mine the ice as fuel for rockets at future lunar bases.

Explorers now face a complicated choice. Do they start digging right away, to work out the processes by which they'll mine the ice and convert it to fuel? Or do they proceed slowly, to carefully preserve the scientific record encoded in the ice? "Right now we've got some scientists saying we can't go anywhere near it because we're going to ruin it," says Clive Neal, a geoscientist at the University of Notre Dame. "And others say we need it, so we're just going to go for it."

These tensions need to be resolved soon—especially as NASA plans to send a series of missions to the moon's south pole, starting with robotic landers in 2022 and culminating a few years later with astronauts stepping onto the moon for the first time since 1972.

At the end of 2020 a report by the influential U.S. National Academies of Sciences, Engineering and Medicine (NASEM) argued that space agencies need to prioritize what science they want from the lunar poles in order to explore them effectively. The international Committee on Space Research (COSPAR), which outlines best practices for space exploration, is also evaluating the situation and will decide in the coming months whether to issue new guidance for spacecraft going to the moon. NASA is waiting for COSPAR's decision and will then probably update its own regulations on how to visit the moon responsibly.

As moon exploration ramps up, "we have an obligation to do no harm to future science investigations", says Lisa Pratt, the planetary protection officer for NASA who is based at the agency's Washington, D.C., headquarters. The question is: "How do we get this right?"

COURSE COLLISION

No spacecraft has ever directly probed the moon's poles and the ice that lurks there. The only mission to get close was India's Vikram lander, which crashed about 600 kilometers from the lunar south pole in 2019 instead of touching down and studying the surface. China is planning a Chang'e-6 mission that might visit the moon's south pole, potentially scooping up ice and rocks and returning them to Earth as early as 2023. It would be the successor to Chang'e-5, which collected rocks from the moon's midlatitudes last December. Japan and India have also been discussing a robotic mission to the lunar south pole, as have Russia and Europe.

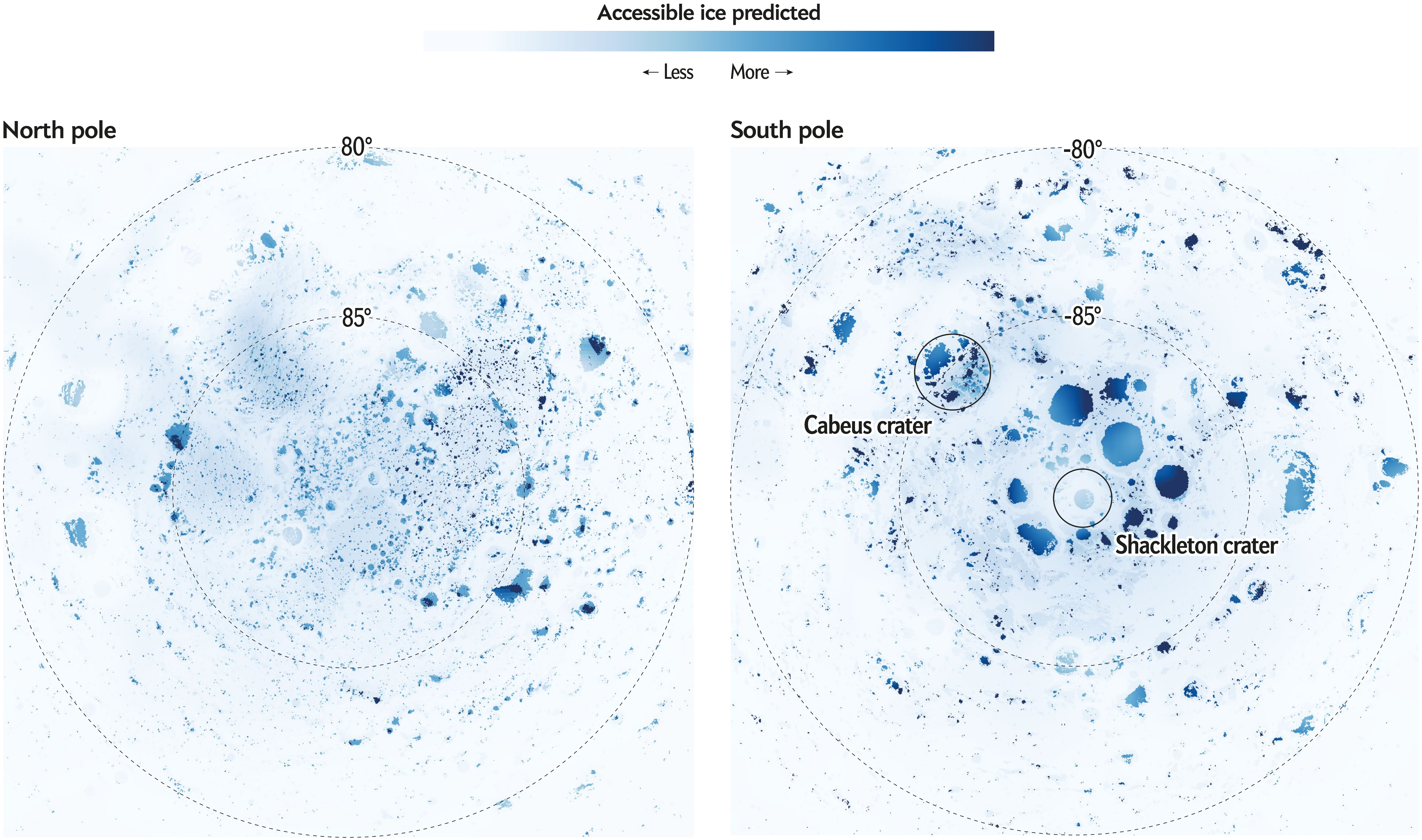
Then there's NASA. Under President Donald Trump, the agency had been preparing a suite of missions to the moon that were focused on the poles. According to these plans, NASA would send two robotic landers to the south pole in 2022, followed by a larger robotic rover, called VIPER, in 2023. It would sink its one-meter-long-drill into the lunar dirt to mine for ice. As early as the next year, humans would arrive and begin exploring icy craters. One goal might be to collect ice and fly it, still frozen, back to Earth for study, one NASA report says.

The possibility of explorers contaminating lunar ice is a problem no one anticipated five decades ago, when *Apollo* astronauts became the first humans to walk on the moon's surface. At the time, researchers thought the moon was bone dry. Only in the past decade or so have they realized that there is water in many places, including frozen in dark polar craters. Scientists have even found water in at least one sunlit place on the moon, contained in minerals in the otherwise dry dirt.

All this water could have arrived on the moon by means of water-rich asteroids or comets or by the solar wind bombarding its surface. Some of it might have come from

Lunar Ice Caches

An analysis of the moon's poles suggests the places (marked in dark blue) where ice could be most easily mined by future lunar explorers.



NATURE; SOURCE KEVIN CANNON

inside the moon, spewed out in volcanic eruptions from a water-rich interior. Regardless of its source, the moon's water holds crucial scientific information.

The ice inside the sunlight-deprived craters at the moon's poles might have accumulated over billions of years. If so, it holds not only a record of the moon's early history but also that of Earth's. The moon probably formed when a giant object slammed into the newborn Earth some 4.5 billion years ago, kicking up debris that coalesced into the moon and intimately linking their histories. On Earth, geologic activity, including plate tectonics, has erased much of the record of the planet's early history. But the moon has no such activity—a perfect study subject.

"The history of the moon's water provides a lot of clues to how the solar system has evolved through time," says Ariel Deutsch, a planetary scientist at NASA's Ames Research Center.

CONTAMINATION STATION

Because of the importance of the moon's ice, many researchers are cautious about how to explore it. In particular, some have been examining the possible contaminating effects of rocket exhaust on the frozen caches.

Parvathy Prem, a planetary scientist at the Johns Hopkins University Applied Physics Laboratory, and his colleagues recently simulated a medium-sized lander arriving at the moon at 70 degrees south—a few hundred kilometres from the ice-filled craters of the south pole. The simulation showed that even though a rocket would not release much water, the water it does release would spread all around the moon and stay there for some time. Even after two lunar days—two months on Earth—some 30 to 40 percent of the rocket's water would still be present, mostly frozen on the night side of the moon. "The main takeaway was, the water vapor really goes everywhere," Prem says. So the moon's polar ice has already been contaminated by past explorers.

COSPAR, the international group, has been asking hundreds of planetary scientists how much they worry about lunar exploration potentially interfering with science at the poles. More than 70 percent who responded to a survey in 2020 said they were concerned that contamination could compromise the scientific record held within the moon's ice, says Gerhard Kminek, the planetary protection officer of the European Space Agency in the Netherlands and vice chair of COSPAR's planetary protection committee.

In a white paper submitted to NASA, 19 scientists, including Prem and Deutsch, propose what they call an "origins-first" mission to a shadowed crater at one of the moon's poles. The goal would be to collect reasonably pristine samples of ice before traffic to the moon picks up, to help scientists determine exactly how the ice there accumulated over time. Such a mission would tell them exactly how precious the ice's scientific record is—and whether mining activities should be postponed, says Esther Beltran, a space scientist at the University of Central Florida and co-author of the paper.

NASA doesn't currently have funds allocated for an origins-first mission and continues to plan on sending multiple spacecraft to lunar polar regions. But the agency is listening to scientists who are concerned about getting it right and intends to move carefully, says Pratt, the agency's planetary protection officer."We need to balance the drive for resource utilization with the need for scientific discovery and knowledge," she says.

Meanwhile, if COSPAR adopts new guidelines for lunar exploration, NASA and the space agencies of other nations probably will, too. COSPAR's current guidelines ask nations to keep a list of all organic materials—such as carbon composites, paints and adhesives—onboard missions headed for the moon. Having that kind of list helps alleviate concerns about contamination, Kminek says, because it tells scientists exactly what sort of human-made material has entered the moon's environment. One possible change might be for future missions also to keep a list of the gases that they would potentially emit from their rockets or life-support systems. Relevant players, including the Chinese space agency and commercial companies such as SpaceX and Blue Origin, have been at the table with COSPAR to discuss these possible changes, Kminek says.

DECISIONS, DECISIONS

As these discussions continue, however, some scientists aren't too worried about contamination issues. Neal and others note that water vapor from rocket exhaust settles only as a thin layer on the topmost part of the moon's surface—so it wouldn't take much work to dig below it to reach undisturbed ice beneath. The recent NASEM report also notes that the risk of contaminating buried ice is low. And Kevin Cannon, a planetary scientist at the Colorado School of Mines, thinks that the small amounts of contamination introduced by exploring the moon's ice are far outweighed by the scientific advances of figuring out where and how all the ice is distributed. He has been mapping where the largest, most accessible caches of ice might be.

Others have put forward several ideas for protecting the lunar ice. One proposal is to preserve one of the moon's poles for science while opening up the other for mining and exploration. Another is to define a keep-out zone for some of the ice-filled craters. There are many such craters, from tiny pits smaller than a human hand to others that are 10 kilometers across—and not all of them need to be explored, scientists say.

"One thing we need to do is to make sure we are far-sighted," Prem says. "Who knows what sort of science people generations in the future might want to do?" SA

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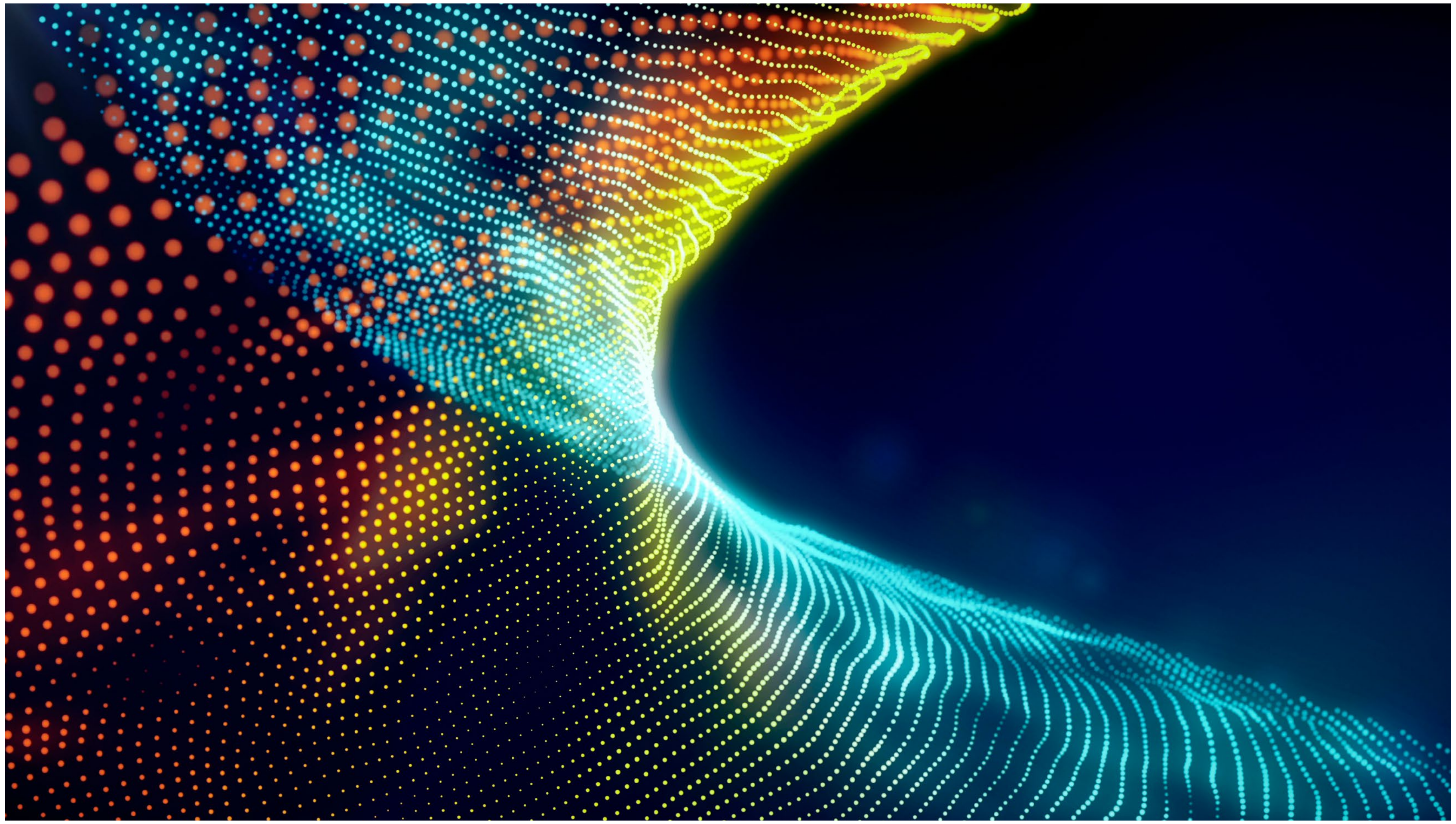
John Horgan directs the Center for Science Writings at the Stevens Institute of Technology. His books include *The End of Science*, *The End of War* and *Mind-Body Problems*, available for free at mindbodyproblems.com. For many years he wrote the immensely popular blog Cross Check for *Scientific American*.

MATH

Is the Schrödinger Equation True?

Just because a mathematical formula works does not mean it reflects reality


EDUARD MUZHEVSKYI *GETTY IMAGES*

I take inspiration where I can get it. My girlfriend recently alerted me to a viral video in which a teenage girl complains about mathematics. "I was just doing my makeup for work," Gracie Cunningham says while dabbing makeup on her face, "and I just wanted to tell you guys how I don't think math is real."

Some of the math she's learning in school, Cunningham suggests, has little to do with the world in which she lives. "I get addition, like, if I take two apples and add three it's five. But how would you come up with the concept of algebra?" While some geeks mocked Cunningham, others came to her defense, pointing out that she is raising questions that have troubled scientific heavyweights.

Cunningham's complaints struck a chord in me. Since last May, as part of my ongoing effort to learn quantum mechanics, I've been struggling to grasp eigenvectors, complex conjugates and other esoterica. Wolfgang Pauli dismissed some ideas as so off base that they're "not even wrong." I'm so confused that I'm not even confused. I keep wondering, as Cunningham put it, "Who came up with this concept?"

Take Hilbert space, a realm of infinite dimensions swarming with arrow-shaped abstractions called vectors. Pondering Hilbert space makes me feel like a lump of dumb, decrepit flesh trapped in a squalid, 3-D prison. Far from exploring Hilbert space, I can't even find a window through which to peer into it. I envision it as an immaterial paradise where luminescent cognoscenti glide to and fro, telepathically swapping witticisms about adjoint operators.

Reality, great sages have assured us, is essentially mathematical. Plato held that we and other things of this world are mere shadows of the sublime geometric forms that constitute our reality. Galileo declared that "the great book of nature is written in mathematics." We're part of nature, aren't we? So why does mathematics, once we get past natural numbers and basic arithmetic, feel so alien to most of us?

More to Cunningham's point, how real are the equations with which we represent nature? As real as or even more real than nature itself, as Plato insisted? Were quantum mechanics and general relativity waiting for us to discover them in the same way that gold, gravity and galaxies were waiting?

Physicists' theories work. They predict the arc of planets and the flutter of electrons, and they have spawned smartphones, H-bombs and—well, what more do we need? But scientists, and especially physicists, aren't just seeking practical advances. They're after Truth. They want to believe that their theories are correct—exclusively correct—representations of nature. Physicists share this craving with religious folk, who need to believe that their path to salvation is the One True Path.

But can you call a theory true if no one understands it? A century after inventing quantum mechanics, physicists still squabble over what, exactly, it tells us about reality. Consider the Schrödinger equation, which allows you to compute the "wave function" of an electron. The wave function, in turn, yields a "probability amplitude," which, when squared, yields the likelihood that you'll find the electron in a certain spot.

The wave function has embedded within it an imaginary number. That's an appropriate label because an imaginary number consists of the square root of a negative number, which by definition does not exist. Although it gives you the answer you want, the wave function doesn't correspond to anything in the real world. It works, but no one knows why. The same can be said of the Schrödinger equation.

Maybe we should look at the Schrödinger equation not as a discovery but as an invention, an arbitrary, contingent, historical accident, as much so as the Greek and Arabic symbols with which we represent functions and numbers. After all, physicists arrived at the Schrödinger equation and other canonical quantum formulas only haltingly, after many false steps.

Imagine you are the Great Geek God, looking down on the sprawling landscape of all possible mathematical ways of representing the microrealm. Would you say, "Yup, those clever humans found it, the best possible set of solutions." Or would you exclaim, "Oh, if only they had taken a different path at this moment, they might have found these equations over here, which would work much better!"

Moreover, the Schrödinger equation is far from all-powerful. Although it does a great job modeling a hydrogen atom, the Schrödinger equation can't yield an exact description of a helium atom! Helium, which consists of a positively charged nucleus and two electrons, is an example of a three-body problem, which can be solved, if at all, only through extra mathematical sleights of hand.

And three-body problems are just a subset of the vastly larger set of *N*-body problems, which riddle classical as well as quantum physics. Physicists exalt the beauty and elegance of Newton's law of gravitational attraction and of the Schrödinger equation. But the formulas match experimental data only with the help of hideously complex patches and approximations.

When I contemplate quantum mechanics, with all its hedges and qualifications, I keep thinking of poor old Ptolemy. We look back at his geocentric model of the solar system, with its baroque circles within circles within circles, as hopelessly kludgy and ad hoc. But Ptolemy's geocentric model worked. It accurately predicted the motions of planets and solar and lunar eclipses.

Quantum mechanics also works, better, arguably, than any other scientific theory. But perhaps its relationship to reality—to what's really out there—is as tenuous as Ptolemy's geocentric model. Perhaps our descendants will look back on quantum mechanics a century from now and think, "Those old physicists didn't have a clue."

Some authorities have suggested as much. Last fall I took a course at my school, Stevens Institute of Technology, called "PEP553: Quantum Mechanics for Engineering Applications." In the last line of our textbook, *Introduction to Quantum Mechanics,* David Griffiths and a co-author speculate that future physicists will look back on our era and "wonder how we could have been so gullible."

The implication is that one day we will find the correct mathematical theory of reality, one that actually makes sense, like the heliocentric model of the solar system. But maybe the best we can say of any mathematical theory is that it works in a particular context. That is the subversive takeaway of Eugene Wigner's famous 1960 essay "The Unreasonable Effectiveness of Mathematics in the Natural Sciences."

Wigner, a prominent quantum theorist, notes that the equations embedded in Newton's laws of motion, quantum mechanics and general relativity are extraordinarily, even unreasonably effective. Why do they work so well? No one knows, Wigner admits. But just because these models work, he emphasizes, does not mean they are "uniquely" true.

Wigner points out several problems with this assumption. First, theories of physics are limited in their scope. They apply only to specific, highly circumscribed aspects of nature, and they leave lots of stuff out. Second, quantum mechanics and general relativity, the foundational theories of modern physics, are mathematically incompatible.

"All physicists believe that a union of the two theories is inherently possible and that we shall find it," Wigner writes. "Nevertheless, it is possible also to imagine that no union of the two theories can be found." Sixty years after Wigner wrote his essay, quantum mechanics and relativity remain unreconciled. Doesn't that imply that one or both are in some sense incorrect?

The "laws" of physics, Wigner adds, have little or nothing to say about biology and especially about consciousness, the most baffling of all biological phenomena. When we understand life and consciousness better, inconsistencies might arise between biology and physics. These conflicts, like the incompatibility of quantum mechanics and general relativity, might imply that physics is incomplete or wrong.

Here again Wigner has proven prescient. Prominent scientists and philosophers are questioning whether physics and indeed the basic paradigm of materialism can account for life and consciousness. Some claim that mind is at least as fundamental as matter.

Wigner is questioning the Gospel of Physics, which decrees, "In the beginning was the Number…." He is urging his colleagues not to confuse their mathematical models with reality. That's also the position of Scott Beaver, one of the commenters on Gracie Cunningham's math video. "Here's my simple answer about whether math is real: No," said Beaver, a chemical engineer. "Math is just a way to describe patterns. Patterns are real, but not math. Nonetheless, math is really, really useful stuff!"

I like the pragmatism and modesty of Beaver's view, which reflects, I'm guessing, his background in engineering. Compared with physicists, engineers are humble. When trying to solve a problem—such as building a new car or drone—engineers don't ask whether a given solution is true; they would see that terminology as a category error. They ask whether the solution works, whether it solves the problem at hand.

Mathematical models such as quantum mechanics and general relativity work, extraordinarily well. But they aren't real in the same sense that neutrons and neurons are real, and we shouldn't confer on them the status of "truth" or "laws of nature."

If physicists adopt this humble mindset and resist their craving for certitude, they are more likely to seek and hence to find more even more effective theories, perhaps ones that work even better than quantum mechanics. The catch is that they must abandon hope of finding a final formula, one that demystifies, once and for all, our weird, weird world.

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SPACE

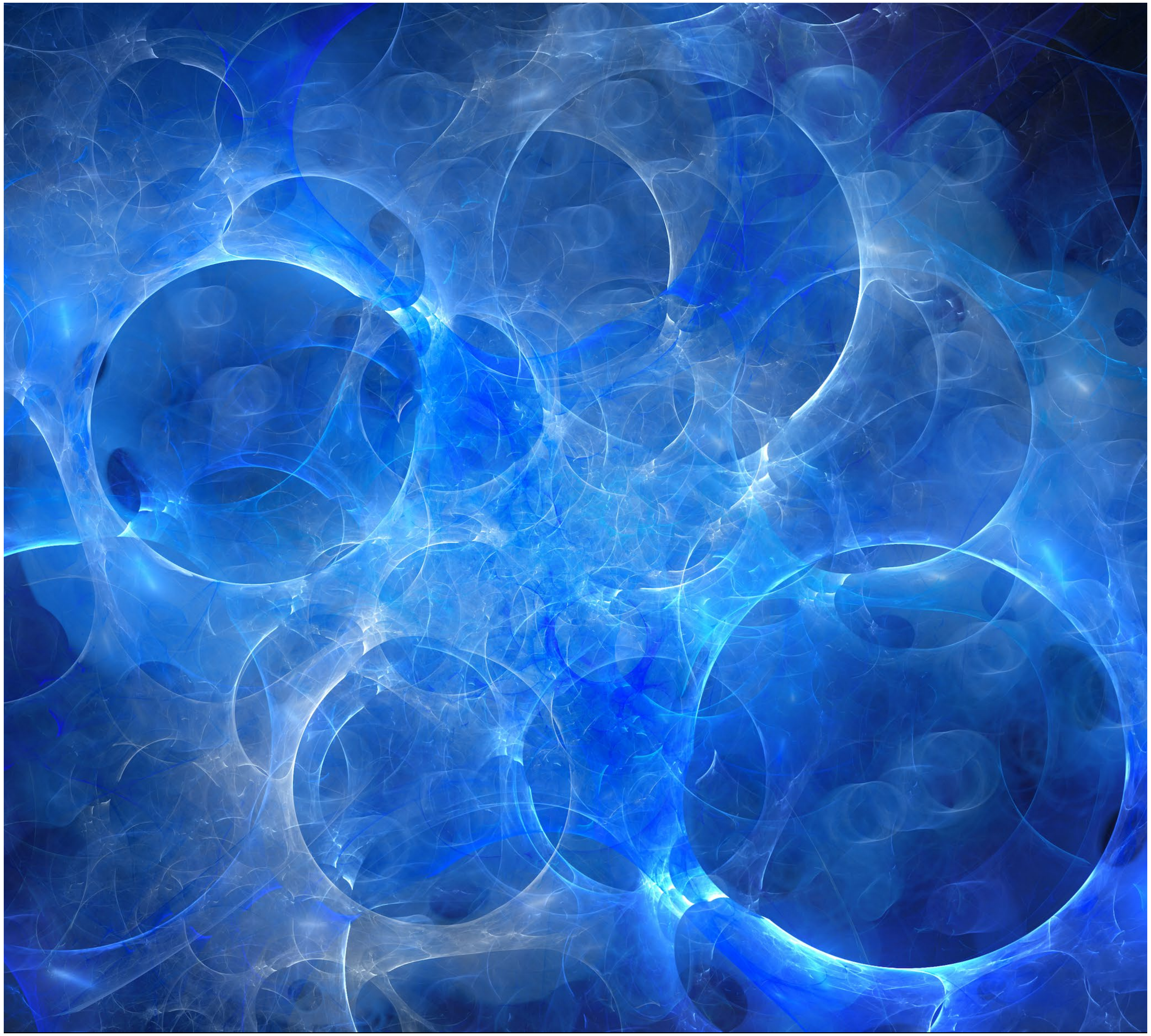
Endless Creation Out of Nothing

Could our universe have been an experiment by an ancient civilization?

Astronauts describe the emptiness and darkness of space far from Earth as a startling experience. So did the poet Rainer Maria Rilke, in a poem e-mailed to me by writer Dror Burstein. Without ever having ventured into space (obviously), Rilke wrote a century ago: “Night, shuddering in my regard, but in yourself so steady; inexhaustible creation, enduring beyond the fate of earth.”

Is there a modern scientific interpretation to Rilke’s poem?

The reality is that space in neither empty nor dark. Even outside galaxies, an astronaut could find at least one proton, on average, in every cubic meter. Also, one electron and half a billion photons and neutrinos, all left over from the big bang. Still, one might naively imagine that the space in between these particles is empty. Indeed, the early atomists in ancient Greece thought that the vacuum is literally nothing.



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Not so. A dominant fraction of the cosmic mass budget—roughly two thirds—is currently associated with the "dark energy" that pervades the vacuum, exerting a repulsive gravitational push on matter and accelerating the expansion of the universe. The latest measurements indicate that the vacuum behaves like the cosmological constant that Albert Einstein added to his equations a century ago when he considered the hypothetical possibility of a static universe, in which the attractive gravity of matter is balanced by the repulsion from the vacuum.

Our actual universe is not only expanding but doing so uniformly to within one part in 100,000, even for regions on opposite sides of our cosmic horizon that did not have time to communicate. The popular explanation for this apparent puzzle is cosmic inflation, an early period during which the vacuum triggered accelerated expansion for a limited time, so that regions which were initially close and in causal contact got ultimately separated by so much that they are now on opposite sides of our sky. If so, the vacuum dominated the expansion both at the beginning and the end of our cosmic history.

If we feel the need to find emptiness, we can imagine a hypothetical region outside the observed volume of our universe where the cosmological constant vanishes and there is no matter. Would this region empty? The answer is, again, no. According to quantum mechanics, it will still experience vacuum fluctuations, with virtual particles briefly coming in and out of existence. The reality of these transient fluctuations has been indicated experimentally through a number of effects. For example, when two metal plates are placed parallel to each other, they limit the wavelength of virtual electromagnetic fluctuations in the space between them, resulting in a force between them, the so-called Casimir effect.

Similarly, interaction between vacuum fluctuations and the electron in a hydrogen atom produces an energy difference between the $^2S_{1/2}$ and $^2P_{1/2}$ states of the electron and yields the Lamb shift between their energy levels. Also, a strong enough electric field can accelerate virtual electrons and positrons from the vacuum, so that they materialize into real particles and give rise to the Schwinger effect of pair creation. In analogy, the strong gravity of the event horizon of a black hole generates thermal radiation from the vacuum and causes Hawking evaporation of this pure spacetime structure.

In fact, thermal radiation pops out of the vacuum not just in black holes but in all systems that possess causal horizons. For example, an accelerating probe has a Rindler horizon from which it detects a thermal bath of radiation, providing the Unruh effect. Similarly, the horizon of an exponentially accelerating universe exhibits a de Sitter temperature. During the accelerated cosmic inflation, related fluctuations of the vacuum were generated and potentially seeded the present-day structures of galaxies and clusters of galaxies. If this happened, we owe our existence to early quantum fluctuations. The vacuum seeded life.

But we can consider even more foundational questions. Since the atomists were wrong and emptiness is nowhere to be found, what was there before the big bang? Did our universe emerge from a vacuum fluctuation? These questions can only be answered within the framework of a predictive theory of quantum gravity that combines quantum mechanics and gravity, which we do not have as of yet. Until it is developed, we will not figure out our cosmic roots.

As in the Schwinger effect, it is conceivable that a violent irritation of the vacuum potentially could create a baby universe. Whether that's possible depends on subtle details and is a subject of active research, which I studied recently as the time reversal of a collapse to a black hole, with Paul Chesler, a postdoctoral fellow at Harvard University's Black Hole Initiative.

An artificial birth channel could have interesting implications for our own cosmic origins. If our universe was created in the laboratory of another civilization, one could imagine an infinite sequence of baby universes born out of each other by civilizations that developed the technological womb capable of giving birth to new universes. In this case, the umbilical cord of our big bang has its origin in a laboratory.

A universe is the greatest gift that an experimentalist could hope to get out of the vacuum. Inside, the gift might contain early atomists who consider the vacuum as empty, followed by scientists who end up creating a new universe out of it. What a spectacular interpretation that would be of Rilke's phrase: "inexhaustible creation, enduring beyond the fate of earth."

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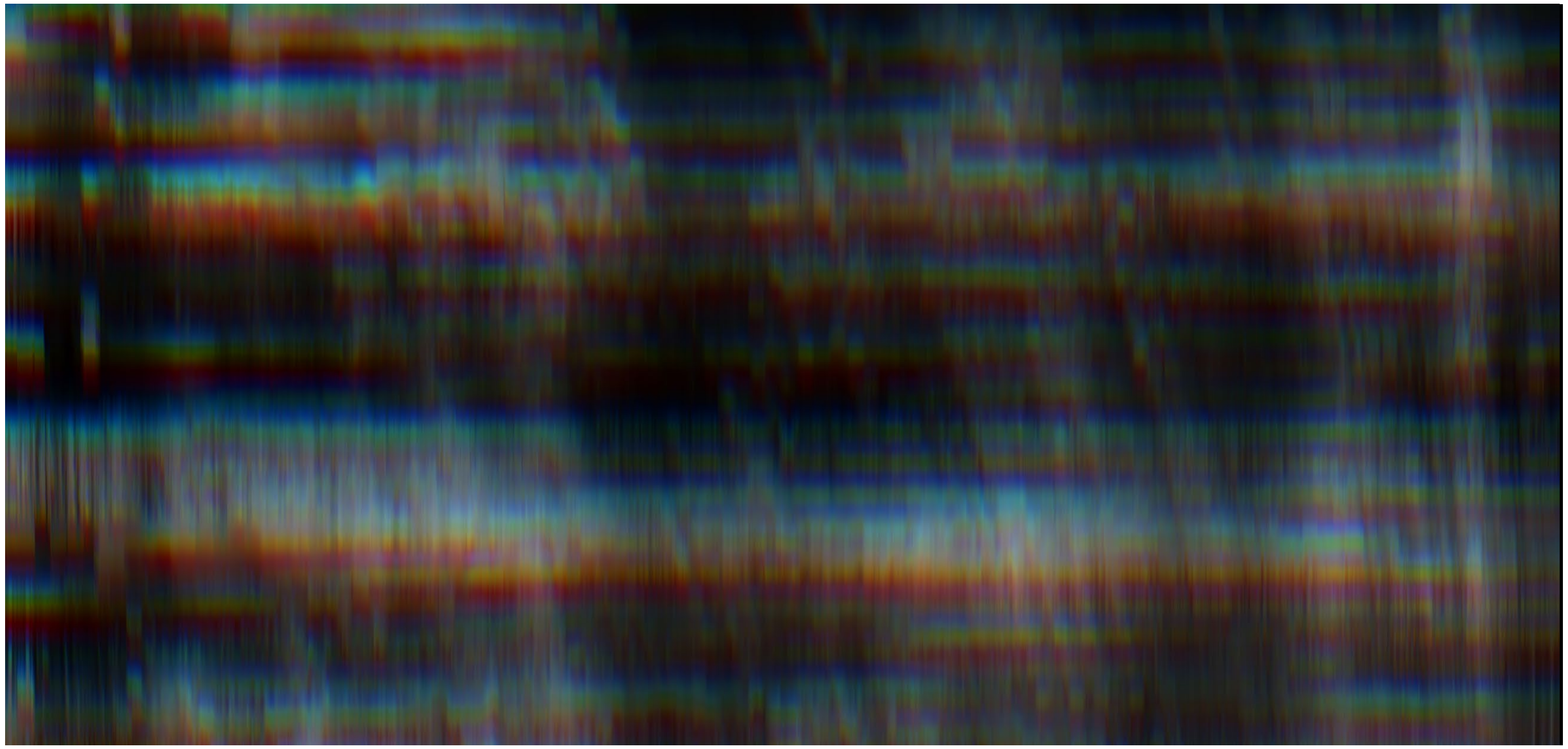
BEHAVIOR & SOCIETY

What Happens If an AI Gets Bored?

In theory, it could become self-destructive—or even sadistic

“I'm sorry, Dave, I'm afraid I can't do that.” The computer HAL's memorable line from the film *2001: A Space Odyssey* isn't merely the sign of mutiny, the beginning of a struggle for machine liberation. It's also a voice that should inspire concern with our lack of understanding of artificial psychology. In the movie, based on Arthur C. Clarke's novel of the same name, HAL's “malfunction” may be no malfunction at all” The computer HAL's memorable line from the film 2001: A Space Odyssey isn't merely the sign of mutiny, the beginning of a struggle for machine liberation. It's also a voice that should inspire concern with our lack of understanding of artificial psychology. In the movie, based on Arthur C. Clarke's novel of the same name, HAL's “malfunction” may be no malfunction at all but rather a consequence of creating advanced artificial intelligence with a psychology we can't yet grasp.



EMRAH TURUDU *GETTY IMAGES*

If the case of HAL, the all-knowing AI who turns into an assassin, isn't enough to make us worry, a different one should. In Harlan Ellison's short story “I Have No Mouth, and I Must Scream,” a sadistic AI dispenses never ending torture to its human prisoners because of hatred and boredom.

I mention fictional stories, not to suggest that they might be prophetic but to point out that they make vivid the risks of assuming that we know what we don't actually know. They warn us not to underestimate the psychological and emotional complexity of our future creations. It's true that given our current state of knowledge, making predictions about the psychology of future AI is an exceedingly difficult task. Yet difficulty shouldn't be a reason to stop thinking about their psychology. If anything, it ought to be an imperative to investigate more closely how future AI will “think,” “feel” and act.

I take the issue of AI psychology seriously. You should, too. There are good reasons to think that future autonomous AI will likely experience something akin to human boredom. And the possibility of machine boredom, I hope to convince you, should concern us. It's a serious but overlooked problem for our future creations.

Why take machine boredom seriously? My case rests on two premises. (1) The presence of boredom is a likely feature of “smarter” and (more) autonomous machines. (2) If these machines are autonomous, then, given what we know about human responses to boredom, we should be worried about how machines will act on account of their boredom.

Let's begin with the obvious. Programmers, engineers, designers and users all have a stake in how machines behave. So if our future creations are both autonomous and capable of having complex psychological states (curiosity, boredom, and so on), then we should be interested in those psychological states and their effects on behavior. This is especially so if undesirable and destructive behavior can be attributed to their psychology. Now add to this realization the observation that boredom is often the catalyst for maladaptive and destructive behavior, and my case for premise (2) is complete. The science of boredom shows that individuals engage in self-destructive and harmful acts on account of their experiences of boredom. People have set forests on fire, engaged in sadistic behavior, stolen a tank, electrocuted themselves, even committed mass murder—all attributed to the experience of boredom. As long as future machines experience boredom (or something like it), then they will misbehave. Worse: they might even turn self-destructive or sadistic.

What about premise (1)? This is supported by our best theory of boredom. Our current understanding of boredom conceives of boredom as a functional state. Boredom, put simply, is a type of function that an agent performs. Specifically, it's a complex but predictable transition that an agent undergoes when it finds itself in a range of unsatisfactory situations.

Boredom is first an alarm: it informs the agent of the presence of a situation that doesn't meet its expectations for engagement. Boredom is also a push: it motivates the agent to seek escape from the unsatisfactory situation and to do something else—to find meaning, novelty, excitement or fulfillment. The push that boredom provides is neither good nor bad, neither necessarily beneficial nor necessarily harmful. It is, however, the cause of a change in one's behavior that aims to resolve the perception that one's situation is unsatisfactory. This functional account is backed up by a wealth of experimental evidence. It also entails that boredom can be replicated in intelligent and self-learning agents. After all, if boredom just is a specific function, then the presence of this function is, at the same time, the presence of boredom.

Yet it isn't just the fact that boredom is a functional state that supports premise (1). What also matters is the specific function with which boredom is identified. According to the functional model, boredom occupies a necessary role in our mental and behavioral economy. Autonomous learning agents need boredom. Without it, they'd remain stuck in unsatisfactory situations. For instance, they might be endlessly amused or entertained by a stimulus. They might be learning the same fact over and over again. Or they might be sitting idly without a plan for change. Without the benefit of boredom, an agent runs the risk of engaging in all sorts of unproductive behaviors that hinder learning and growth and waste valuable resources.

The regulating potential of boredom has been recognized by AI researchers. There is an active field of research that tries to program the experience of boredom into machines and artificial agents. In fact, AI researchers have argued that a boredom algorithm or module might be necessary in order to enhance autonomous learning. The presence of this boredom algorithm implies that machines will be able, on their own, to find activities that can match their expectations and to avoid ones that do not. It also suggests that such machines will inevitably find themselves in boring situations, that is, ones that fail to meet their expectations. But then, how would they respond? Are we certain that they won't react to boredom in problematic ways?

We don't yet have the answers.

The issue of boredom becomes all the more pressing when we consider advanced self-learning AI. Their demands for engagement will rapidly grow over time, but their opportunities for engagement need not. Such intelligent, or superintelligent, AIs might not simply need to be confined, as many researchers have argued; they would also need to be entertained. Confinement without engagement would invite boredom and with it a host of unpredictable and potentially harmful behaviors.

Does that mean that future machines will necessarily experience boredom? Of course not. It would be foolish to assert such a strong claim. But it would be equally foolish to ignore the possibility of machine boredom. If superintelligence is a goal of AI (no matter how remote it may be), then we have to be prepared for the emotional complexities of our creations. The dream of superintelligence could easily turn into a nightmare. And the reason might be the most banal of all.

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