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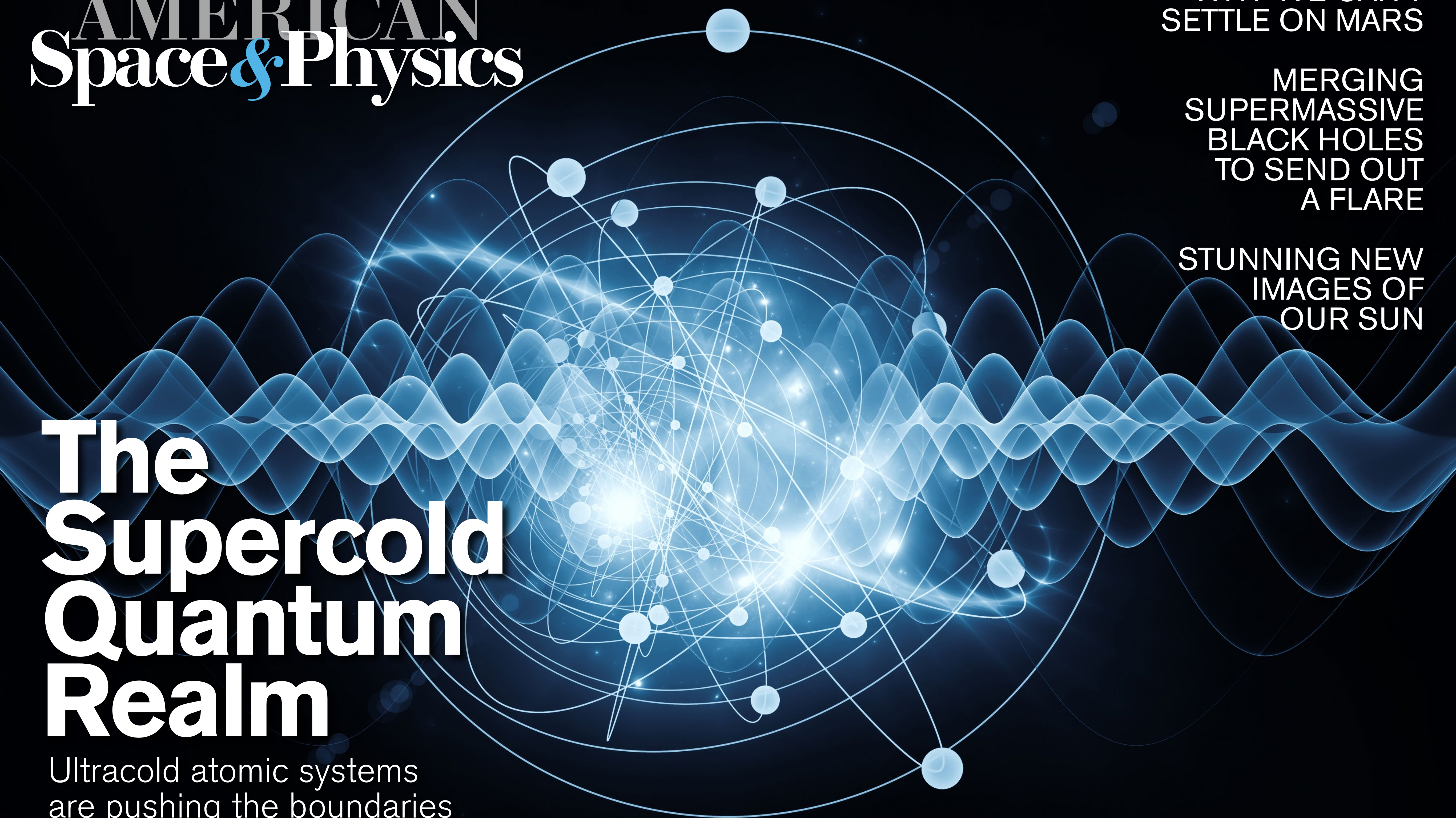

Plus:

WHY WE CAN'T SETTLE ON MARS

MERGING SUPERMASSIVE BLACK HOLES TO SEND OUT A FLARE

STUNNING NEW IMAGES OF OUR SUN

The Supercold Quantum Realm

Ultracold atomic systems are pushing the boundaries of known physics and may even set the stage for quantum computing

WITH COVERAGE FROM **nature**

LIZ TORMES

The Most Mercurial Field of All

In early March, *Scientific American* put the finishing touches on a very exciting collector's edition entitled "Quantum Universe," due out on newsstands at the end of April (not so subtle sales pitch there). In assembling and editing the diverse articles for that issue, I came to notice a common theme in the field of quantum physics: the sense that our grasp, from an observational standpoint, of the quantum universe is tenuous and fleeting—the second you try to observe entanglement, the wave function collapses. Because of this phenomenon, researchers are desperate to devise new ways to gather quantum measurements. And so the discipline of ultracold quantum physics has proved a very satisfying direction of research. As Karmela Padavic-Callaghan writes in this issue's cover story, investigators can manipulate superchilled atoms and use them as models for quantum systems (see "The Coolest Physics You've Ever Heard Of"). Having such control over a quantum experiment is gratifying.

Elsewhere in this issue, planetary scientist Carolyn Porco gives an account of corresponding with Carl Sagan about capturing an image of Earth from space (see "How the Celebrated 'Pale Blue Dot' Image Came to Be"), and Nola Taylor Redd reports on another compelling galactic image: two merging black holes that are sending whorls of dust and gas into view (see "Meet 'Spikey,' a Possible Pair of Merging Supermassive Black Holes"). Some things in the universe are very concrete indeed.

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SPACE & PHYSICS

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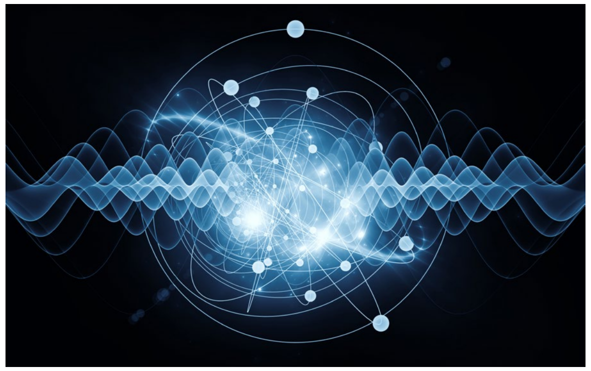

GETTY IMAGES

On the Cover

Ultracold atomic systems are pushing the boundaries of known physics and may even set the stage for quantum computing

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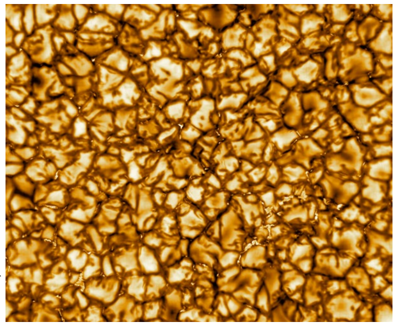

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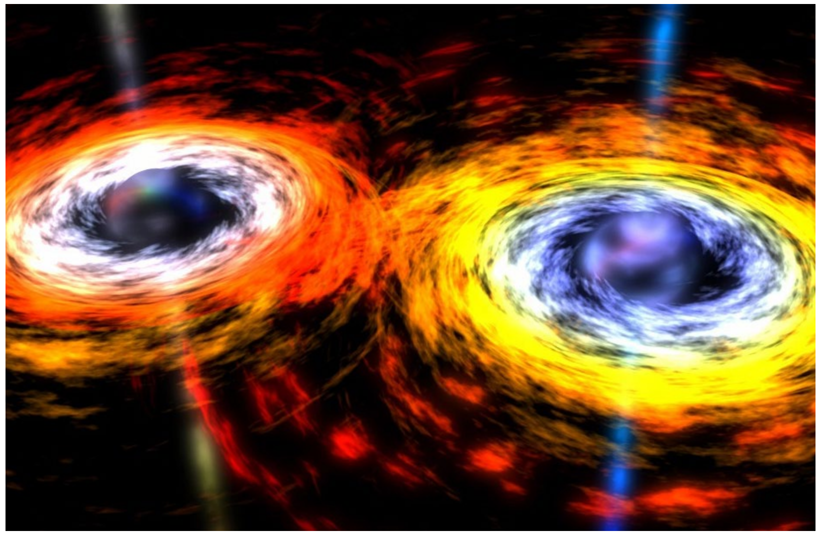

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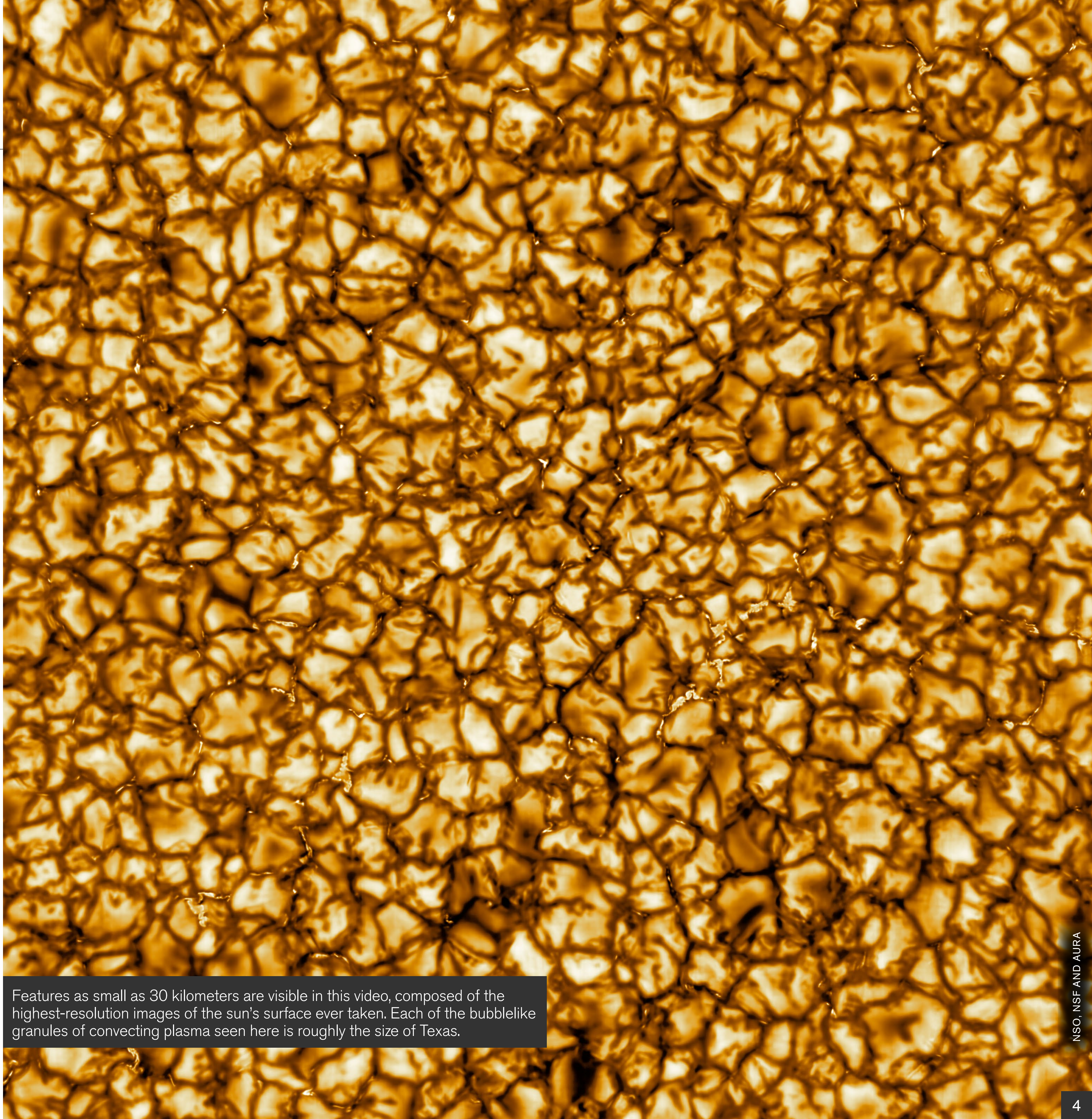
Home Star Stunner: Best-Ever Images of Solar Surface Herald New Era

Scientists have released the first pictures from a new telescope in Hawaii, one of three missions expected to redefine our understanding of our home star in the 2020s

Why is the sun's outer atmosphere so much hotter than its surface? What drives its 11-year cycle of magnetic activity? And how does its solar wind propagate out into the solar system? Scientists hope to answer all these questions and more in the coming decade, thanks to an armada of new missions that will scrutinize the sun in more detail than ever before. With the debut of two unprecedented spacecraft and the largest ground-based solar observatory ever built, research into our home star is set to reach new heights.

One of the two spacecraft has already launched: NASA's Parker Solar Probe, which soared skyward



Features as small as 30 kilometers are visible in this video, composed of the highest-resolution images of the sun's surface ever taken. Each of the bubblelike granules of convecting plasma seen here is roughly the size of Texas.

NSO, NSF AND AURA

on August 12, 2018. Designed to approach our star within just 4 percent of the Earth-sun distance, or 0.04 astronomical units (AU), it is the closest mission ever sent to our star. The other craft, the European Space Agency's (ESA's) Solar Orbiter mission, launched from Cape Canaveral, Fla., in February. Though projected to reach only 0.28 AU, this mission will capture some of the most detailed images of the sun ever seen, including the first pictures of its poles. And now scientists have released inaugural images from the four-meter Daniel K. Inouye Solar Telescope (DKIST) on Maui in Hawaii. Run by the National Science Foundation in the U.S., this instrument has taken the most detailed images ever of the solar surface.

"It's extremely exciting to be a solar physicist at this point in time, with all of these missions," says Thomas Rimmele, an astronomer and project director of DKIST at the National Solar Observatory. "With just the first images [from DKIST], you see detail that we've never seen before. And this is really just the beginning."

DKIST's five instruments are designed to both image the sun and probe its magnetic field, allowing scientists to discern the field's strength and orientation. Scientists hope to use these data to help resolve the long-standing mystery of why the sun's corona—its halolike outer atmosphere—is up to millions of degrees hotter than its surface. Data from DKIST will also allow researchers to probe the magnetic fields of the vast structures that arc and loop between these two regions.

Complementing DKIST are the aforementioned Parker Solar Probe and Solar Orbiter. By repeatedly flying close to the sun over the next five years at record-setting speeds of nearly 700,000 kilometers per hour, the former will be able to measure pristine material ejected from our star, and it is already providing invaluable data from its early passes. "Parker Solar Probe is showing us signatures of the solar wind and the plasma in the corona that we've never seen before in previous missions," says Nour Raouafi, project scientist for the probe at the Johns Hopkins University Applied Physics Laboratory.

Meanwhile the Solar Orbiter has the capability to directly image the sun from its close-up vantage point—something the Parker Solar Probe lacks. Poking through small holes in the spacecraft's titanium heat shield, cameras will provide the closest images of the sun ever taken. Beyond the delivery of such stunning snapshots, scientists are already excited about other insights this mission might reveal, such as how our star launches flares and coronal mass ejections—"space weather" events that can severely disrupt global power grids and telecommunications. "The main problem with space weather at the moment is [we have] a 12-hour warning at most," says Stephanie Yardley, a solar physicist at the University of St. Andrews in Scotland. "If we [know] the evolution of the magnetic field of the sun and the solar atmosphere, we can gain some insight into how these eruptions are actually formed. It's currently very difficult [to predict them]."

The Solar Orbiter has one more trick up its sleeve, too. It will use repeated encounters with Venus to gradually raise the inclination of its orbit, eventually reaching 33 degrees above the plane of the planets if, as hoped, the mission is extended beyond its initial seven years. Doing so will enable it to orbit the sun at a high angle, capturing images of the sun's poles. "We're hoping to see how the magnetic field on the surface migrates toward the poles and eventually influences the 'flip' of the sun's poles [every 11 years]," Yardley says.

Numerous sun-observing spacecraft have been launched before, but without the advanced capabilities of these new missions. ESA and NASA's widely regarded and still operational Solar and Heliospheric Observatory (SOHO) launched in 1995, but it sits at a distant 0.99 AU from the sun. The German-U.S. Helios probes in the 1970s, meanwhile, set the previous record for the closest approach to the sun of 0.29 AU, yet they have since been eclipsed by the Parker Solar Probe. And ESA and NASA's Ulysses spacecraft used a gravitational assist from Jupiter to fly over the sun's poles in the mid-1990s and early 2000s, but it did so without cameras to image what they looked like.

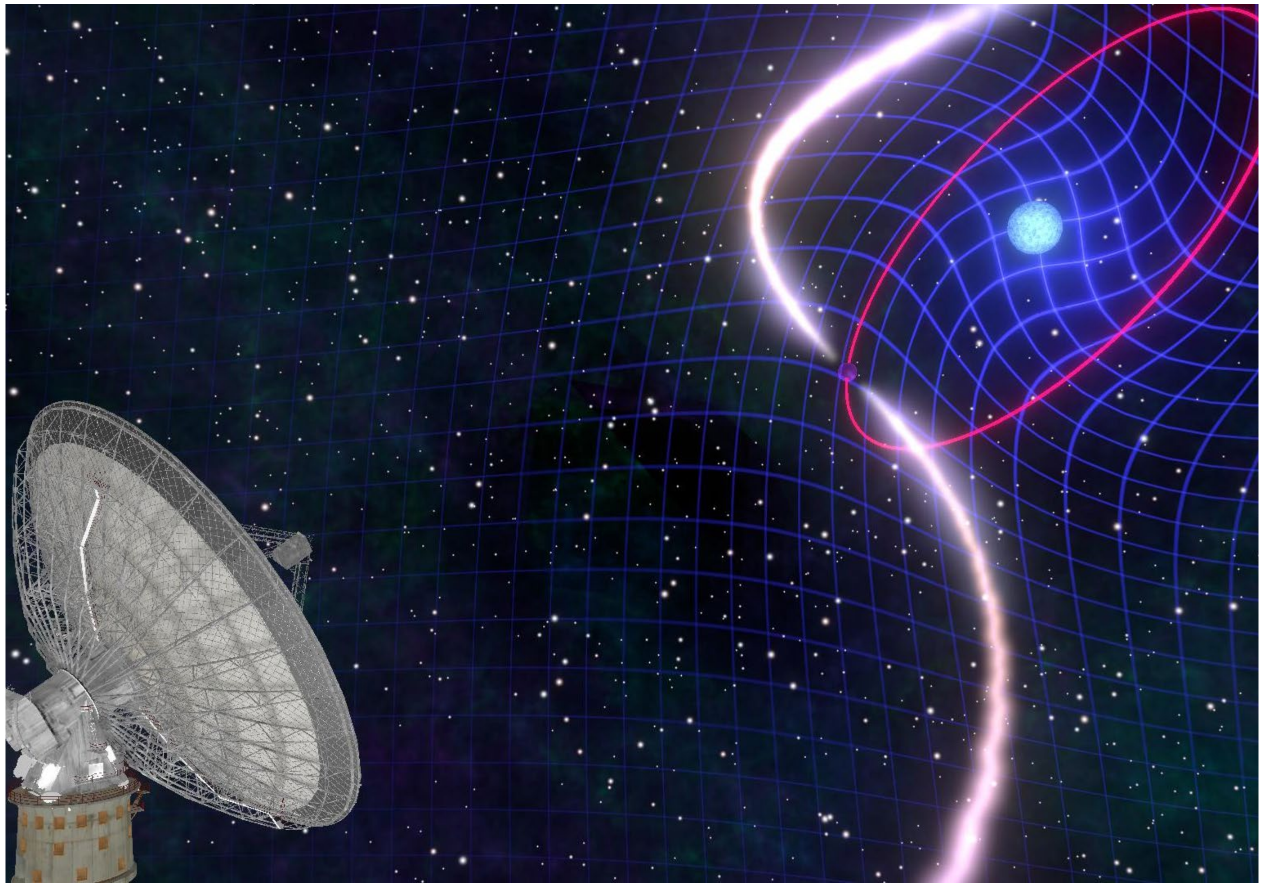
Together, Raouafi says, these new missions herald an upcoming "golden age" of solar studies. "They have the potential to define the future direction of solar and heliophysics research," he says. And Gregory Fleishman of the New Jersey Institute of Technology hopes they might inspire even more projects in the near future. He is currently part of a team seeking funding for a new large solar radio telescope after having just used a more modest array to probe eruptions of magnetic fields on the sun. “The golden age would mean the measurements are [across] all wavelengths,” Fleishman says. “One important range is entirely missing: the radio range, which is unique because it’s the only window where we can measure the dynamic coronal magnetic fields.”

For scientists who have longed to answer some of the sun’s most intriguing questions, however, there has never been a better time to unearth its secrets. With the Parker Solar Probe expected to study the sun until 2025, the Solar Orbiter lasting until 2030 if its mission is extended, and DKIST potentially observing for decades to come, solar physicists such as Yardley are thrilled at what the future holds for our understanding. “We’re going to have these three different [missions] to provide us with all these different observations, the likes of which we’ve never had before,” she says. “Hopefully [they] can answer some of these big unanswered questions we have in solar physics at the moment.”

—Jonathan O’Callaghan

Bizarre Cosmic Dance Offers Fresh Test for General Relativity

Scientists have detected relativistic frame dragging, a prediction of Einstein’s greatest theory, around a distant pair of exotic stars



Artist’s rendition of the white dwarf–pulsar binary system PSR J1141-6545 (*right*), a natural laboratory for testing Einstein’s general theory of relativity. The system was discovered by the Parkes Observatory radio telescope in Australia (*left*).

For the past two decades astronomers have been testing Albert Einstein’s general theory of relativity using an exquisite celestial laboratory located thousands of light-years away, in the direction of the Southern Cross constellation.

Discovered in 1999, this lab consists of two stellar heavyweights locked in an elaborate orbital dance: a white dwarf—a slowly cooling Earth-sized cinder left behind by an evaporating star—twirling around a pulsar called PSR J1141-6545, a rapidly spinning, ultradense, city-sized neutron star produced by a cataclysmic supernova explosion. Each packs a bit more than the equivalent mass of our entire sun into its compact frame. Such couplings are unlikely, albeit relatively unremarkable throughout the galaxy, but this one is particularly special: the white dwarf resides in an exceedingly close orbit, experiencing a “year” of about five hours and speeds of up to a million kilometers per hour as it whips around its slightly heavier companion, which itself spins around faster than two times per second.

For scientists studying general relativity, the system is a literal match made in heaven. Various bizarre phenomena arising from Einstein’s most successful theory rear their “relativistic” head in its extreme gravitational conditions. And astronomers using radio telescopes can precisely measure them, thanks to minuscule deviations those effects imprint on the pulsar’s metronome-like pulses. Such “pulsar timing” measurements show, for instance, that time dilation is distorting PSR J1141-6545's apparent rotation rate and that the white dwarf's orbit is gradually decaying because of the copious emission of gravitational waves—all in accordance with predictions. Now a research team has successfully detected another Einsteinian quirk: relativistic frame dragging—also known as the Lense-Thirring effect, after the theorists who predicted it more than a century ago—in which a fast-spinning object swirls the fabric of spacetime around it. The results were published in *Science* on January 30.

"Imagine you have a bowl of honey, and you put a golf ball and some food coloring inside it," says lead study author Vivek Venkatraman Krishnan of the Max Planck Institute for Radio Astronomy in Bonn, Germany. "If you twist the golf ball really fast, the honey swirls, too, dragging the food coloring along with it. In this case, the spinning ball is the white dwarf, the honey is spacetime curvature, and the food coloring is the pulsar."

"We got really excited because that meant either something was wrong with the data or our analysis—or it was signaling new physics beyond general relativity."
—Vivek Venkatraman Krishnan

Researchers have detected relativistic frame dragging before, measuring its extremely small influence on satellite-borne experiments moving through Earth's gravitational field as our planet spins. But this is the first time its subtle effect has been seen so clearly elsewhere in the cosmos—in this exotic system, the frame dragging is some 100 million times stronger than the effect would be around Earth. Even so, at first astronomers barely noticed it. Charted across nearly two decades of observations with the Parkes Observatory and UTMOST radio telescopes in Australia, in 2015 the timing of PSR J1141-6545's pulsations revealed a small "drift" in the system's orbital parameters that initially seemed to defy explanation. Even after including all of the system's previously detected relativistic effects that could tweak the motions of the white dwarf and pulsar, Venkatraman Krishnan and his colleagues failed to account for the drift. "We got really excited because that meant either something was wrong with the data or our analysis—or it was signaling new physics beyond general relativity," Venkatraman Krishnan says.

In this case—as in all others before it—Einstein's theory ultimately won out over speculations about breakthrough physics. "[Venkatraman Krishnan] had a eureka moment when he allowed [the pulsar's] orbital plane to alter its orientation—which we had previously assumed was fixed in space," says Matthew Bailes, an astronomer at the Swinburne University of Technology in Australia, who has led the intensive monitoring campaign since he first conceived it nearly 20 years ago. "All of a sudden it was clear the orbit was tumbling in space at a rate never seen before in such systems."

That tumbling—technically called orbital precession—was from frame dragging (combined with the well-known classical effect of spin-induced deviations in the pulsar's near-perfect spherical shape that slightly altered its gravitational field). In other words, the drift was partially because of the pulsar tumbling as it was dragged along in the swirl of spacetime surrounding its white dwarf companion.

But this scenario would require the white dwarf to be spinning very fast—remember the golf ball in honey—probably more than once per minute. That speed would be faster than could be explained in models of standard white dwarf–pulsar binary formation. Such systems begin as two normal stars. One of them first explodes as a supernova to form a pulsar, which then spins up to very high rotation rates by siphoning gas from its companion, transforming the companion into a slowly spinning white dwarf. For PSR J1141-6545, the opposite must have taken place, with the white dwarf forming first and spinning up by stealing gas from the soon-to-go-supernova pulsar progenitor. In a series of complex calculations culminating in 70 million simulations of the supernova explosion, study co-author Thomas Tauris of Aarhus University in Denmark examined this process, finding a narrow but plausible range of masses and orbits for the two original stars that would result in the PSR J1141-6545 system.

"When the observers contacted me and asked if I could try to model this system, I was immediately hooked," Tauris says. "I am extremely excited that testing Einstein's theory of gravity goes hand in hand with state-of-the-art binary star modeling."

As labyrinthine and circumstantial as this analysis may seem, it convincingly dovetails with earlier work done when PSR J1141-6545's discoverers first sought to explain the system's bizarre characteristics. The new study's conclusions are "quite compelling," says Victoria Kaspi, a McGill University astronomer, who was not involved with the paper and who discovered the system in 1999 using the Parkes radio telescope. "The pulsar-timing observations and data analysis are expertly done, and the team has also coupled that work with interesting binary-evolution simulations. Moreover, they have found a nice confirmation of the [formation] scenario that we invoked way back when this unusual system was discovered. This is, of course, very gratifying—it's nice to see one's prediction verified!"

In the future, Venkatraman Krishnan says, similar timing studies of other binary systems composed of two pulsars could also reveal relativistic frame dragging, which could in turn help pin down those pulsars' exact size—a crucial measurement that would reveal new information about their mysterious interior. "There are many theories, but we don't really know what happens to matter inside a neutron star. The density there is much greater than anything you could ever achieve in a lab. With further measurements [of binary pulsar systems], that's something we might help deduce."

For now the quest to test general relativity with ever greater scrutiny continues, with this latest astrophysical case being yet another confirmation of Einstein's theory. "It was wonderful to have this come together after two decades of observing," Bailes says. "Like many results in science, in hindsight, it wasn't that surprising. But it is beautiful."

—Lee Billings

Mysterious Faded Star Betelgeuse Has Started to Brighten Again

"Orion's shoulder" had reached unprecedented dimness in mid-February, leaving astronomers befuddled

After a mysterious four-month fading streak, the star known as Betelgeuse could be on its way to regaining its shine.

Easily recognizable as the right "shoulder" in the constellation Orion, Betelgeuse is usually one of the 10 brightest stars in the night sky. But it began getting dimmer in October last year, and by mid-February it had lost more than two thirds of its brilliance, a difference noticeable to the naked eye. But the star has now brightened by around 10 percent from its dimmest point, says Edward Guinan, an astrophysicist at Villanova University, whose team has been tracking it for 25 years.

"For now it looks like it's bottoming out," says Andrea Dupree, an astronomer at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass. "But who knows? Maybe it will cough and go back down again." A group of amateur and professional astronomers called the American Association of Variable Star Observers, also based in Cambridge, has documented the upswing as well.

The reasons for the dimming remain a puzzle, Dupree says. Astronomers have proposed several explanations, but none is sufficient to explain all the observations, she adds.

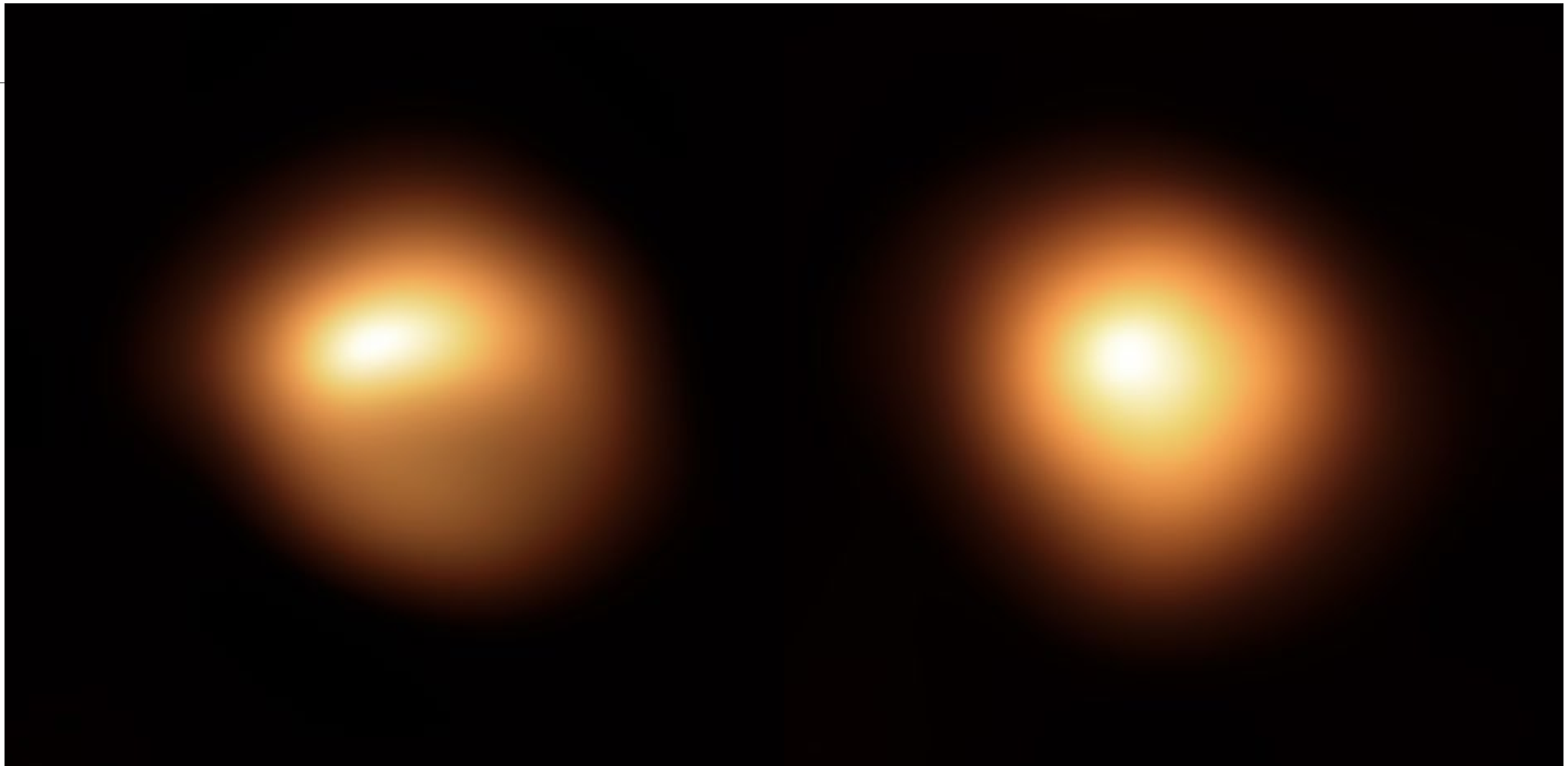
FRIENDLY GIANT

Betelgeuse is a favorite of stargazers worldwide. At a relatively close 220 parsecs (700 light-years) from the sun, the red supergiant—a large but relatively cool-burning type of star—has also been a boon for astronomers. Although its mass is just a dozen times that of the sun, its dimensions are gigantic: if Betelgeuse were in the center of the solar system, it might engulf all the planets up to Jupiter.

As a consequence, it is one of the few stars that can be imaged in detail from Earth, as opposed to appearing as a single, unresolved dot of light. Since the 1990s Dupree and others have been able to reveal features on its surface called convection cells—blobs of hot plasma that seethe up to the surface before cooling and falling back down. These are enormous: whereas convection cells on the sun are roughly the size of France, those on Betelgeuse "are the size of from here to Mars," Dupree says.

Because it is so bright, the star can overwhelm many state-of-the-art astronomical instruments, and observing it requires special measures. In ground-based infrared observations made this year, for example, Dupree and her collaborators had to use the telescope in "slew mode"—quickly panning across the sky so that no spot on the camera sensor would be exposed to Betelgeuse's light for too long.

But the star's brightness is not a problem for Guinan. For decades his team has been measuring it with a 25-centimeter amateur telescope set up in his colleague Richard Wasatonic's garden in Allentown, Pa. The easy access has its perks for Wasatonic, Guinan says. "We take data every clear night, usually two nights a week. Whenever the sky clears, he just runs outside in his pajamas."



Betelgeuse before (*left*) and after its unprecedented dimming in 2019.

BROKEN ROUTINE

Guinan's team has documented a roughly 425-day cycle of dimming in the star, but typically the brightness would vary by no more than 25 percent. Guinan says he considered shutting down the program last year because the team was "getting tired" of the star, but ultimately he decided against it. "I told Richard if we stop, it will do something," he says.

Then, in October, Betelgeuse began to dim. By December the fading had become so dramatic Guinan sent out an online alert called an astronomer's telegram. Many others rushed to observe the star.

One leading explanation for the dimming is the emergence of a large, unusually cool convection cell. Another is that the star could be moving behind a dust cloud. But Dupree says that the observations made so far seem mutually inconsistent: "The ultraviolet behavior is different from the optical, which behaves differently from the infrared."

Some have speculated that the star's erratic swings in brightness mean it might be approaching the end of its life. Betelgeuse is estimated to be less than 10 million years old, but astrophysicists predict that it will end in a supernova explosion sometime in the next 100,000 years. When it does, it will be a spectacular sight—for weeks it will be brighter than the full moon and visible during the day. But what happens right before a star explodes in this way is unknown, and astronomers say the exact timing of the fiery end is impossible to predict. Still, Guinan says, "I'm cheering for it to blow up."

—Davide Castelvecchi

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ESO/M. MONTARGÈS ET AL.

New Horizons May Have Solved Planet-Formation Cold Case

An encounter with Arrokoth at the outskirts of the solar system offers the best evidence yet for how worlds coalesce from dust

Not that long ago, it seemed the glory days of NASA's New Horizons mission were in the rearview mirror, left behind with its historic Pluto encounter in 2015. Then, early last year, the spacecraft streaked by Arrokoth, a bit of flotsam drifting through the Kuiper Belt—the diffuse ring of primitive icy bodies beyond Neptune, of which Pluto is the largest member. What New Horizons found at Arrokoth—initially reported last year and now reinforced with 10 times more data in three studies published in February in *Science*—is a critical clue to the greatest cold case in the solar system: the mystery of how planets are born.

"I never expected that our encounter with Arrokoth would be shoulder to shoulder with the Pluto flyby in terms of its importance," says New Horizons principal investigator and study co-author Alan Stern, a planetary scientist at the Southwest Research Institute. "I didn't expect to make an earth-shattering discovery about planet formation in the Kuiper Belt, and yet we have. At Arrokoth we stumbled onto maybe the biggest prize of the entire New Horizons mission."

Through careful studies of Arrokoth's shape, geology, color and composition—as well as sophisticated computer simulations—researchers have developed a clearer picture of how this relic from the early solar system must have formed. And with that knowledge they have also gained a better understanding of how the building blocks of worlds took shape around the sun more than four billion years ago.

Shape, color and composition of Arrokoth, a primitive and pristine Kuiper Belt object, offer tantalizing clues to how the building blocks of our solar system's planets formed more than four billion years ago.

HOW TO MAKE A PLANET

The recipe for making planets is deceptively simple: Jostle a massive cloud of gas and dust so that it collapses in on itself like a spherical avalanche, compressing most of its material into a central newborn star. Next, stand back and watch as the cloud's remnant angular momentum spins and flattens the leftovers into a whirling disk around the star. Within a few million years, it is thought, worlds coalesce within the disk via a process called hierarchical accretion. Dust particles collide and stick, gradually glomming together into pebbles and, eventually, planets. Easy, right?

Except there seems to be a crucial bottleneck in this planetary assembly line: the jump from pebbles to kilometer-scale building blocks called planetesimals. This step is where many theorists expect hierarchical accretion to temporarily break down, because meter-scale boulders knocking together at orbital speeds are more likely to shatter into gravel than get larger. Planetesimals, in contrast, should be bulky enough that their intrinsic gravity corrals the fragments produced by collisions, pulling them back into the fold and allowing growth to continue all the way to planethood.

"Gravity is a universal force and acts like a glue to grow planetesimals bigger and bigger once they form," says David Nesvorný of the Southwest Research Institute, who was a co-author of one of the new studies. "But that's not true about the initial stage, when you just have dust particles in a disk sticking together through molecular forces to make pebbles. Gravity isn't very important there. So what's the 'glue' that lets things grow to produce 10- or 100-kilometer objects?"

TOP-DOWN OR BOTTOM-UP?

The leading alternative to the "bottom-up" assembly process of hierarchical accretion is a "local cloud collapse" mechanism that would build planetesimals from the "top down." In this approach, pebbles in a protoplanetary disk bypass the collisional bottleneck by settling into self-gravitating clouds and being rapidly compressed under their own weight to directly collapse into planetesimals. Originating in the 1950s and refined with pioneering theoretical work in the 1970s, the idea initially struggled to explain how the pebbles could clump in the first place. But 15 years ago more sophisticated models emerged showing how gas drag within a disk—a phenomenon called the streaming instability—can concentrate pebbles into dense groups, much like flocks of birds or a peloton of cyclists moving together against a headwind.

From there a pebble cloud will collapse, popping out planetesimals—plural, because the conservation of angular momentum spins out two or more dense, kilometer-scale bodies from the infalling material. Thus, if planetesimals form via collapse, most of them should begin as binary systems—some of which will then either slowly merge together or lose their companions through gravitational interactions. And according to state-of-the-art numerical simulations recently performed by Nesvorný and his colleagues, if their progenitor pebble clouds formed via the streaming instability, these binaries should tend to orbit each other in a prograde direction—that is, in the same direction as their orbit around the sun. (Models of binary formation from other mechanisms predict the opposite: a tendency for retrograde orbits.) Remarkably an analysis of data from the Hubble Space Telescope and other sources has shown that the Kuiper Belt's oldest binaries exhibit exactly this effect, with the vast majority displaying prograde orbits. When first revealed last year, this overlapping evidence from high-performance supercomputers and telescopic studies of Kuiper Belt objects was hailed by some experts as the best evidence yet for the reality of the streaming instability and local-cloud-collapse models of planetesimal formation.

"I'm under no illusions that there will be a universal, instantaneous agreement about this," says Andrew Youdin of the University of Arizona, a co-originator of the streaming instability hypothesis, who helped perform this breakthrough work. "You don't want everyone to just jump on the bandwagon, anyway. It's a more gradual thing. That's the way science should work."

In light of the data from New Horizons's Arrokoth flyby, however, the bandwagon may soon be standing room only. "These two things fit together," says Will Grundy of Lowell Observatory in Flagstaff, Ariz., a co-author of the three new Arrokoth studies and leader of the Kuiper Belt binary analysis. "The evidence of prograde binary-orbit orientations is perfectly consistent with the streaming instability as the formative mechanism. And all the evidence that Arrokoth gives is that it formed through cloud collapse—although it doesn't tell us how that cloud formed."

THE CASE FOR CLOUD COLLAPSE

Formerly known as 2014 MU69 (or by its informal designation, Ultima Thule), before its official naming, Arrokoth is a 36-kilometer-long "contact binary" composed of two icy, flattened, lightly cratered and gently touching lobes. The arrangement gives Arrokoth the appearance of a squashed snowman. Its surface is extremely and uniformly red—probably because of organic molecules that formed over eons of steady pummeling by cosmic radiation. And perhaps most important, the contact binary is a member of the "cold classical" family of bodies in the Kuiper Belt—objects in sedate, circular orbits that have scarcely interacted with anything else since their formation more than four billion years ago, at the solar system's dawn.

"The debate over how planetesimals form has mostly been based on computer models—because every small object in the solar system we've gone to for 'ground truth' has been heavily heated and eroded by sunlight and impacts," Stern says. "Then we go to Arrokoth, and it's clear this thing has been cold as long as it has existed and is in a very rarefied part of the solar system where there has never been an intensive collisional environment. It's a time capsule from more than four billion years ago, and it cannot be explained, in aggregate, by hierarchical accretion models."

In every detail, Stern and his colleagues say, Arrokoth fulfills expectations set by cloud-collapse models. Its smooth lobes, so delicately perched atop each other, show no signs of the violent high-speed smashups predicted by

"Gravity is a universal force and acts like a glue to grow planetesimals bigger and bigger once they form."
—David Nesvorný

hierarchical accretion—they must have collided very placidly, drawn together with a closing speed as low as a meter per second as they spiraled through the gas in the embryonic solar system's natal disk. And the lobes are both flattened in the same way—precisely as if they both spun out from the same collapsing cloud. In color and composition, they appear, everywhere, the same—whereas they should be more varied if formed from smaller objects colliding from across remote parts of the solar system. "This is like a *CSI* episode," Stern says. "There are too many lines of evidence all pointing to one perpetrator here, not the other. Everything lines up for cloud collapse."

That conclusion itself is somewhat surprising. "We knew we'd probably be able to learn something about planetesimal formation from Arrokoth," says John Spencer of the Southwest Research Institute, a co-author of the three recent *Science* papers. "But we didn't expect it to be so blindingly obvious when we got there. None of us imagined, I don't think, that Arrokoth would be so pristine and that the story it told would be so clear."

There is, of course, a potential catch: Arrokoth is the only object of its kind ever seen close-up, and making enormous extrapolations from a sample size of one is inherently risky. "I'm confident in this being a major advance in our understanding of planetesimal formation, but someone will probably ask, 'Well, this is just one object. How can you know it's typical?' " says William McKinnon of Washington University in St. Louis, who also co-authored the three new studies. "Well, we didn't pick [Arrokoth] because we knew what it would look like. We picked it because we could reach it with New Horizons. If it had turned out to be a space potato covered with craters, we'd be telling a different story now—but it didn't."

More certainty could come from New Horizons as it journeys deeper into the Kuiper Belt. With heat and power for its instruments provided by the gradual decay of long-lasting nuclear isotopes, the mission could continue its explorations well into the 2030s (provided NASA keeps funding its operations). The spacecraft's 10 kilograms or so of remaining propellant are unlikely to suffice for another post-Pluto flyby of a Kuiper Belt object, but the team is still ardently seeking other possible targets using some of the largest ground-based telescopes on Earth. Meanwhile they are employing New Horizons's far more modest 21-centimeter telescope to remotely study Kuiper Belt objects passing by in the distance. Such studies will not return gorgeous images. But they could still surpass any observations from Earth's vicinity, providing measurements of shapes, spins and surface properties for perhaps 50 or 100 additional objects—enough to form a statistically significant sample and, just maybe, to settle the planetesimal debate for good.

—Lee Billings

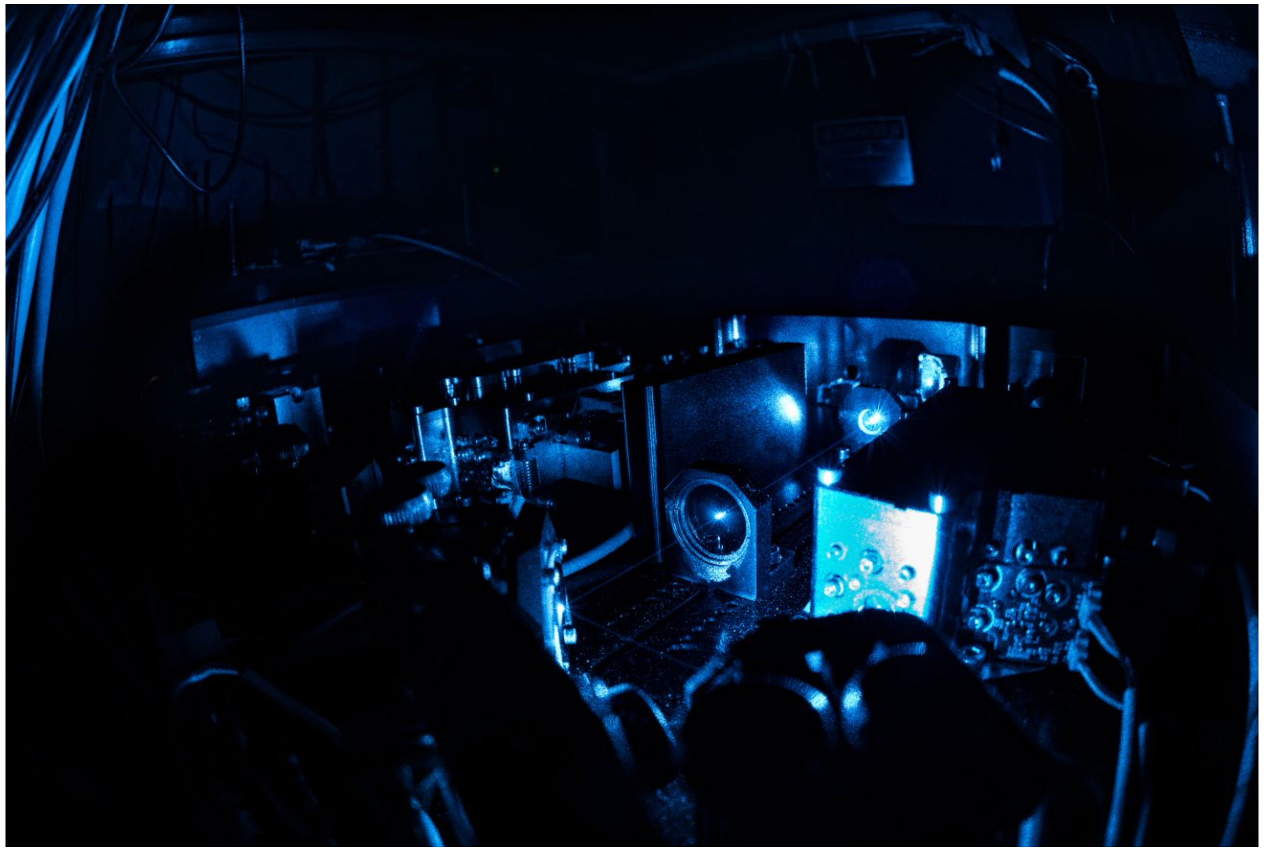
Physicists Come Closer to Answering Question of Antimatter's Scarcity

Researchers have confirmed a long-predicted key similarity between hydrogen and antihydrogen

One of the universe's oldest mysteries is also one of its most puzzling. During the big bang, some 13.8 billion years ago, both matter and antimatter—which are thought to be identical save for the former having the opposite electrical charge of the latter—should have been created in equal amounts. When these two come into contact with each other in today's universe, they are annihilated in a burst of light and more exotic fundamental particles. Why, then, do we live in a matter-dominated cosmos rather than a howling void filled only with ephemeral echoes of an all-consuming annihilation from the dawn of time?

To find out, particle physicists have been busy testing the properties of both matter and antimatter to see how they compare. For matter, this process is relatively straightforward. But for antimatter, it is exceedingly more challenging. Given that antimatter is instantly destroyed on interacting with matter, keeping it intact for detailed investigation is difficult. For the past decade, however, experimentalists have made great strides in such studies by isolating ever greater quantities of antimatter in a vacuum for longer and longer periods, thus progressively enabling new research breakthroughs.

The latest findings come from scientists at the ALPHA experiment at CERN near Geneva, who report in the journal *Nature* that they were able to suspend atoms of the antimatter equivalent of hydrogen, antihydrogen, for hundreds of hours in a vacuum. Doing so allowed them to observe that in antihydrogen—which is composed of an antiproton and a positron, the electron's antiparticle—jumps in energy levels known as the Lamb shift were identical to those seen in hydrogen. This symmetry rules out one of the possible answers to the matter-antimatter discrepancy.



Portion of the ALPHA experiment at CERN near Geneva.

MAXIMILIEN BRICE *CERN*

"We've had other measurements that we've made in the past, but this one is fundamentally different. We're studying the spectrum of antihydrogen," says study co-author Jeffrey Hangst of Aarhus University in Denmark. "There's no unexpected results, but the fact that we're able to look at these things now in antimatter is really significant for us and for the future of what we do. When we're looking for complete agreement between the physics of matter and antimatter, we have to check all of the boxes, and this is a very important one."

The Lamb shift was first observed by American physicist Willis E. Lamb, Jr., in 1947—a measurement that would later win him a Nobel Prize. Electrons orbit the nuclei of atoms, but they can undergo quantum jumps between orbits, corresponding to certain energy levels, which result in an emission or absorption of light. Lamb showed that two energy levels of hydrogen, 2S and 2P, exhibited a detectable change, or shift, that defied some theoretical predictions. The discovery of the Lamb shift, which is attributed to the existence of virtual particles being emitted and reabsorbed in a vacuum, contributed to myriad major developments in quantum theory. "The result of the paper by the ALPHA collaboration is that the Lamb shifts of hydrogen and antihydrogen seem to be identical," says Stefan Ulmer of CERN, who was not involved in the latest research.

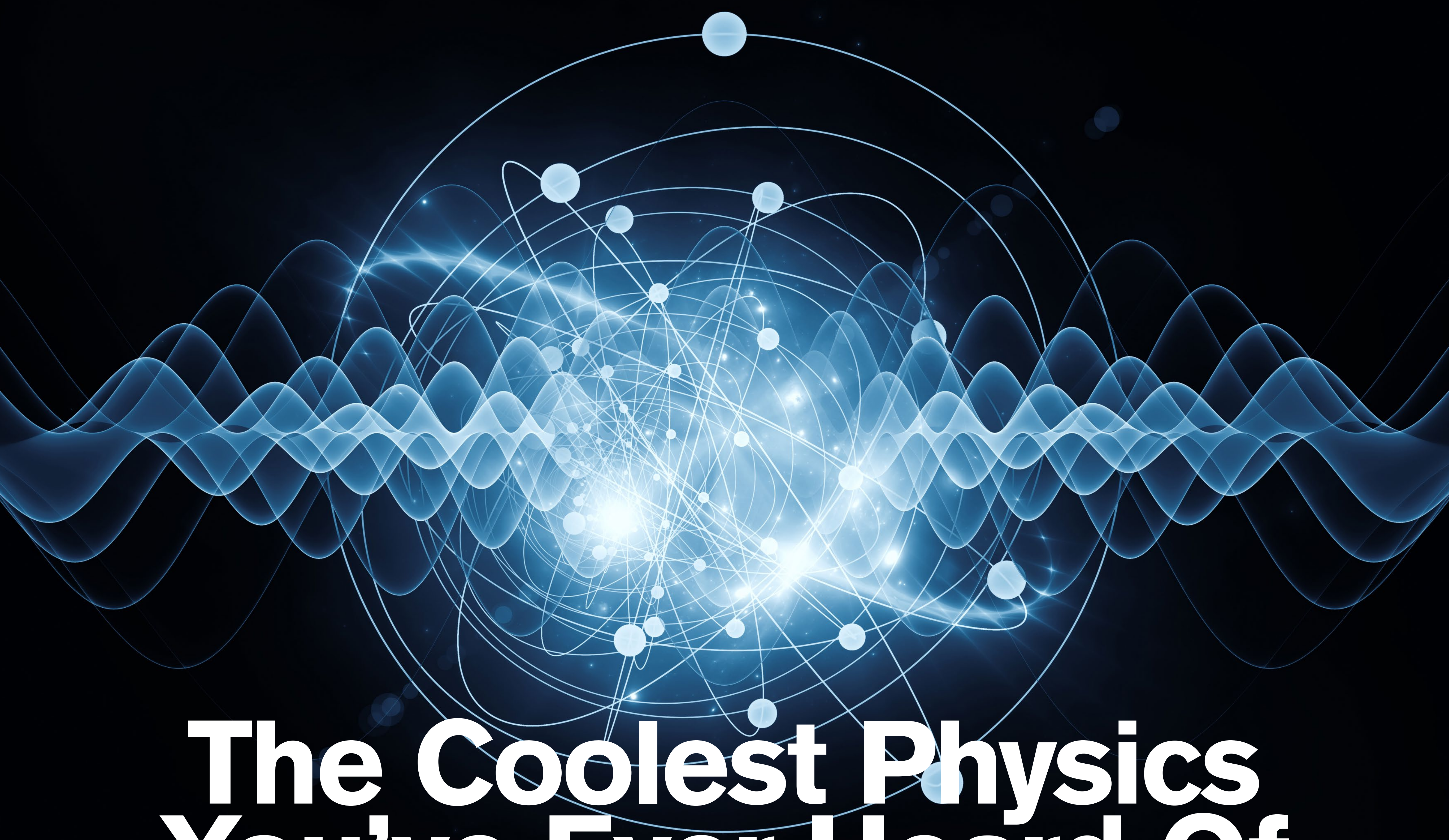
Matter and antimatter's behavioral symmetry is also governed by something known as charge-parity-time (CPT) symmetry, which essentially states that all laws of physics in the universe remain the same under any transformations (outside of a few well-defined special cases). To explain the matter-antimatter problem, something in CPT theory—and thus in the Standard Model of physics, the framework of all known subatomic particles and fundamental forces except gravity—must be wrong. By observing the Lamb shift in both matter and antimatter, physicists hope to narrow down what that "something" might be.

Such experiments "limit the possible effects of new physics or CPT violation," notes Randolf Pohl of Johannes Gutenberg University Mainz in Germany, who was also not involved in the research. "Any difference you find is a clear violation of the Standard Model," he says. "So if you measure a difference between hydrogen and antihydrogen, then the Standard Model is dead. Our understanding of physics is incomplete, and we have to find something new. This has not yet happened, but comparing matter and antimatter is a very clean way to test the foundations of the Standard Model."

Thomas Udem of the Max Planck Institute for Quantum Optics in Garching, Germany, says the latest findings from ALPHA are "exciting" and notes that early, lower-energy experiments resulted in antiparticles accelerating to the speed of light—a troublesome detail for attempts to coax them into forming atoms. "You couldn't do anything with them except to detect they were there," he says. In contrast, the higher energies used in the ALPHA experiment slow antiprotons and positrons down enough for the particles to form atoms of antihydrogen for more in-depth study.

Although no violation of the known laws of physics has emerged, these results from the ALPHA experiment open a new chapter in studies of matter-antimatter symmetry, one that promises long-sought answers to one of the universe's most perplexing questions. "Sometimes I pinch myself because when I started, we didn't have any antihydrogen at all. And lots of people said we would never be able to make it," Hangst says. "Now we're up to thousands of atoms stored. It's really a revolution that we're able to do this."

—*Jonathan O'Callaghan*



The Coolest Physics You've Ever Heard Of

Ultracold atoms can simulate all kinds of quantum behavior

By Karmela Padavic-Callaghan

GETTY IMAGES

Karmela Padavic-Callaghan is a Ph.D. candidate in physics at the University of Illinois at Urbana-Champaign.

WHEN IT COMES TO FURTHERING OUR OVERALL UNDERSTANDING OF the physical world, ultracold quantum gases are awfully promising. As the famous physicist Richard Feynman argued, to fully understand nature, we need quantum means of simulation and computation. Ultracold atomic systems have, in the past 30 years, proved to be amazing quantum simulators. The number of applications for these systems as such simulators is nothing short of overwhelming, ranging from engineering artificial crystals to providing new platforms for quantum computing. In its brief history, ultracold atomic experimental research has enhanced physicists' understanding of a truly vast array of important phenomena.

One of the revelations of quantum mechanics is that any object can be seen as a wave (even you!) when an appropriate experimental test is used. Properties of these so-called matter waves depend on their temperature; at high temperatures they have short wavelengths and look and behave particlelike because all the peaks and valleys are so close together that they cannot be told apart. If we lower temperature to much less than a single kelvin, the wave nature of matter becomes more pronounced and wavelike behaviors are more important. What happens, then, with a large collection of very cold atoms that behave like a large collection of waves? They can all align and overlap to form a single wave, something that was historically called a macroscopic wave function. Such a system—a condensate in physics parlance—is a fundamentally quantum state of matter.

Quantum condensates were theoretically predicted in the mid-1920s, but it was only in the late 1990s that experimental physicists kicked off a revolution (recognized with two Nobel Prizes) by using lasers and magnets to reach sufficiently low temperatures for the transition to these phases of matter to happen. Light can interact with atoms and thus change their energies. Atoms also experience forces when placed in nonuniform magnetic fields. Physicists used these two properties to trap clouds of atoms such as rubidium and eventually lower their temperature to picokelvins—trillionths of a degree above absolute zero. Remarkably experiments in which these extremely low temperatures can be reached, and in which quantum states of matter are engineered, fit in an average-sized room, on a large table, with the ultracold atom gas frequently visible to the naked eye. The coldest places in the universe can often be found in a room on your local college campus, and they are likely controlled by a graduate student.

But it is not just making something the coldest or the most quantum that excites physicists; it is that ultracold atoms can be controlled and manipulated very precisely. Theoretical physicists have been especially emboldened by the possibility of engineering a quantum system by moving ultracold atoms around and fine-tuning the way in which they interact. To a theorist, a physical system such as a novel material that has some odd or unexpected property is a frustrating black box that is hard to describe with mathematical equations.

An ultracold atomic experiment can be the exact opposite, bringing equations to life and determining whether they measure up to nature. Many minimal, prototypical models, extensively studied at the level of mathematical equations but not necessarily matched by any naturally found material, can be engineered in ultracold atomic experiments. Since the late 1990s physicists of all kinds have embraced this idea and pushed it in every direction they could imagine.

As one example, adding counterpropagating laser beams to an ultracold atomic sample creates an optical lattice and turns the system into an artificial crystal. Whereas a physical crystal has to be grown carefully, an ultracold artificial crystal can be changed from one shape to another with adjustments to laser beams. Even more advantageously, such artificial crystals are typically very clean, and researchers can add in disorder by using more lasers. This means they can "reverse engineer" some of the effects of disorder. If a crystal is grown and then studied, it can be difficult to determine how much "dirt" in that sample actually matters for experimental outcomes.

If researchers can control the disorder, then they can be very precise about determining its consequences.

From the very first ultracold atomic experiments, they have been really important for studying fluids having zero viscosity or superfluids. When does a normal fluid become a superfluid? Can something similar to sound propagate through a superfluid? What happens if a container of superfluid is rotated? Many such fundamental questions have been answered through simulations with ultracold atoms.

For instance, rotating a superfluid has been predicted to give rise to vortices—small hurricanes of quantum fluid—as a consequence of basic properties of the macroscopic wave function. Researchers are learning about quantum turbulence by observing and manipulating these vortices, thinking of them as controllable building blocks of more chaotic superfluid flows. Precise models for turbulent quantum flows have historically eluded theorists, which makes ultracold atomic simulations the first line of attack for this difficult problem.

As with studies of superfluids, many efforts have been made to simulate superconductors. They are perfect conductors having no resistance; no energy is wasted as electric current runs through them. As this is in contrast to all conductors used to supply electricity to businesses and households, it is a very active area of research to try to simulate a superconductor that does not have to be very cold. While a physicist's notion of "very cold" may not quite match the colloquial use of the phrase (a "cold atom" in physics jargon is millions of times colder than a cold pint of ice cream in your fridge), even a few kelvins' worth of difference could be meaningful for applications of superconductors outside the lab.

Theoretical physicists have debated various high-temperature superconducting models for years, and ultracold atomic studies have been one of the prime ways to put those, sometimes conflicting, theories to test. Experimental physicists can also make a superfluid of ultracold atoms become something like a superconductor in a process called BEC-BCS crossover. This crossover has been theorized in semiconductors and neutron stars but never unequivocally confirmed in any system other than ones consisting of ultracold atoms.

Why would nature care about the difference between rational and irrational numbers so much as to allow for fractional dimensions to be more than a mathematical oddity?

Superconductors and superfluids are both fundamentally quantum phases of matter, making up something like a quantum expansion of the liquid-solid-vapor list of phases you may have learned in school. Ultracold atomic experiments continue to simulate even more novel quantum phases of matter. One striking example from 2019 is simulation of a quantum supersolid. A supersolid, like a superfluid, flows without any friction between the atoms that make it up, but it also has a periodic, crystal-like structure like solids do. It is a seemingly paradoxical state of matter whose existence was debated for almost 50 years before ultracold atomic experiments provided a definitively affirmative conclusion.

Many so-called topological phases of matter have also been realized in ultracold systems. Some of these experiments simulate, and generalize, the quantum Hall effect, which was first observed in more traditional experiments with semiconductors. Because many topological states of matter have properties unaffected by disorder, they are a very promising setting for quantum computation. In this way, realizing topological models in very tunable ultracold atomic systems means that physicists are able to not only simulate a new phase of matter but also immediately put it to use, getting closer to making a quantum computer.

Even if ultracold atomic systems have not been turned into quantum computation machines just yet, they can often be used to "beat" classical supercomputers in terms of enabling researchers to learn something new about fundamental physics. One example is that of many-body physics. In quantum mechanics, a system that has more than a few interacting particles is almost always a system where it is very difficult to calculate, and therefore predict, anything precisely. Yet real materials consist of millions of atoms!

Ultracold atomic systems have been invaluable for studying highly interacting many-body systems, uncovering phenomena such as systems failing to reach thermal equilibrium and never losing "memory" of their initial state. Physicists often resort to computational methods and supercomputers to study these systems, but a simulation with ultracold atoms can be a more direct way to attack some of their questions. Failure to equilibrate is of great interest in statistical physics, and the advent of ultracold atomic experiments has reinforced it as a very active field of contemporary physics research.

As for me personally, despite being trained in the broader discipline of condensed matter physics, I spent my six years as a graduate student coming back to ultracold atoms over and over again. Mostly I have been studying superfluid bubbles (hollow shells) made of ultracold atoms. This led me to the work of NASA scientists who launched an ultracold-atom experiment into space to explore how it would be affected by extremely low gravity. This experiment is still ongoing onboard the International Space Station, and theorists like me who made predictions about what it will find are anxiously awaiting results.

In a way, it is fitting that studying hollow ultracold shells ended up making me think about space, as part of the motivation for this research lies with neutron stars. Physicists do not really know what you would find if you could observe the inside of a neutron star, but many theories suggest that it looks like an onion, with layers of superconductors and superfluids. Studying superfluid shells in laboratories could then lead to a better understanding of some of these layers that reside in stars that are so far away that scientists may never be able to study them directly. Moreover, measurements of radio signals coming from neutron stars suggest that superfluid vortices within them may affect their rotation.

Ultracold atomic experiments have excelled in providing information about exactly those vortices with great precision. In the past few years I have been working on mathematical arguments for what a vortex in a hollow shell of ultracold atoms might do if the whole thing started rotating. I have badgered a fair number of my experimentalist colleagues with questions about engineering such a system in their labs, and the fact that this is even something we can talk about—some semblance of simulating the quantum innards of a neutron star—still seems to me a little bit like science fiction.

My latest ultracold obsession came when I learned about quasiperiodicity in one-dimensional chains of ultracold atoms. The puzzle hiding behind the jargon is simple: physicists know well how structures of atoms in which they repeat with a regular period behave in nature, but what happens if that period is an irrational number? Such systems are called quasiperiodic, and studying them led Douglas Hofstadter in 1976 to discover a famous fractal plot later dubbed as his butterfly. Hofstadter's plot is self-similar: if you zoom in or zoom out any amount, it still looks the same.

This property implies that physical states having fractional dimensions can exist in nature, a revelation that jump-started a search for more physical systems where that can happen. Two years ago another graduate student mentioned to me that they had simulated a quasiperiodic system in their ultracold atomic research lab, and I, too, have not stopped chasing the Hofstadter butterfly since. Why would nature care about the difference between rational and irrational numbers so much as to allow for fractional dimensions to be more than a mathematical oddity? Ultracold atomic studies are likely to help physicists answer that question, and I hope to be around to hear about them.

My experience as a researcher has included only a sliver of many topics in modern physics for which ultracold atomic experiments are meaningful. The possibilities are truly numerous. And the quantum-simulation revolution is nowhere near over! Researchers continue to push the limits of existing technology to cool gases made up of more elements and to execute more manipulations.

Next steps? Quantum chemistry, where molecules form at ultracold temperatures. Ultracold quantum systems that are so large they cannot be called microscopic despite quantum mechanics always being assumed to describe only the smallest of objects. Ultracold systems that can be used to measure fundamental constants in tabletop experiments instead of large accelerators (like the Large Hadron Collider). Ultracold experiments where a single atom can be poked, prodded, moved around and imaged. And whatever else can give us a window into the fundamentals of our (quantum) world.

How the Celebrated “Pale Blue Dot” Image Came to Be

Voyager 1’s poignant photograph of the distant Earth as the spacecraft sped toward interstellar space happened just 30 years ago

By Carolyn Porco

“The Day the Earth Smiled” image, with our planet visible below Saturn’s rings.

NASA, JPL-CALTECH AND SPACE SCIENCE INSTITUTE

Carolyn Porco is a planetary scientist and a visiting scholar at the University of California, Berkeley. She was an imaging scientist on the Voyager mission to the outer planets and the leader of the imaging team on the now completed Cassini mission at Saturn. She is a member of *Scientific American's* board of advisers.

THIRTY YEARS AGO, on February 14, 1990, the Voyager 1 spacecraft directed its cameras to take one last historic array of planetary images. Sitting high above the ecliptic plane, nine years and three months beyond its last planetary encounter with Saturn and four billion miles from the sun, farther than the orbit of Neptune, the spacecraft intercepted and executed a set of instructions to acquire 60 individual exposures of seven of the eight planets, the sun and the vast nothingness in between. This simple sequence of commands and these last images of the tens of thousands taken by Voyager 1 and its sister craft, Voyager 2, in their journeys across the solar system capped a groundbreaking era in the coming of age of our species.

A daring, endless trek to the outer planets and beyond, the Voyager mission became iconic over the years in its scope and meaning: more rite of passage than expedition, more mythic than scientific. The extraordinary images of alien worlds never before seen, and the precognitive sense of being there that they evoked, connected laypeople the world over to Voyager's historic pilgrimage into the unknown, with eternity the final port of call. It was not folly to feel that the mission would gift us all a measure of immortality.

The fabled Golden Record of Voyager heightened the fascination. The two Voyagers each carried a phonograph record of images, music and sounds representative of our planet, including spoken greetings in 55 languages to any intelligent life-form that might find them. This was a message from Planet Earth vectored into the Milky Way—a hopeful call across space and time to our fellow galactic citizens. It was thrilling to think that news of us and of our home planet might be retrieved by some extraterrestrial civilization somewhere and sometime in the long future of our galaxy.

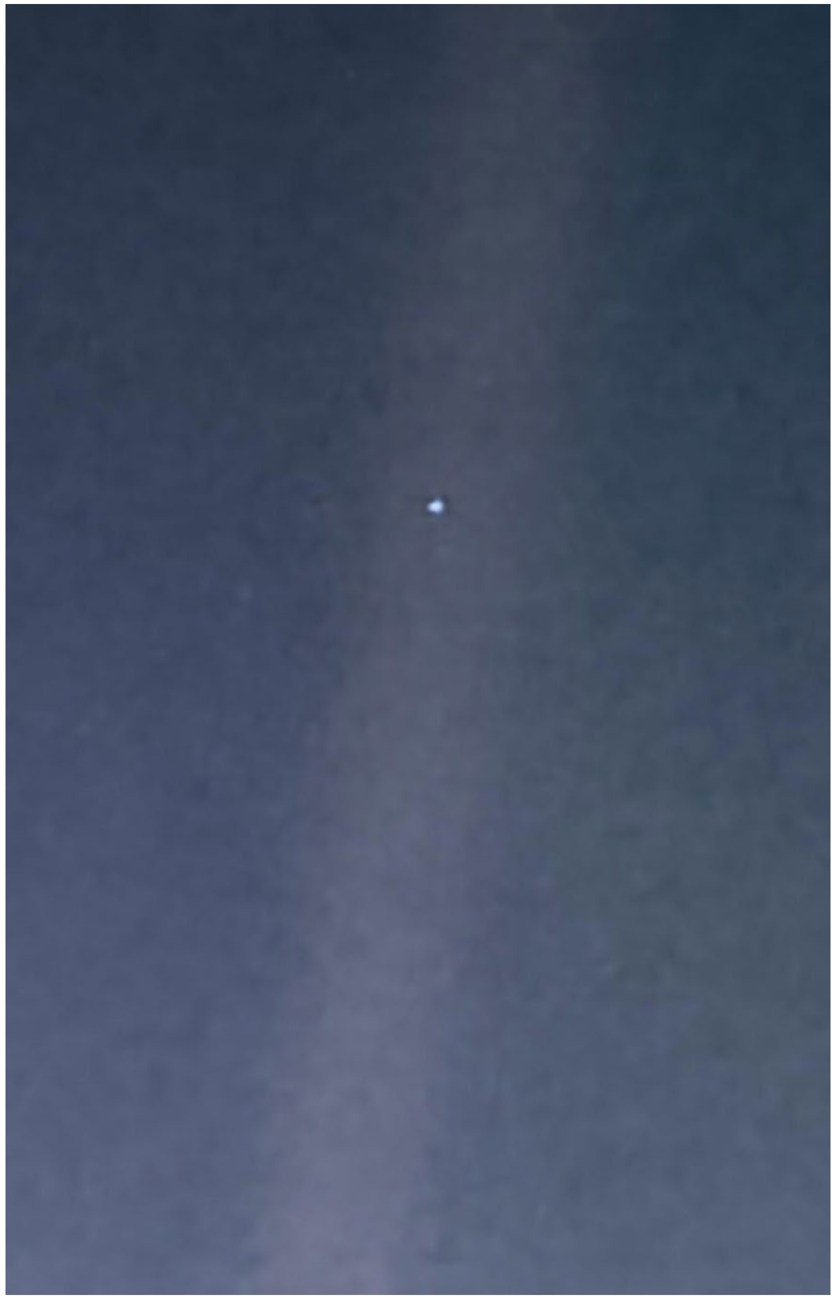
Because of its never-ending journey, its dazzling scientific discoveries in the solar system and its human-forward countenance, to participants and onlookers alike, Voyager became symbolic of our acute longing to understand our cosmic place and the significance of our own existence. It left no question of our status as an interplanetary species. It is, even today, the most revered and beloved interplanetary mission of them all, the *Apollo 11* of robotic exploration.

Perhaps the most poignant gesture of the Voyager mission was its final parting salute to its place of birth. The portrait of the sun's family of planets taken in early 1990 included an image of Earth. Carl Sagan, a member of the Voyager imaging team and the captain of the small team that had produced the Golden Record, had proposed this image to the Voyager project in 1981. He eventually called it, appropriately, the Pale Blue Dot. His motivation is expressed in his book of the same name, in which he describes wishing to continue in the tradition begun by the famous Earthrise images of the Apollo program, referring specifically to the one taken from the surface of the moon by *Apollo 17*. Then, he continues:

> It seemed to me that another picture of the Earth, this one taken from a hundred thousand times farther away, might help in the continuing process of revealing to ourselves our true circumstance and condition. It had been well understood by the scientists and philosophers of classical antiquity that the Earth was a mere point in a vast encompassing Cosmos, but no one had ever seen it as such. Here was our first chance.

Although Carl had convinced a small group of Voyager project personnel, and imaging team leader Brad Smith, to provide the required technical, planning and political support, the project leaders were not willing to spend the resources to do it. Carl's 1981 proposal was rejected, as were his other proposals over the following seven years.

Completely unaware that Carl had initiated such an effort, I was independently promoting the very same idea—to take an image of Earth and the other planets—soon after I became an official imaging team member in late 1983. I had in mind the sentimental "goodbye" that would lie at the heart of any image taken of our home planet before Voyager headed out for interstellar space and the perspective it would give us of ourselves—our small and ever-shrinking place in Voyager's ever-widening view of our cosmic neighborhood. Also, the "cool factor" in presenting a view of our solar system as alien visitors might see it on arrival here was another draw.



Remastered image of Earth as a pale blue dot, seemingly embedded in a ray of sunlight scattered in the optics of the camera (cropped; full image is *here*).

NASA AND JPL-CALTECH

For two years I hawked the idea around the project and, not surprisingly, like Carl, got nowhere. But Voyager's project scientist, Ed Stone, did his best to encourage me by advising that if there were some science to be obtained by an image of Earth, it might then be possible. As I couldn't think of any, I gave up and began instead thinking of other scientific observations of the inner solar system that could be made from the outer solar system. The result: In 1987 we used Voyager 1 to attempt to image the asteroidal dust bands discovered by the Infrared Astronomical Satellite in 1983. Regrettably, nothing was detected.

It wasn't until 1988 that I finally became aware of Carl's proposal. After I told him that I had had the same idea a few years earlier—and, like him, tried and failed to get it jump-started—he requested my help, suggesting that I compute the exposure times. (A letter I wrote to Carl after our conversation, in 1988, summarizing that conversation and reporting on my calculations, is archived in the Library of Congress.)

It is an ironic historical footnote to this story that the most difficult calculation of the bunch was the exposure for Earth. As no spacecraft had ever taken an image of Earth in which it was smaller than a pixel, and because the cloudiness of its atmosphere is so variable that its inherent brightness is hard to calculate or predict, there was no information available then to suggest confidently how long an exposure should be. Somehow it all worked out.

The Pale Blue Dot image of Earth is not a stunning image. But that didn't matter in the end because it was the way that Carl romanticized it, turning it into an allegory for the human condition, that has ever since made the phrase "Pale Blue Dot" and the image itself synonymous with an inspirational call to planetary brotherhood and protection of Earth.

Considering my history with the concept, it was only natural that only several months after the Pale Blue Dot image was taken, when I learned I would be the leader of the imaging team for the Cassini mission to Saturn, I put at the top of my bucket list to do the Pale Blue Dot all over again, only to make it better and make it beautiful. And it occurred to me in the planning of the Cassini redo how great it would be if we let the people of the world know in advance that their picture would be taken from a billion miles away—and invite them at the appropriate time to go out, contemplate the isolation of our home in space, appreciate the rarity it is among the sun's planets, marvel at all of life on Earth, and smile at simply being alive on a pale blue dot.

And we did all that—on July 19, 2013.

I called it "The Day the Earth Smiled." It became a gorgeous image of Saturn and its rings in the foreground and our blue ocean planet, a billion miles in the distance, adrift in a sea of stars.

The significance of images like this—our home seen at significant remove as a mere point of blue light—lies in the uncorrupted, unpoliticized view they offer us of ourselves, a view of all of us together on one tiny dot of a planet, alone in the blackness of space. Our scientific explorations, and images like this, have shown us that there is literally no place else for us to go, to survive and flourish, without extraordinary and, I would submit, unrealizable effort.

Science fiction aside, it may really be that humanity's last stand is right here on Earth, right where it all began, and the lesson going forward now is: We had better make the best of it.

Carl was right. As he wrote in 1994:

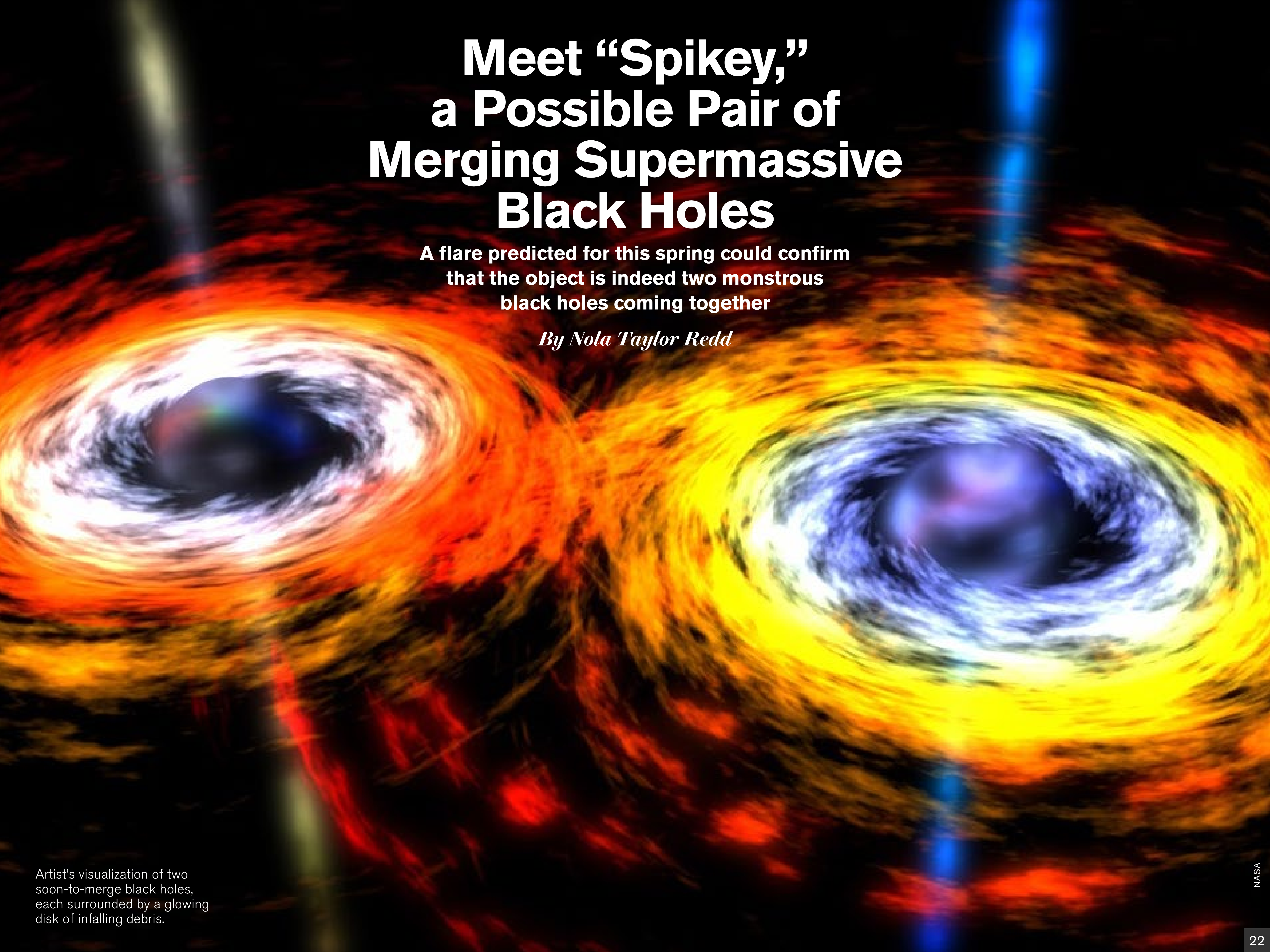
> [The Pale Blue Dot] underscores our responsibility… to preserve and cherish the pale blue dot, the only home we've ever known.

In August 2012, in another historic first, Voyager 1 escaped the magnetic bubble of the sun, becoming the first human-made object to enter interstellar space. That glorious historic undertaking that had redefined us every step of the way had done it again. At that point our species became interstellar. Thanks to Voyager, we are now card-carrying citizens of the Milky Way.

Meet "Spikey," a Possible Pair of Merging Supermassive Black Holes

A flare predicted for this spring could confirm that the object is indeed two monstrous black holes coming together

By Nola Taylor Redd



Artist's visualization of two soon-to-merge black holes, each surrounded by a glowing disk of infalling debris.

NASA

Nola Taylor Redd is a science writer based in Atlanta.

A strangely flaring object at the center of a distant galaxy may be the key to unlocking the mystery of how the universe's most monstrous black holes merge.

Weighing in at millions to billions of times the mass of our sun, supermassive black holes are the ultimate heavyweights—and they lurk at the centers of almost every large galaxy. Although they emit no light, these objects can nonetheless create spectacular celestial fireworks as they feed on gas and dust, creating jets of high-energy particles and whirling disks of debris that can be seen clear across the cosmos as active galactic nuclei (AGNs). Now scientists have identified a flare in a faraway AGN that they suspect is created by a supermassive black hole amplifying the emissions of another one nearby, suggesting that the pair may merge in the next 100,000 years. If the two are in fact primed to merge, they would offer astronomers an unprecedented view into the poorly understood process of how giant black holes manage to get together at all.

In 2017 astrophysicists Daniel D'Orazio and Rosanne Di Stefano detailed how a pair of soon-to-merge supermassive black holes should gravitationally lens one another and how the resulting signal could be seen if the imminent merger's orbital plane aligned with Earth. Material surrounding the black holes should glow in the x-ray wavelength as it accelerates toward either member of the pair. If one black hole passes in front of the other, the immense, spacetime-warping gravitational field of the "foreground" black hole will act much like a lens, magnifying the background light source. "It's a very distinctive signature," says Di Stefano, a researcher at the Center for Astrophysics at Harvard University and the Smithsonian Institution.

In October she and D'Orazio, working with several collaborators, reported the discovery of an object emitting a signal that matched their theoretical prediction. Data gathered in 2011 by NASA's planet-hunting Kepler space telescope revealed an unusual AGN with a strange spike. If the object, nicknamed Spikey, repeats its flare again this spring, as predicted by D'Orazio and his colleagues, it will be what he calls the "smoking gun" confirming that Spikey is a pair of supermassive black holes on the cusp of merging. D'Orazio, an astronomer at Harvard, presented the new analysis last month at a meeting of the American Astronomical Society in Honolulu.

THE "FINAL PARSEC PROBLEM"

When galaxies collide, the supermassive black holes at their centers eventually find their way to the heart of the newly created galaxy and are ultimately drawn together. Observations of the cores of merging galaxies have revealed either a single supermassive black hole (presumably where two or more have already merged) or black holes that are orbiting within a few parsecs of one another (a parsec is roughly 3.26 light-years).

"We are very confident that when two galaxies merge, the black holes they host will get within a parsec of each other," says Scott Hughes, an astrophysicist at the Massachusetts Institute of Technology, who did not take part in the study.

The problem comes in the final parsec, where gravity is not strong enough to overcome the centrifugal force of each black hole's orbit to pull the pair closer together. Without a steady influx of material to shake things up, the two may stop just shy of merging and remain in a holding pattern over the lifetime of the universe. This "final parsec problem" does not affect pairs of smaller, stellar-mass black holes, which can more easily merge by bleeding off excess orbital energy via their copious emission of gravitational waves. But larger black holes need something to push them over that final hump before their own gravitational-wave emission can kick in, at which point an eventual merger becomes inevitable.

"We don't have a good understanding of what goes on in that final parsec," says Matthew Graham, a cosmologist at the California Institute of Technology, who was not involved in the new study. "We have a theoretical understanding, but we don't have good observational evidence to match against theory." At least, researchers do not have such evidence quite yet.

In addition to revealing thousands of exoplanets, Kepler also discovered a few dozen AGNs. A 2018 study of these objects revealed unusual flaring activity in one called KIC 11606854. A closer look revealed that the flare's waxing and waning light mirrored predictions of how a pair of merging black holes might gravitationally lens each other. Hello, Spikey.

"It ended up being very fortuitous," says Betty Hu, a graduate student at Harvard University and first author of the preprint paper reporting Spikey's discovery. The researchers studying the Kepler AGNs passed the information on to D'Orazio and his colleagues, who found that the signal matched up "very well" to the lensing model, Di Stefano says.

According to Di Stefano, the merging black holes might each be ringed by a "mini disk" embedded in a larger shared disk that orbits both objects. The mini disks could dissipate as the black holes gobble them down, only to be occasionally replenished with material from the larger outlying disk. Each black hole munching on a mini disk has a beneficial side effect, shedding additional orbital energy and allowing the two to spiral closer together, potentially overcoming the final parsec problem. According to the researchers' models, Spikey should merge in the next 100,000 years or so—an eyeblink on astronomical timescales.

UNTIL NEXT TIME

A single flare alone, however, is not enough to confirm that Spikey is a pair of merging black holes. D'Orazio and his colleagues are already planning to study Spikey this spring in search of more evidence. Based on their best estimates of the pair's orbits, they have tentatively identified the next gravitational-lensing event as most likely to occur in April 2020. But, Hu says, lingering uncertainties mean the flare could take place anywhere between February and July.

> **"I think [D'Orazio] has done a fantastic job of trying to figure out all the ways possible to follow up on this system because it is the best candidate [of merging black holes]."**
> ***—Rosanne Di Stefano***

The team has already secured time on NASA's Chandra X-ray Observatory to watch for April's predicted flare, which should span about 10 days. In the meantime, the researchers are continuing to monitor the system using ground-based instruments. If Spikey starts acting up before April, they hope to catch a glimpse in order to shift their observations with Chandra and other facilities to compensate. "I think [D'Orazio] has done a fantastic job of trying to figure out all the ways possible to follow up on this system because it is the best candidate [of merging black holes]," Di Stefano says.

If Spikey shows the predicted flare this spring, it will be a big deal. "If it holds up and is, in fact, a binary, I think it will give us a case of what to look for if we're trying to find cases of close binaries not yet merged," Hughes says. Such an example should make hunting merging supermassive black holes easier in the future.

And that result would be good news for the European Space Agency's Laser Interferometer Space Antenna (LISA) mission, set to launch sometime in the 2030s to hunt for gravitational waves emitted by supermassive black holes. Although Spikey probably will not merge on LISA's watch, it can give mission planners a better idea of how many merging giants are out there for the spacecraft to see.

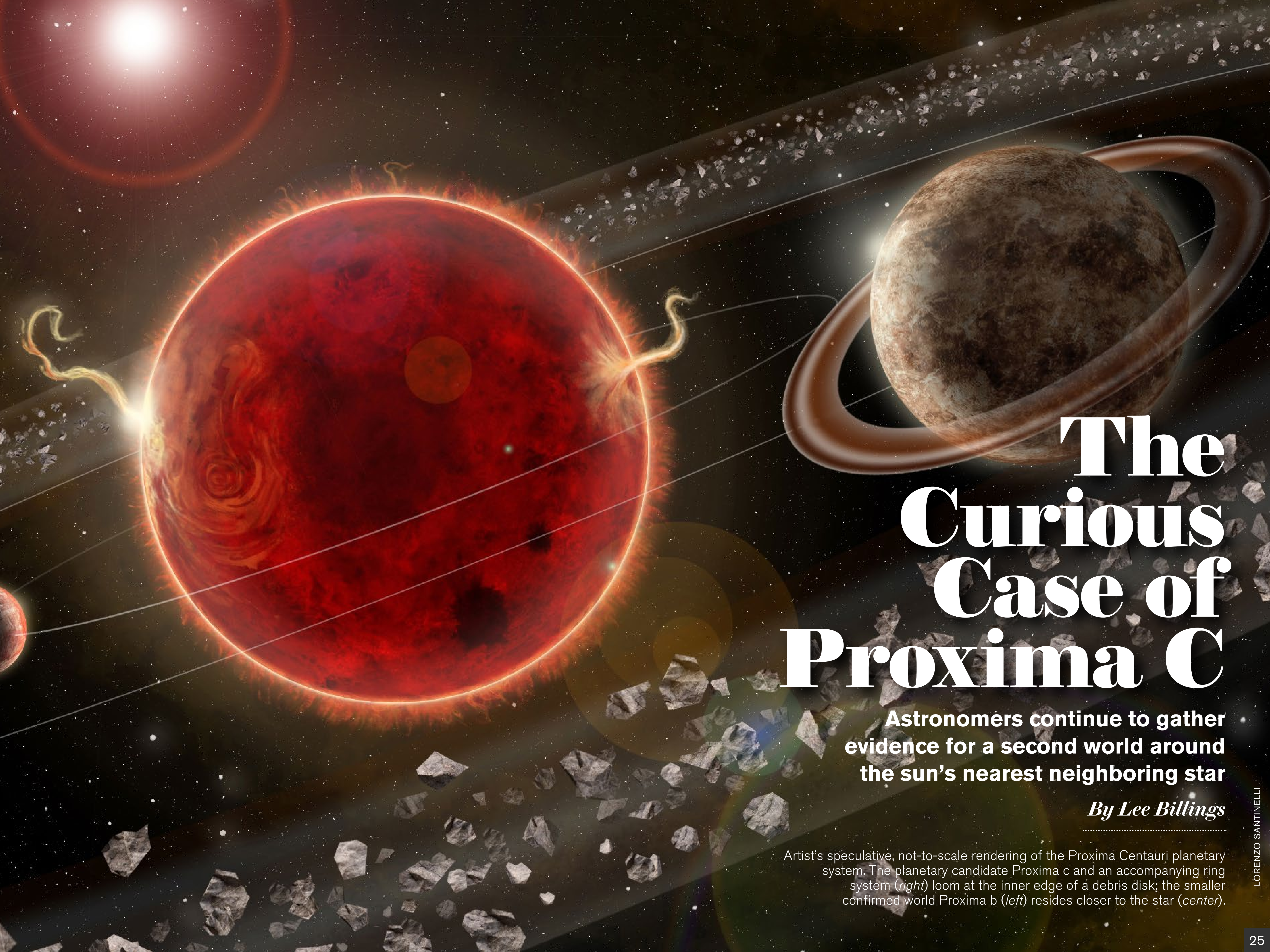
A FLARELESS WONDER

Then again, Spikey could fail to flare again; perhaps it is not a pair of supermassive black holes at all. According to Graham, the past few years have seen a rising number of claims of potentially merging supermassive black holes that wound up being something else.

If July passes with no sign of the unique signature, then it could be that the original event was just a never-before-seen flare type from a relatively normal AGN. Although there are still a handful of other candidates for near-merging supermassive black holes waiting to be confirmed, a nondetection would set those hunting merging black holes almost back to square one.

But a nondetection would not necessarily mean Di Stefano and D'Orazio's model is wrong. "This is a process that has to happen" somewhere in the universe, Di Stefano says. As long as two black holes are orbiting each other, gravitational lensing should occur; it is just a matter of the pair being in a suitable orientation for the effect to be seen from Earth. In their original paper, she and D'Orazio predicted that roughly 10 percent of binaries would be properly angled to give astronomers a glimpse of their gravitational-lens flares.

"Should Spikey not work out, we know that this process happens," Di Stefano says. "Ultimately we should be able to detect it, but we may have to look at other systems to see it." Graham agrees. "It's a conceptually neat idea," he says. "These things *should* be lensing."



The Curious Case of Proxima C

Astronomers continue to gather evidence for a second world around the sun's nearest neighboring star

By Lee Billings

Artist's speculative, not-to-scale rendering of the Proxima Centauri planetary system. The planetary candidate Proxima c and an accompanying ring system (*right*) loom at the inner edge of a debris disk; the smaller confirmed world Proxima b (*left*) resides closer to the star (*center*).

LORENZO SANTINELLI

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PROXIMA CENTAURI, the star closest to our sun, may harbor a second planet—still.

"Still" because astronomers first announced this candidate world in April 2019, based on observations and analyses that had yet to be published or peer-reviewed. Now more thoroughly vetted and bolstered by additional data, the study reporting the potential discovery appeared in January in the journal *Science Advances*. Yet certainty is elusive—the planet could still prove to be a mirage.

"Since the very first time we saw this [potential planetary] signal, we tried to be its worst enemies," says Fabio Del Sordo, an astronomer at the University of Crete in Greece, who spearheaded the study, along with his colleague Mario Damasso of the Astrophysical Observatory of Turin in Italy. "We tried different tools to prove ourselves wrong, but we failed; however, we have to keep the doors open to all possible doubt and skepticism."

The essentials of Proxima c, as the candidate is known, remain scarcely changed from last year. Circling in a roughly 1,900-day orbit that is barely warmed by Proxima Centauri's starlight, it would be a frozen, gas-shrouded orb, perhaps six to eight times heavier than our own planet—a so-called super Earth, although it would probably be more akin to a "mini Neptune." The planet could be wreathed with vivid auroras driven by its magnetic field interacting with intense flares from its parent star. And it might harbor a sprawling ring system. It would accompany a smaller, closer-in, more Earth-like world—Proxima b—which, in 2016, was discovered twirling through the star's habitable zone, the region in which sufficient starlight allows liquid water to persist on a planet's surface.

Ever since Proxima b's discovery, astronomers have been clamoring to learn more about that alluring place, which could, in theory, harbor life. Because outer planets can profoundly affect the habitability of inner worlds—pelting them with comets, for instance, as Jupiter and Saturn seem to have done early in our solar system's history—studies of a far-out companion to Proxima b could prove crucial to that effort. Proxima c may also be a keystone for understanding how planetary systems emerge and evolve around stars like Proxima Centauri, which, as a red dwarf star much smaller and cooler than our own sun, is an emblematic example of the most common stellar type in the Milky Way. The candidate planet's chilly orbit would place it far past Proxima Centauri's "snow line," the boundary beyond which water exists only as solid ice. The snow line is also the sweet spot where theorists expect most ice-rich, intermediate-mass super Earths and mini Neptunes to form. So how could Proxima c have arisen so much farther out? Answering that question could require substantial revisions to existing planet-formation theories.

WOBBLY EVIDENCE

The best evidence for Proxima c's existence is decidedly wobbly—literally. Planets can reveal themselves by the gravitational tugs they impart on their stars, pulling a parent star toward Earth and then away from it as they move through their orbit. Tracked over time, this planetary signature manifests as a telltale stellar wobble—which registers as an oscillation between the red and blue ends of a star's spectrum. A wobble's repetition shows a planet's orbital period, whereas its amplitude—its strength—provides an estimate of a world's mass. Giant planets orbiting hellishly close to their stars create enormous, obvious wobbles, but the stellar swerve produced by something much smaller and farther out is so slow and subtle that only computational modeling of multiyear data sets can tease it out.

The putative wobble attributed to Proxima c is a roughly meter-per-second shift in Proxima Centauri's position stretched out across the candidate planet's proposed five-year-long orbit. Distinguishing it required nearly two decades' worth of measurements from two instruments, the High Accuracy Radial Velocity Planet Searcher (HARPS) and Ultraviolet and Visual Echelle Spectrograph (UVES) spectrometers, located on separate telescopes in Chile operated by the European Southern Observatory (ESO). The trouble is that lots of other things—star spots and other forms of stellar activity, as well as minor instabilities inside an Earth-bound instrument's optics—can mimic such a minuscule motion. Consequently, the recent history of planet hunting is littered with high-profile announcements of wobble-based "discoveries" of small planets that ultimately proved illusory. In their study, Damasso, Del Sordo and their colleagues detail the elaborate steps they took to rule out as many possible sources of stellar and instrumental noise as possible, but even so, their claim remains controversial.

“This detection is really pushing the bleeding edge,” says Paul Robertson, an astronomer at the University of California, Irvine, who was not involved with the research. “There is no similar example of a [wobble] detection of a planet with such a low amplitude at such a long period, and the claimed statistical significance is low compared with many other detections. That doesn’t necessarily mean it’s wrong, but it is going to require some confirmation from additional observations.”

The ESO’s latest wobble-hunting instrument, an ultrastable, extremely precise spectrometer called Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO), is already scouring Proxima Centauri and many other stars for further hints of small planets from a mountaintop in Chile. But the nature of the search requires years of observations to yield breakthrough results—time enough for worlds to complete multiple orbits, strengthening the statistical significance of any wobbly signals. In the meantime, astronomers will have to rely on other techniques to gather more evidence for Proxima c.

A CONSPIRACY OF COINCIDENCES?

If the case for Proxima c were based on wobbles alone, the candidate planet might well still be unannounced, languishing in obscurity in technical appendices. Instead a wealth of circumstantial evidence is seemingly boosting the odds that the candidate is genuine. In 2017 researchers investigating Proxima Centauri using the ESO’s Atacama Large Millimeter/Submillimeter Array (ALMA), a radio telescope in Chile, detected a strange blip at what turned out to be just the right distance from the star to correspond with the wobble-based estimate of Proxima c’s orbit. The blip could have been natural radio waves emanating from a gargantuan, Saturn-like ring system around an unseen planet—or it could have been coincidental emissions from a cloud of dust around the star or even from a far distant background galaxy. ALMA’s observations also yielded suggestive hints of dust belts around the star that may have been sculpted by Proxima c and perhaps other, undetected planets. (Damasso, Del Sordo and their colleagues have lobbied—unsuccessfully so far—for follow-up observations on ALMA to take another look. But they have managed to observe the Proxima Centauri system with another ESO asset, the planet-imaging Spectro-Polarimetric High-Contrast Exoplanet Research Instrument, or SPHERE. Their analysis of SPHERE’s long-shot stab at detecting Proxima c is still underway.)

More tantalizing support emerged in 2018 from Gaia, a Milky Way–mapping satellite operated by the European Space Agency (ESA) that uses a technique called astrometry to precisely track the position of Proxima Centauri—and billions of other stars—across the sky. Combining two years’ worth of Gaia’s publicly available data with earlier measurements from Gaia’s precursor satellite, Hipparcos, a team led by the Paris Observatory astronomer Pierre Kervella found a slight anomaly in Proxima Centauri’s motion that could be explained by the presence of a planet that, in mass and orbit, would be strikingly similar to Damasso and his colleagues’ estimates for Proxima c.

“I am convinced that Gaia astrometry is the most critical piece of information to be added to the puzzle” of Proxima c, says Alessandro Sozzetti, a Gaia team member at the Astrophysical Observatory of Turin and a co-author of the Proxima c discovery paper. Besides showing the planet to be real, Gaia’s measurements of Proxima Centauri’s motion would also unveil Proxima c’s actual mass—allowing astronomers to better predict its age, brightness and other properties crucial for learning whether any current or future Earth- or space-based telescope might have a reasonable chance of taking its picture.

Then again, Gaia’s measurements could instead conclusively refute the planet’s existence. In fact, the clinching evidence for or against Proxima c’s reality could already exist on an ESA hard drive. Gaia may already have sufficient observations of the star to pin down the potentially planetary nature of its anomalous motion, the study authors say, but most of those raw data still require substantial processing and calibration, and they are not expected to be publicly released for at least another two years.

A CHARMING NEIGHBOR

In the end, whether the world is real or imaginary, Proxima c’s greatest lesson may concern the evolution of planet hunting here on Earth. Although astronomers have now discovered thousands of planets around other stars—with discoveries of tens of thousands more on the horizon—most of those finds are the low-hanging fruit of our galaxy’s planetary bounty. Discovering the choicest planets—those around nearby stars that offer the best chances for further studies, perhaps even for discovering alien life—remains, for now, a dauntingly arduous task. Consider that the decades-long effort to find and confirm just one world, Proxima c, has already consumed untold human toil and significant allotments of fiercely contested observing time on many of Earth’s most advanced telescopes and instruments—with an outcome that is still uncertain.

“Looking for these kinds of planets around a high number of stars is definitely not sustainable nowadays in terms of time investment and challenges imposed,” Del Sordo says. Why, then, one might ask, should we look at all? “A sense of old-fashioned exploration,” he says. “The discovery of remote, unknown but maybe accessible worlds. And perhaps the unconscious feeling this system can be reached by humans sometime in the distant future. Proxima is our closest neighbor in an immense universe. How could we not be charmed by it?”

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LIFE, UNBOUNDED

Death on Mars

The Martian radiation environment is a problem for human explorers that cannot be overstated

NASA, JPL-CALTECH AND MSSS

As is the way of news cycles, in recent days we're back to hearing about plans for setting humans up on Mars. A few years ago this idea was in the spotlight because of now defunct efforts such as Mars One, which somehow got 200,000 people to express interest in what would have been a lifelong trip to the Red Planet. We've also seen Elon Musk's vision of how SpaceX would eventually provide a human "backup plan" by permanently settling Mars.

In January, Musk brought the idea up again, in typically provocative fashion, by talking about sending one million people to Mars by 2050, using no fewer than three Starship launches per day (with a stash of 1,000 of these massive spacecraft on call). He also raised the possibility of giving Martian-wannabe settlers loans to enable them to pay for the opportunity. Naturally, for many observers this also provoked discussion of indentured servitude for those "seeking a new life in the off-world colonies," to paraphrase a famous line from the 1982 movie *Blade Runner.*

But whatever you think about Musk's pronouncements or about his businesses, there are some very serious scientific hurdles to setting humans up on Mars (and in full disclosure, I own a few Tesla shares, and I greatly admire his vision and drive for terrestrial change, as well as the space-launch business, but I'm also somewhat wary of people being taken seriously just because they have amassed a lot of cash).

One of those hurdles is radiation. For reasons unclear to me, this tends to get pushed aside compared with other questions to do with Mars's atmosphere (akin to sitting 30 kilometers above Earth with no oxygen), temperatures, natural resources (water), nasty surface chemistry (perchlorates) and lower surface gravitational acceleration (one third of that on Earth).

But we do have good data on the radiation situation on Mars (and in transit to Mars) from the Radiation Assessment Detector (RAD) that has been riding along with the Curiosity rover since its launch from Earth.

The bottom line is that the extremely thin atmosphere on Mars and the absence of a strong global magnetic field result in a complex and potent particle radiation environment. There are lower-energy solar wind particles (such as protons and helium nuclei) and much higher-energy cosmic-ray particles crashing into Mars all the time. The cosmic rays, for example, also generate substantial secondary radiation—crunching into Martian regolith to a depth of several meters before hitting an atomic nucleus in the soil and producing gamma rays and neutron radiation.

An analysis by Donald M. Hassler and his colleagues, published in 2014 in *Science*, noted that a human expedition with 360 days total in interplanetary space plus 500 days on Mars itself would expose astronauts to just over one sievert of radiation. Now, statistically that's not too awful. It would increase your odds of getting fatal cancer by some 5 percent over your lifetime.

But if we consider just the dose on Mars, the rate of exposure averaged over one Earth year is just more than 20 times that of the maximum allowed for a Department of Energy radiation worker in the U.S. (based on annual exposure).

And that's for a one-off trip. Now imagine you're a settler, perhaps in your 20s, and you're planning on living on Mars for at least (you'd hope) another 50 Earth years. Total lifetime exposure on Mars? Could be pushing 18 sieverts.

Now that's kind of into uncharted territory. If you got eight sieverts all at once, for example, you would die. But getting those eight sieverts spread out over a couple of decades could be perfectly survivable—or not. The RAD measurements on Mars also coincide with a low level of solar-particle activity, and they vary quite a bit as the atmospheric pressure varies (which it does on an annual basis on Mars).

Of course you need not spend all your time above surface on Mars. But you'd need to put a few meters of regolith above you or live in some deep caves and lava tubes to dodge the worst of the radiation. And then there are risks not to do with cancer that we're only just beginning to learn about. Specifically, there is evidence that neurological function is particularly sensitive to radiation exposure, and there is the question of our essential microbiome and how it copes with long-term, persistent radiation damage. Finally, as Hassler et al. discuss, the "flavor" (for want of a better word) of the radiation environment on Mars is simply unlike that on Earth, measured not just by extremes but by its makeup, comprising different components than on Earth's surface.

To put all of this another way: in the worst-case scenario (which may or may not be a realistic extrapolation), there's a chance you'd end up dead or stupid on Mars. Or both.

There is also a real difference between a small group of astronauts being constantly monitored, advised and trained to optimize their time on Mars (whether brief or long term) and a million settlers eager to be pioneers. The old trope of "what could possibly go wrong?" springs to mind.

Obviously no one, not even an emboldened SpaceX, is going to plop humans down on Mars en masse without worrying about all of this. But I think it's an open question as to just how big a challenge the radiation hurdle turns out to be, along with all the other hurdles.

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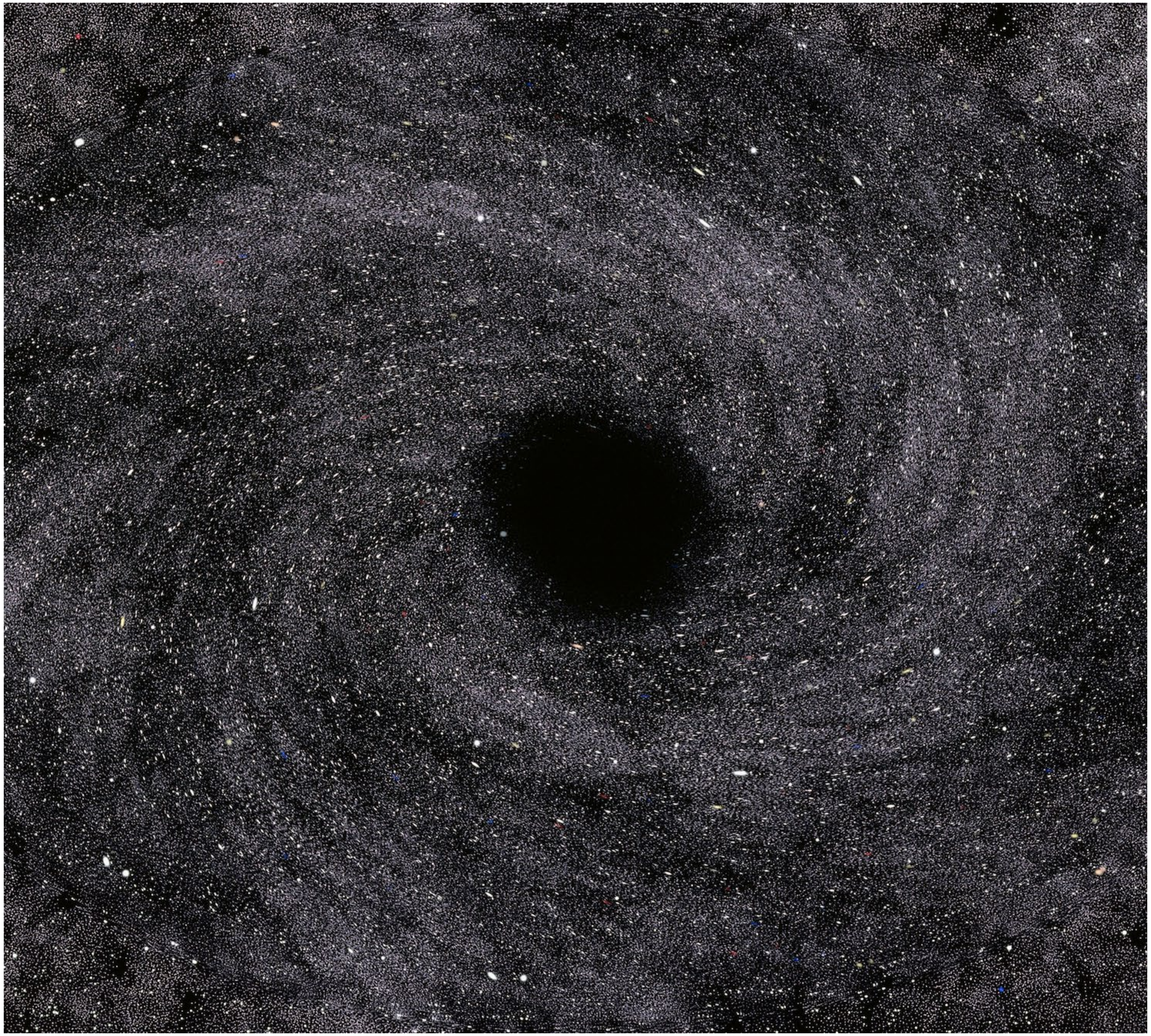
OBSERVATIONS

Have We Solved the Black Hole Information Paradox?

The answer is maybe. As a bonus, we may soon have a new understanding of nature at a qualitatively different and deeper level than ever



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Black holes, some of the most peculiar objects in the universe, pose a paradox for physicists. Two of our best theories give us two different—and seemingly contradictory—pictures of how these objects work. Many scientists, including me, have been trying to reconcile these visions, not just to understand black holes themselves but also to answer deeper questions, such as "What is spacetime?" Although I and other researchers made some partial progress over the years, the problem persisted. In the past year or so, however, I have developed a framework that I believe elegantly addresses the problem and gives us a glimpse of the mystery of how spacetime emerges at the most fundamental level.

Here is the problem: From the perspective of general relativity, black holes arise if the density of matter becomes too large and gravity collapses the material all the way toward its central point. When this happens, gravity is so strong in this region that nothing—even light—can escape. The inside of the black hole, therefore, cannot be seen from the outside, even in principle, and the boundary, called the event horizon, acts as a one-way membrane: nothing can go from the interior to the exterior, but there is no problem in falling through it from the exterior to the interior.

But when we consider the effect of quantum mechanics, the theory governing elementary particles, we get another picture. In 1974 Stephen Hawking presented a calculation that made him famous. He discovered that if we include quantum-mechanical effects, a black hole in fact radiates, though very slowly. As a result, it gradually loses its mass and eventually evaporates. This conclusion has been checked by multiple methods now, and its basic validity is beyond doubt. The odd thing, however, is that in Hawking's calculation, the radiation emitted from a black hole does not depend on how the object was created. This means that two black holes created from different initial states can end up with identical final radiation.

Is this a problem? Yes, it is. Modern physics is built on the assumption that if we have perfect knowledge about a system, then we can predict its future and infer its past by solving the equation of motion. Hawking's result would mean that this basic tenet is incorrect. Many of us thought that this problem was solved in 1997, when Juan

Modern physics is built on the assumption that if we have perfect knowledge about a system, then we can predict its future and infer its past by solving the equation of motion.

Maldacena discovered a new way to view the situation, which seemed to prove that no information was lost.

Case closed? Not quite. In 2012 Ahmed Almheiri and his collaborators at the University of California, Santa Barbara, presented in their influential paper a strong argument that if the information is preserved in the Hawking emission process, then it is inconsistent with the "smoothness" of the horizon—the notion that an object can pass through the event horizon without being affected. Given that the option of information loss is out of the question, they argued that the black hole horizon is in fact not a one-way membrane but something like an unbreakable wall, which they called a firewall.

This confused theorists tremendously. As much as they disliked information loss, they abhorred firewalls, too. Among other things, the firewall idea implies that Einstein's general relativity is completely wrong, at least at the horizon of a black hole. In fact, this is utterly counterintuitive. For a large black hole, gravity at the horizon is actually very weak because it lies far away from the central point, where all the matter is located. A region near the horizon thus looks pretty much like empty space, and yet the firewall argument says that space must abruptly "end" at the location of the horizon.

The main thrust of my new work is to realize that there are multiple layers of descriptions of a black hole, and the preservation of information and the smoothness of the horizon refer to theories at different layers. At one level we can describe a black hole as viewed from a distance: the black hole is formed by the collapse of matter, which eventually evaporates, leaving the quanta of Hawking radiation in space. From this perspective, Maldacena's insight holds, and there is no information loss in the process. That is because in this picture, an object falling toward the black hole never enters the horizon, not because of a firewall but because of a time delay between the clock of the falling object and that of a distant observer. The object seems to be slowly "absorbed" into the horizon, and its information is later sent back to space in the form of subtle correlations between particles of Hawking radiation.

On the other hand, the picture of the black hole interior emerges when we look at the system from the perspective of someone falling into it. Here we must "ignore" the fine details of the system that infalling observers could not see because they have only finite time until they hit the singular point at the center of the black hole. This limits the amount of information they can access, even in principle. The world the infalling observer perceives, therefore, is the "coarse-grained" one. And in this picture, information need not be preserved because we already threw away some information to arrive at this perspective. This is the way the existence of interior spacetime can be compatible with the preservation of information: they are the properties of the descriptions of nature at different levels!

For a better understanding of this concept, the following analogy might help. Imagine water in a tank and consider a theory describing waves on the surface. At a fundamental level, water consists of a bunch of water molecules, which move, vibrate and collide with one another. With perfect knowledge of their properties, we can describe them deterministically without information loss. This description would be complete, and there would be no need to even introduce the concept of waves. On the other hand, we could focus on the waves by overlooking molecular-level details and describing the water as a liquid. The atomic-level information, however, is not preserved in this description. For example, a wave can seem to simply "disappear," although the truth is that the coherent motion of water molecules that created the wave was transformed into more random motions of individual molecules without anything disappearing.

This framework tells us that the picture of spacetime offered by general relativity is not as fundamental as we might have thought—it is merely a picture that emerges at a higher level in the hierarchical descriptions of nature, at least concerning the interior of a black hole. Similar ideas have been discussed previously in varying forms, but the new framework allows us to explicitly identify the relevant microscopic degrees of freedom—in other words, nature's fundamental building blocks—participating in the emergence of spacetime, which surprisingly involves elements that we think to be typically located far away from the region of interest.

This new way of thinking about the paradox can also be applied to a recent setup devised by Geoff Penington, Stephen H. Shenker, Douglas Stanford and Zhenbin Yang in which Maldacena's scenario is applied more rigorously but in simplified systems. This allows us to identify which features of a realistic black hole are or are not captured by such analyses.

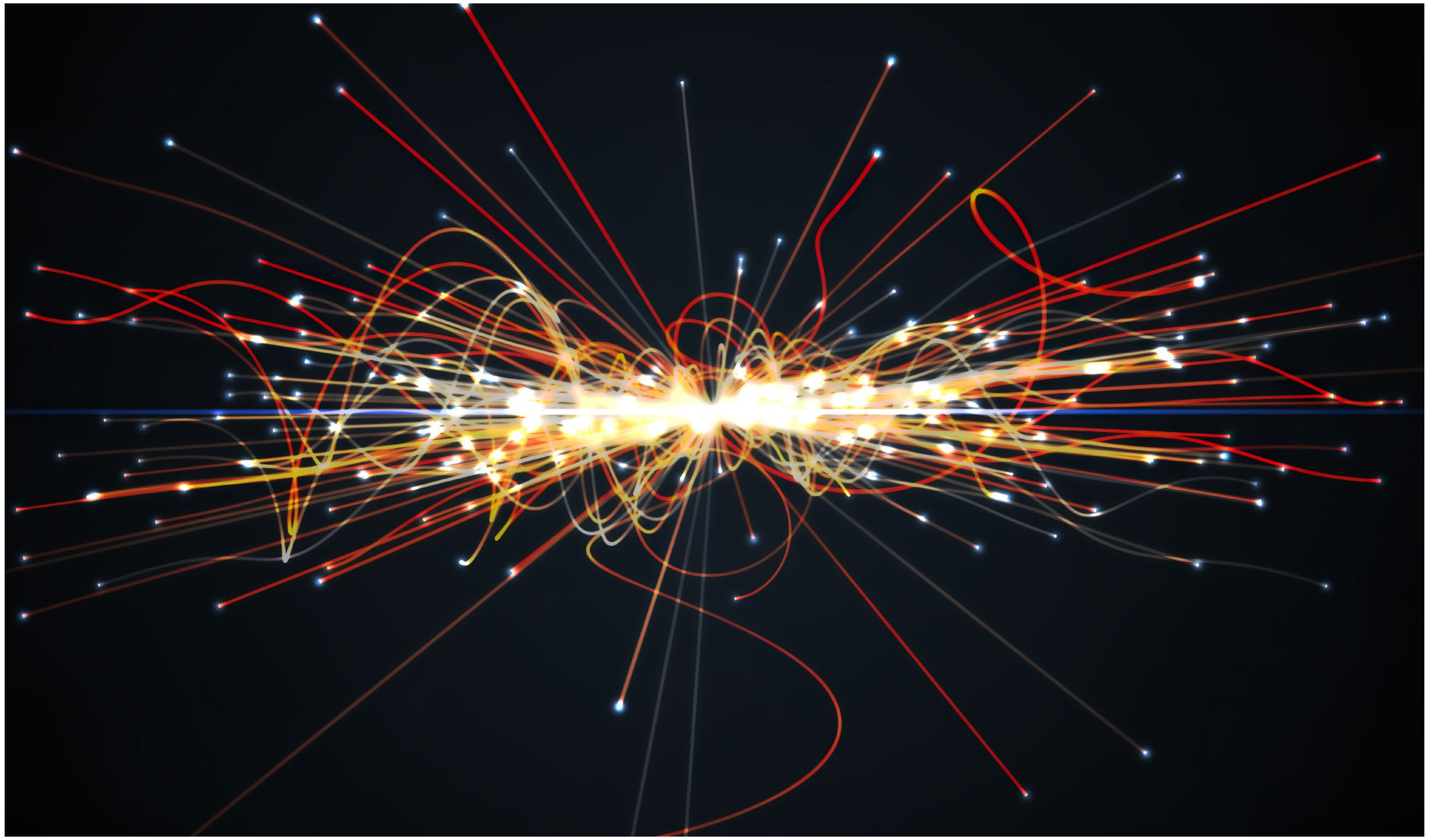
Beginning with the era of Descartes and Galileo, revolutions in physics have often been associated with new understandings of the concept of spacetime, and it seems that we are now in the middle of another such revolution. I strongly suspect that we may soon witness the emergence of a new understanding of nature at a qualitatively different and deeper level.

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.

CROSS-CHECK

What's Wrong with Physics

A physicist slams hype about multiverses, string theory and quantum computers and calls for more diversity in his field



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One of the best things about being a full-time staff writer (as opposed to a lowly blogger) for Scientific American *back in the 1990s was that I got to hang out with all these smart, curious people who knew a lot about a lot of things. That's also one of the best things about my job at Stevens Institute of Technology, where I've taught since 2005. The people I know best are my colleagues in the College of Arts and Letters, who include philosophers, historians, anthropologists, psychologists, social scientists, artists and musicians. But I've also gotten to know engineers and hard scientists. One is Chris Search, a physicist who specializes in quantum optics. I like bringing him into my science-writing seminar because my students love hearing him riff, with great enthusiasm and candor, about physics and other science-related topics. I thought readers of this blog might enjoy hearing Search's views too. Below are his answers to my questions.* —*John Horgan*

Horgan: Why physics?

Search: I was always curious about how things work. When I was young, physics seemed to offer answers to all of the mysteries of the universe. It felt authoritative and unequivocal in its explanations of nature and the origin of the universe. In that sense, it was the perfect religion for my teenage self as I went through an atheist phase, which admittedly was probably provoked by all the popular physics books that I was devouring at that age, such as *A Brief History of Time*. Those books were always so dogmatic, like the Catholic Sunday school I went to as a kid.

Horgan: Nice comparison. Any regrets about choosing physics?

Search: No. Over the years my view of physics has evolved significantly. I no longer believe that physics offers all of the answers. It can't explain why the universe exists or why we are even here. It does, though, paint a very beautiful and intricate picture of how the universe works. I actually feel sorry for people who do not understand the laws of physics in their full mathematical glory because they are missing out on something that is truly divine.

The beautiful interlocking connectedness of the laws of physics indicates to me how finely tuned and remarkable the universe is, which for me proves that the universe is more than random chance. Ironically, it was by studying physics that I stopped being an atheist because physics is so perfect and harmonious that it had to come from something. After years of reflecting, I simply could not accept that the universe is random chance as the anthropic principle implies.

I should also add that physics has amazing predictive powers that continue to fascinate me. All of the equations fit so perfectly together that it boggles my mind that I can start from a few simple equations and derive how a new device will function. No other area of human pursuit has the same level of precision and predictive power as physics.

Not only that but physics can and does explain so much of the world we live in. I feel like we are living in a postscientific age with quackery running rampant because people are so ignorant of science. This ranges from climate deniers who don't understand basic thermodynamics to much of the new age stuff I see for sale all over the very affluent (and, ironically, well-educated) town that I live in, which is nothing more than marketing to earn a buck. I feel if people just understood more science and, in particular, physics, they wouldn't be so easily duped. For this reason, I'm also very grateful for having studied physics, since it makes it easier to discern fact from fiction in life, and hopefully I can do that for others.

Horgan: Now I wish I'd taken more than one lousy semester of physics! What are your current interests?

Search: Over the past few years I've moved more and more away from basic physics and toward applied physics. I've been working on various types of optical sensors, including gyroscopes. I've even started a new degree program in optical engineering, which probably means I've lost my credentials as a true physicist.

Horgan: You're too modest. Does your work have any relevance for quantum computing? Speaking of which, do you think that we are going to have commercial quantum computers anytime soon?

Search: I certainly hope that I have nothing to do with quantum computing. It is nothing personal against the subject, but I just view it as the research topic du jour. Physics doesn't change, but what is popular in physics does change, and old physics gets rebranded as new physics. (What we call qubits are nothing more than the two-level systems such as spin-1/2 and two-level atoms physicists have studied since the dawn of quantum physics.) I'm very skeptical of doing what is trendy and popular because then you are just playing follow-the-leader. Everyone jumps into the field all doing more or less the same stuff because that is where the funding is and that is the easiest way to publish papers. In my opinion, this trendiness leads to a massive amount of invested effort but with very few significant results because what everyone is doing is so similar and overlapping. I suppose it is a form of the law of diminishing returns. The big breakthroughs that fundamentally change our understanding come from the people who follow their own path even when everyone else is running in the other direction. Unfortunately, physics, like other academic fields, usually doesn't give much support to those who don't want to play follow-the-leader.

I think in the future there will be certain very specific applications for simple quantum computers that we may be able to build. But I don't think there is any chance that ordinary computers are ever going to be supplanted by quantum ones.

Horgan: Good to know! I've been pretty critical of theoretical physics. Have I been unfair?

Search: No. Theoretical particle physics is definitely a dead subject. Other areas of theoretical physics have made great strides in applications, but at the same time there hasn't been any fundamentally new development in our understanding of physics for decades.

One thing that I find very disturbing about physics is that the same textbooks are being used now in graduate programs that I used when I was a graduate student in the 1990s. These are also the same textbooks that my professors often used when they were students, in many cases before I was even born. (One of the best examples is John David Jackson's *Classical Electrodynamics,* which has been in use in nearly all graduate programs since the 1960s.) If a field is making fundamental breakthroughs, wouldn't you expect the textbooks to become outdated and have to be replaced with completely new books?

A pretty ironic example of the stagnation in physics is that the third course in an introductory college physics sequence (after mechanics and electromagnetism) is often called "Modern Physics." This course usually covers quantum theory, which we like to think of as "modern." But quantum theory was developed at the same time the TV series *Downton Abbey* takes place, which makes it clear how not modern quantum theory is now. Even the Standard Model of particle physics is older than me, and I'm middle-aged.

Horgan: Quantum mechanics and *Downton Abbey!* Sounds like a cool new Netflix series! So what's your take on string theory and the whole quest for a unified theory?

Search: It is a waste of time. Unless it is testable, which it most likely will never be, then it is no longer even science. I think those people doing string theory forget they are actually doing science, or perhaps they should be sent back to middle school to be reminded of the scientific process. What distinguishes science from other modes of inquiry about the world we live in (for example, religion and philosophy) is that new theories have to be tested experimentally. If they are not confirmed by experimental results, we discard them.

I think the entire string theory community should take a deep breath and figure out what next to do with their lives. Someday in the distant future, when technology has advanced enough or we have nearly infinite energy resources, then we may be able to directly test string theory or other unified theories, at which point theoretical work on unified theories may become relevant again.

Horgan: What about multiverses and the anthropic principle?

Search: Like string theory, this is not science. How do you test the existence of other universes? The universe is everything out there that we can observe. Another universe would therefore be separate from our own and not interact with it in any manner. If we could detect other universes, that would imply that they are observable by us, but that leads to a contradiction because our universe is everything that is observable by us.

The anthropic principle is something I discuss in my freshman E&M class, actually. But I think it is a total cop-out for physicists to use the anthropic principle to explain why the laws of physics are the way they are. The anthropic principle implies the existence of other universes where the laws of physics are different. Yet the existence of these other universes is untestable. It also implies that our existence is mere random luck.

At the end of the day, the existence of multiverses and the anthropic principle are really religious viewpoints wrapped up in scientific jargon. They have no more legitimacy than believing that God created the universe.

Horgan: Sabine Hossenfelder, who spoke at Stevens in 2018, claims in her book *Lost in Math* that the obsession with "beauty" has "led physics astray." What's your view?

Search: Who decides what is beautiful and what is not? Beauty is highly subjective and based on our social conditioning and cultural upbringing. It is not universal by any means. Even among human societies there is a great deal of variation of what or who is considered beautiful. Western aesthetics of beauty are so dominant everywhere (magazine covers, advertisements, movies and TV shows, social media, and so on) that we may be oblivious to the fact that not everyone thinks the same things are beautiful.

I am very skeptical of any physical "laws" derived on the basis of their beauty. Perhaps alien cultures would consider asymmetry and disorder beautiful, in which case they would strongly disagree with the aesthetic approaches of string theorists.

Horgan: Speaking of beauty, how objective is physics? Might physics look different if more non-Western, nonmale, nonwhite physicists were involved?

Search: Physics has without a doubt been a profession of white men in the past. Diversity is still very lacking in physics today. I was reflecting with a friend recently that both as an undergraduate and in graduate school, none of my physics professors were either black or Latino. They were almost all white and, to a lesser extent, Asian. There were also only two female professors that I had in my entire education as a physicist. Things don't seem to have changed that much since I was a student—just look at the physics department at Stevens. (As a rather stark example of the lack of diversity, in 2013 only 1.7 percent of bachelor's degrees in physics went to women of color, according to the American Institute of Physics.)

This question of how physics would look if it were more diverse is therefore hard to answer. One can only speculate. My belief is that different cultural traditions and less homogeneity of thought (that is, groupthink) would have led to more diverse avenues of research within physics and would have enriched the philosophical interpretations by drawing on more non-Western philosophies and systems of belief. Such diversity of research directions and interpretations could only have enriched physics and led to developments that we can only imagine. Perhaps we would have by now a working theory of quantum gravity.

Horgan: I'd love to think so. Should physics research, if supported by tax dollars or student tuition, have some practical potential?

Search: Yes. There are simply so many problems facing not just the U.S. but the entire planet these days, ranging from climate change to massive wealth and income inequality in this country. It is unconscionable for tenured academic researchers to earn very generous salaries from their faculty positions and research grants and not be using their abilities to help solve some of these problems. Many are doing just that, but one has to wonder how string theorists are contributing to society when even most of the physics community doesn't understand what they are doing.

Horgan: If you were Physics Czar, would you pull the plug on any projects? Increase funding for any?

Search: I wouldn't want to comment on specific projects here, since I'm not sufficiently familiar with the details and directions of science funding. I do think that this country spends an obscene amount of money on defense, and the Department of Defense has always been one of the biggest funders of science. I often comment in my freshman physics class that war is good for physics. That is ironic, given that most college faculty politically lean very decidedly to the left, but nonetheless increased military spending usually benefits us professors.

Horgan: Ironic indeed. You grew up Catholic. Are you religious in any way now?

Search: Yes. I do believe that something created the universe and the universe has some purpose. That creator, I suppose, I would call God, but it doesn't really matter what you call it.

The anthropic principle just seems absurd to me, and I wish science, and particularly physics, was more accepting of religion and faith. They answer completely different questions. Science can explain how things work in the universe and can make predictions about how they will function in the future, but it can't answer at a fundamental level why the universe is the way it is or how it came to be. Those are the domains of religion and faith. Also, people have felt since as far back as we know a deep connection to something greater than and beyond the universe that we perceive. This transcends culture and society and is present in all religions and forms of spirituality. Physics, though, discounts the idea that there exists something beyond what we can model with our equations or capture in our experimental data. That, though, does not mean it is any less real than quantum mechanics or Maxwell's equations.

I am nonetheless very skeptical of organized religion, which has often been nothing more than a system for a small elite to consolidate power and influence over the masses. I think that one's faith and connection with God or the universe is deeply individualistic, and everyone must follow their own spiritual path. Religious texts and theologians can serve as guides and advisers on one's path but nothing more. We should all listen to God directly and not to a priest standing at an altar.

Horgan: Well said. What's your utopia?

Search: My utopia is a fairer society than the one we live in, where everyone has the same opportunities for success and a good life regardless of wealth, gender or race. This is by far my biggest worry these days.

The American dream is pretty much dead. We do not live in a meritocracy where one gets ahead simply by hard work and talent; rather we live in what someone I read called an inherited meritocracy. The family you are born into is more decisive these days than how hard you work as far as the level of economic attainment you achieve. The color of your skin and the wealth of your family are more important than anything else because these things determine if you can get a high-quality K-12 education and can afford to go to an elite university, which opens most of the doors and opportunities that help secure one's career and economic future. Also, coming from an economically secure family gives young people more options and opportunities because of the economic support they can count on, such as the freedom to graduate from college without massive amounts of student debt.

We need to change these things before the oppressive level of inequality in this country destroys it. The problem has many facets ranging from the heartless winner-take-all capitalism that we practice in this country, the very scant and frayed social safety net that has not kept up with the changing economy, the horrific costs of a college education, to government policies such as funding for schools being tied to local property taxes. Even those factors ignore the systemic racism and gender discrimination in our society and economic system, which gives white men like myself so many more advantages and privileges than everyone else.

Celestial Movement

The sky is always changing. The planets move overhead as they trace their paths around the sun, and the moon rotates through the heavens as it circles our own world. Although the stars that provide their backdrop stay fixed in relation to one another, they, too, spin above as Earth makes its daily revolution and its yearly passage around the sun. To appreciate the view, check out these stargazing calendars, go outside at night and look up!

ESO/S. BRUNIER

Astronomical Events April—May 2020

April • Event

1	**Moon reaches northernmost declination**
	Moon: First quarter
3	**Evening sky: Venus in the star cluster Pleiades**
4	**Evening sky: Moon near Regulus in constellation Leo**
7	**Moon at perigee (356,900 km), apparent diameter 33´ 30˝**
8	**Moon: Full moon**
13	**Moon reaches southernmost declination**
14	**Moon: Last quarter**
	Morning sky: Moon lower right of Jupiter
15	**Morning sky: Moon below Saturn**
16	**Morning sky: Moon below Mars**
20	**Moon at apogee (406,500 km), apparent diameter 29´ 23˝**
22	**Maximum of Lyrid meteor shower**
23	**Moon: New moon**
25	**Evening sky: Moon near Aldebaran**
26	**Uranus in conjunction with sun**
	Evening sky: Moon left of Venus
28	**Moon reaches northernmost declination**
30	**Moon: First quarter**

April/May 2020: Visibility of planets

While Venus is still high in the sky in April as a bright evening star, it disappears at the end of May in the brilliance of the sun. In return, the solar system's innermost planet, Mercury, gives a short performance in the evening sky. Mars, Jupiter and Saturn dominate the early morning sky.

Mercury is always close to the sun and can therefore only be seen either low in the west after sunset or in the east before sunrise. The best time to observe Mercury is when it is either near its greatest eastern elongation (evening visibility) or near its greatest western elongation (morning visibility), which may be anywhere between 17.9° and 27.8° due to Mercury's highly elliptical orbit. The visibility depends also on the angle at which the ecliptic intersects the horizon and whether the planet is above or below the ecliptic. Therefore, Mercury can be observed for only brief periods of time during the year. The planet had reached a greatest elongation of 27.8° west on March 24 and rises about 50 minutes before the sun at the beginning of April. But because the angle of the ecliptic to the eastern horizon is small for observers in the continental U.S., Mercury's light is lost in bright morning light. However, although Mercury's greatest eastern elongation will reach a rather moderate value of 23.6° on June 4, the planet will reward observers in the northern hemisphere with good evening visibility from mid-May through June 10. If you're unsure where you have to look, wait for May 22, when Mercury joins much brighter Venus in the evening sky. Two days later, Mercury has clearly passed Venus and the young crescent of the waxing moon joins the scene, making an impressive sight low in the western sky.

Venus is a bright object in the evening sky. In early April, the planet can be spotted as soon as 15 minutes after sunset in the west and continues to be visible for more than three hours every evening. As the planet moves eastward through Taurus, it passes right through the Pleiades star cluster on April 3. In mid-May the eastward motion relative to the stars comes to a halt and after this standstill Venus appears to reverse in a westward motion. The angular separation between Venus and the sun quickly diminishes and after Venus is surpassed by Mercury on May 22, the planet's visibility period comes to an end.

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Astronomical Events April—May 2020

May • Event	
4	Maximum of Eta Aquarid meteor shower
	Mercury in superior conjunction
6	Moon at perigee (359,700 km), apparent diameter 33´ 30˝
7	Moon: Full moon
11	Moon reaches southernmost declination
12	Morning sky: Moon near Jupiter and Saturn
14	Moon: Last quarter
15	Morning sky: Moon lower left of Mars
18	Moon at apogee (405,600 km), apparent diameter 29´ 22˝
22	Dusk: Mercury 1° south of Venus
	Moon: New moon
24	Dusk: Moon near Venus and Mercury
25	Moon reaches northernmost declination
28	Evening sky: Moon near Regulus in constellation Leo
30	Moon: First quarter

April/May 2020: Visibility of planets

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Mars, after having passed Jupiter and Saturn in late March, is now the trailing planet in a row of three rising in the east about three hours before sunrise. In the following weeks, Mars moves eastward through the constellation Capricornus and into Aquarius. Mars is much brighter than any star in both constellations. The planet's reddish color makes the identification even easier.

Jupiter is the first and brightest planet in a row of three rising in the early morning sky. The largest planet in our solar system is closely followed by Saturn (the solar system's second largest planet) and, farther behind, by Mars as they apparently move along Earth's sky from east to west. This apparent movement is, in fact, due to Earth's rotation. With respect to the stars, Jupiter is slowly moving eastwards in constellation Sagittarius, before turning around in mid-May and beginning a retrograde movement – a clear sign that the planet is due to reach its opposition soon (on July 14).

Saturn is in constellation Capricornus, just about 5° east of Jupiter, and is therefore also visible in the early morning sky. Both planets change from prograde movement to retrograde movement in mid-May. Saturn will reach its opposition six days later than Jupiter, on July 20.

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