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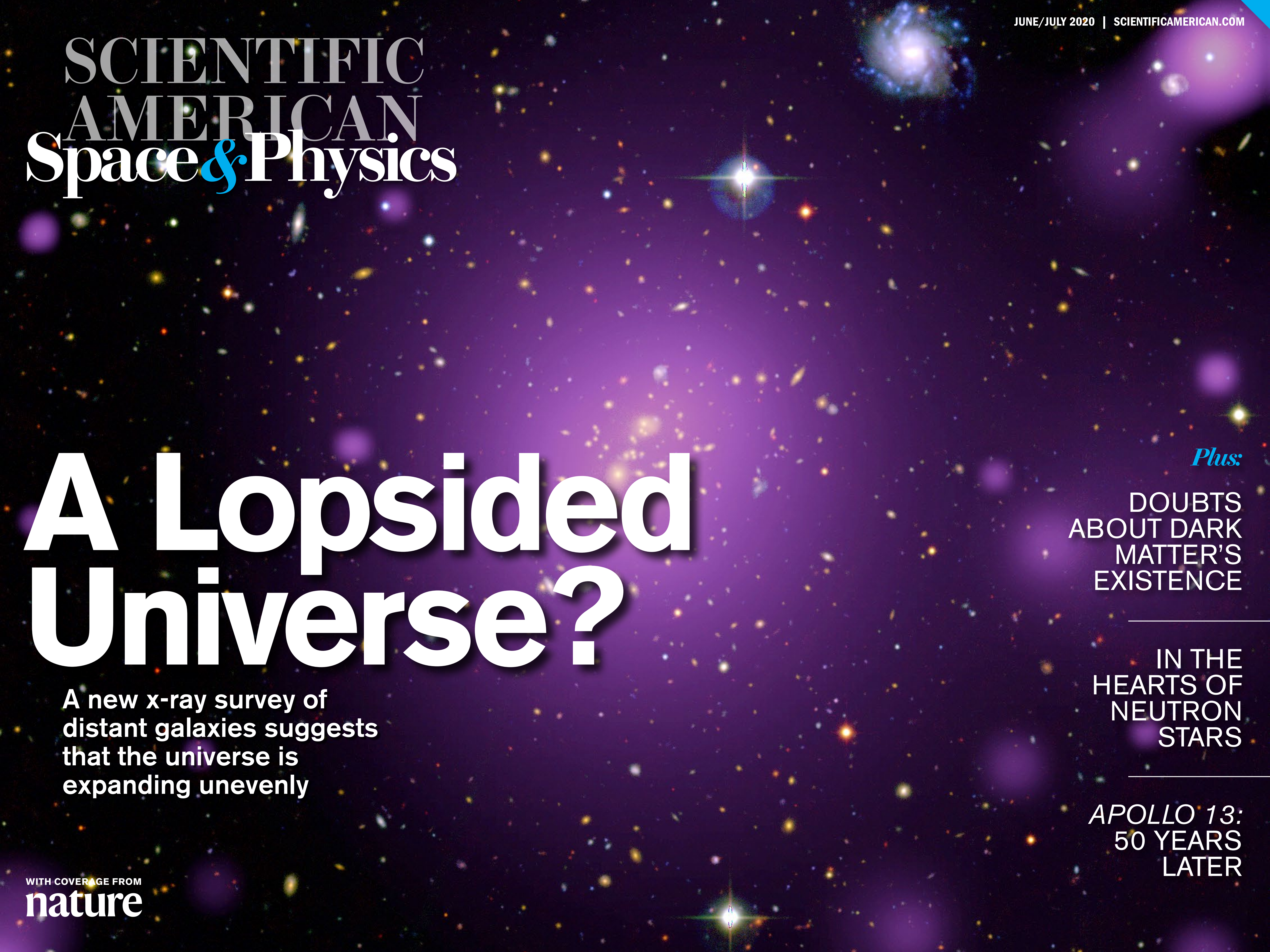

A Lopsided Universe?

A new x-ray survey of distant galaxies suggests that the universe is expanding unevenly

Plus:

DOUBTS ABOUT DARK MATTER'S EXISTENCE

IN THE HEARTS OF NEUTRON STARS

APOLLO 13: 50 YEARS LATER

WITH COVERAGE FROM
nature

LIZ TORMES

The Beautiful, Irregular Universe

In my eighth-grade science class, our teacher explained to us the Doppler effect: that objects moving away from us would display stretched-out sound or light waves, whereas objects moving toward us would show crunched-up sound or light waves. The instructor cited as an example that astronomers could determine whether cosmological objects are moving toward or away from Earth depending on if their light waves were stretched out (redshifted for longer wavelengths) or were shorter wavelengths (blueshifted). This captured my imagination immediately, and I pictured an ever expanding universe spreading out away from Earth evenly like the ripples formed by dropping a stone in a pond. And indeed, measurements of the cosmic microwave background radiation suggest that the universe spread evenly following the big bang. But now, as senior editor Lee Billings reports in this issue's cover story, the expansion of the universe may not be uniformly distributed but may be occurring more rapidly in certain regions (see "Do We Live in a Lopsided Universe?"). As with much astronomical research, it sometimes takes years to see below the surface of what we thought we understood.

Elsewhere in this issue, one candidate source of dark matter is at risk of being ruled out (see "Milky Way Dark Matter Signals in Doubt after Controversial New Papers"), and be sure to check out some of the Hubble Space Telescope's most famous images, such as the Eagle Nebula, the Lagoon Nebular, and others (see "A Birthday Message from the Hubble Telescope"). Dive in!

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SPACE & PHYSICS

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ESA AND XMM-NEWTON (*X-RAYS*); CFHT-LS (*OPTICAL*); XXL SURVEY

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NEWS

YUICHIRO CHINO *GETTY IMAGES*

Are We Ready for Quantum Computers?

Hardware hasn't caught up with theory, but we're already lining up many previously intractable problems for when it does

A recent paper by Google claiming that a quantum computer performed a specific calculation that would choke even the world's fastest classical supercomputer has raised many more questions than it answered. Chief among them is this: When full-fledged quantum computers arrive, will we be ready?

Google achieved this milestone against the backdrop of a more sobering reality: Even the best gate-based quantum computers today can only muster around 50 qubits. A qubit, or quantum bit, is the basic piece of information in quantum computing, analogous to a bit in classical computing but so much more.

Gate-based quantum computers operate using logic gates, but in contrast with classical computers, they exploit inherent properties of quantum mechanics such as superposition, interference and entanglement. Current quantum computers are so noisy and error-prone that the information in its quantum state is lost within tens of microseconds through a mechanism called decoherence and through faulty gates.

Still, researchers are making demonstrable, if slow, progress toward more usable qubits. Perhaps in 10 years, or 20, we'll reach the goal of reliable, large-scale, error-tolerant quantum computers that can solve a wide range of useful problems.

When that day comes, what should we do with them?

We've had decades to prepare. In the early 1980s American physicist Paul Benioff published a paper demonstrating that a quantum-mechanical model of a Turing machine—a computer—was theoretically possible. Around the same time, Richard Feynman argued that simulating quantum systems at any useful scale on classical computers would always be impossible because the problem would get far, far too big: the required memory and time would increase exponentially with the volume of the quantum system. On a quantum computer, the required resources would scale up far less radically.

Feynman really launched the field of quantum computing when he suggested that the best way to study quantum systems was to simulate them on quantum computers. Simulating quantum physics is *the* app for quantum computers. They're not going to be helping you stream video on your smartphone. If large, fault-tolerant quantum computers can be built, they will enable us to probe the strange world of quantum mechanics to unprecedented depths. It follows different rules than the world we observe in our everyday lives and yet underpins everything.

On a big enough quantum computer, we could simulate quantum field theories to study the most fundamental nature of the universe. In chemistry and nanoscale research, where quantum effects dominate, we could investigate the basic properties of materials and design new ones to understand mechanisms such as unconventional superconductivity. We could simulate and understand new chemical reactions and new compounds, which could aid in drug discovery.

By diving deep into mathematics and information theory, we already have developed many theoretical tools to do these things, and the algorithms are farther along than the technology to build the actual machines. It all starts with a theoretical model of the quantum computer, which establishes how it will harness quantum mechanics to perform a useful computation. Researchers write quantum algorithms to perform a task or solve a problem using that model. These are basically a sequence of quantum gates together with a measurement of the quantum state that provides the desired classical information.

Current quantum computers are so noisy and error-prone that the information in its quantum state is lost within tens of microseconds through a mechanism called decoherence and through faulty gates.

So, for instance, Grover's algorithm shows a way to perform faster searches. Shor's algorithm has proved that large quantum computers will one day be able to break computer security systems based on RSA, a method widely used to protect, for instance, e-mail and financial Web sites worldwide.

In my research, my colleagues and I have demonstrated very efficient algorithms to perform useful computations and study physical systems. We have also demonstrated one of the methods in one of the first small-scale quantum simulations ever done of a system of electrons, in a nuclear magnetic resonance quantum information processor. Others have also followed up on our work and recently simulated simple quantum field theories on the noisy intermediate-scale quantum computers available today and in laboratory experiments.

As we wait for the hardware to catch up with theory, researchers in quantum information science will continue to study and implement quantum algorithms useful for the currently available noisy, fault-ridden machines. But many of us are also taking a longer view, pushing theory deep into the intersection of quantum physics, information theory, complexity and mathematics and opening up new frontiers to explore, once we have the quantum computers to take us there.

—Rolando Somma

Astronomers May Have Captured the First Ever Image of Nearby Exoplanet Proxima C

It could be an unprecedented view of a world in the closest planetary system to our own, but uncertainties aplenty remain

Little is more enticing than the prospect of seeing alien worlds around other stars—and perhaps one day even closely studying their atmosphere and mapping their surface. Such observations are exceedingly difficult, of course. Although more than 4,000 exoplanets are now known, the vast majority of them are too distant and dim for our best telescopes to discern against the glare of their host star. Exoplanets near our solar system provide easier imaging opportunities, however. And no worlds are nearer to us than those thought to orbit the cool, faint red dwarf Proxima Centauri—the closest star to our sun at 4.2 light-years away.

In 2016 astronomers discovered the first known planet in this system: the roughly Earth-sized Proxima b. But because of its star-hugging 11-day orbit around Proxima Centauri, Proxima b is a poor candidate for imaging. Proxima c, by contrast, offers much better chances. Announced in 2019, based on somewhat circumstantial evidence, the planet remains unconfirmed. If real, it is estimated to be several times more massive than Earth—a so-called super Earth or mini Neptune—and to orbit Proxima Centauri at about 1.5 times the span between Earth and the sun. Its size and distance from its star make the world a tempting target for current and near-future exoplanet-imaging projects. Now, in a new preprint paper accepted for publication in the journal *Astronomy & Astrophysics*, some astronomers say they might—just might— have managed to see Proxima c for the first time.

“This planet is extremely interesting because Proxima is a star very close to the sun,” says Raffaele Gratton of the Astronomical Observatory of Padova in Italy, who is the study’s lead author. “The idea was that since this planet is [far] from the star, it is possible that it can be

View of the Alpha Centauri system. The bright binary star Alpha Centauri AB lies at the upper left. The much fainter red dwarf star Proxima Centauri is barely discernible toward the lower right of the picture.

DIGITIZED SKY SURVEY 2; ACKNOWLEDGEMENT: DAVIDE DE MARTIN AND MAHDI ZAMANI

observed in direct imaging. We found a reasonable candidate that looks like we have really detected the planet."

Last year Gratton and his team were first alerted to the possibility of imaging the planet by Mario Damasso of the Astrophysical Observatory of Turin in Italy, who was the lead author of the original paper on Proxima c's possible discovery. Damasso and his colleagues had presented evidence for Proxima c's existence based on its star's telltale wobbling, which they inferred was caused by the pull of an unseen orbiting planet. Confirming a world's existence in this way requires seeing the same wobble occur again—and again—in a process that often takes many months or even years.

Damasso wondered if there might be another way. Thus, he asked Gratton and his team to look through data from the SPHERE (Spectro-Polarimetric High-Contrast Exoplanet Research) instrument on the European Southern Observatory's Very Large Telescope (VLT) in Chile to see if they could actually see the planet. "As soon as our paper on Proxima c was considered for publication, I contacted [Gratton] to discuss the possibility of pushing SPHERE to its limits," Damasso says. "The [planetary] system is potentially so cool that it is worthy to try other techniques."

If you squint a bit while staring at the SPHERE data, a picture of the mysterious planet seems to swim into view. By focusing on Proxima c's predicted position and separation from its star within multiple, stacked infrared images from SPHERE, Gratton and his colleagues were able to pick out 19 potential appearances of the planet across several years of routine observations. Of these candidate detections, one stood out as being particularly enticing: it appeared in the images about six times brighter than their "noise"—that is, unwanted light from artifacts or background stars. "It's a possible candidate that has a low probability of being a false alarm," says Emily Rickman of the Geneva Observatory, who is a co-author of the paper.

If that detection is genuine, it poses intriguing questions. The object believed to be the planet would be at least seven times the mass of Earth—large enough to place it firmly beyond the super Earth category. "This would definitely be some kind of mini Neptune," says Sara Seager, a professor of planetary science at the Massachusetts Institute of Technology, who was not involved in the new paper. The object also appears to be 10 to 100 times brighter than a planet of its mass should be. This luminosity, the study authors reason, could arise from a large amount of dust surrounding the planet, perhaps in a vast ring system that is three to four times larger than that of Saturn. To some, that situation seems too strange to be true.

"It would be a huge ring system around a relatively old star," says astrophysicist Bruce Macintosh of Stanford University, who also was not part of the work. "It's certainly possible for things like this to exist. But for your first detection of something like this to have that massive ring system, you'd have to postulate a universe in which most Neptune-sized planets have massive ring systems enormously bigger than Saturn's. And that seems like an unlikely universe to live in."

If genuine, this detection—this image—would have profound implications for our understanding of our nearest neighboring planetary system. It would give us definitive proof of the existence of Proxima c and also provide the angle at which the planet orbits its star, relative to our own—something that watching a star's wobbles alone cannot provide. The detection would also all but ensure that we could soon study the planet's atmosphere with a new generation of powerful observatories, such as the upcoming European Extremely Large Telescope (E-ELT) and NASA's Wide-Field Infrared Survey Telescope (WFIRST).

Perhaps more important, pinning down Proxima c would also likely reveal the orbital angle of Proxima b, because planets would be expected to orbit in the same plane like those in our solar system do. This information, coupled with the wobbles Proxima b raises on its star, would tell us that world must be somewhere between 1.5 and 1.8 times the mass of Earth, which would let us refine theories about its characteristics. Such a mass would "strongly point to the fact [that Proxima b] is rocky," says Elizabeth Tasker, an exoplanet scientist at the Japan Aerospace Exploration

Agency, who was not involved in the study. In addition to our knowledge that Proxima b orbits in its star's habitable zone, where liquid water and thus life as we know it can exist, proof that the world is rocky would catapult it to the top of any astrobiologist's list of promising exoplanets.

Such spectacular possibilities, however, call for steely-eyed skepticism. Indeed, the new paper's authors acknowledge there is a decent chance their image is not actually a planet at all but rather just random noise in the data. They also note that the apparent motion of their putative planet conflicts with earlier estimates of Proxima c's position, based on observations of its star made by the European Space Agency's Gaia spacecraft. Thus, other astronomers are treating the potential finding with a considerable amount of caution. "It's tough for me to conclude that [this] is a decisive detection," says Thayne Currie, an exoplanet scientist at NASA's Ames Research Center, who was also not part of the work.

Unfortunately, the ongoing global shutdown in response to the COVID-19 pandemic means that the result cannot be checked for the time being, because most of the world's observatories—including the VLT—are not operational. "It could be [confirmed or refuted] tomorrow, but the observatories are closed," says astronomer Guillem Anglada-Escudé, who led the discovery of Proxima b in 2016 and was not involved in the new study. Time is running out for an immediate follow-up: in July, Proxima Centauri will pass out of view behind our sun until February 2021.

So for now the prospect of Proxima c having been seen for the first time remains an enticing but elusive possibility. Even if it proves to be a mirage—an astronomical false alarm—this potential detection is unlikely to dampen enthusiasm for further studies. Other teams will try again with upcoming instruments, more advanced than SPHERE, operating on supersized telescopes such as the E-ELT. But if the detection is real, which Gratton says he is "two-thirds" confident about, it would be a historic initial glimpse of a planet orbiting the closest start to our own. "If this is true, it's very exciting," Anglada-Escudé says.

—Jonathan O'Callaghan

Will String Theory Finally Be Put to the Experimental Test?

Physicists have found a way the theory might limit the cosmic inflation that is thought to have expanded the early universe

Many physicists consider string theory our best hope for combining quantum physics and gravity into a unified theory of everything. Yet a contrary opinion is that the concept is practically pseudoscience, because it seems to be nearly impossible to test through experiments. Now some scientists say we may have a way to do exactly that, thanks to a new conjecture that pits string theory against cosmic expansion.

What it comes down to is this question: Does the universe show us all of its quantum secrets, or does it somehow hide those details from our classical eyes? Because if the details can be seen, string theory might not be able to explain them.

One way to rule out the idea is if we can prove that it does not predict an essential feature of the universe. And string theory, it turns out, has a persistent problem describing the most popular account of what went on during the universe's earliest moments after the big bang: inflation.

"Inflation is the most compelling explanation for why our universe looks the way it does and where the structure came from," says Marilena Loverde, a physicist at Stony Brook University. Inflation explains how, in a sense, we got everything in the universe from nothing. The theory says that the early universe went through a phase of extreme expansion. The process magnified random blips in the quantum vacuum and converted them into the galaxies and other stuff around us.

Theorists have had difficulty, though, showing how, or if, inflation works in string theory. The most promising road to doing so—the so-called KKLT construction—does not convince everyone. "It depends who you ask," says Suddhasattwa Brahma, a cosmologist at McGill University. "It has been a lingering doubt in the back of the minds of many in string theory: Does it really work?"

In 2018 a group of string theorists

took a series of suggestive results and argued that this difficulty reflected an impossibility—that perhaps inflation just cannot happen in the theory. This so-called de Sitter swampland conjecture claimed that any version of the concept that could describe de Sitter space—a term for the kind of universe in which we expect inflation to take place—would have some kind of technical flaw that put it in a "swampland" of rejected theories.

No one has proved the swampland conjecture, and several string theorists still expect that the final form of the theory will have no problem with inflation. But many believe that although the conjecture might not hold up rigidly, something close to it will. Brahma hopes to refine the swampland conjecture to something that would not bar inflation entirely. "Maybe there can be inflation," he says. "But it has to be a very short period of inflation."

Any limit on inflation would raise the prospect of testing string theory against actual data, but a definite test requires a proof of the conjecture. According to Cumrun Vafa, a physicist at Harvard University and

PASIEKA *GETTY IMAGES*

one of the swampland conjecture's authors, researchers can start to build a case for the idea if they can connect it to trusted physical laws. "There are two levels of it," he says. "First is being more confident in the principle. And then there's explaining it."

One approach to building confidence might try to explain what sort of physical rule would limit inflation—or, to put the inquiry in a more practical way: How could string theorists hope to persuade cosmologists to reconsider a favored theory?

These kinds of questions led Vafa and his Harvard collaborator Alek Bedroya to seek out a physics-based reason that could justify the swampland conjecture. They found a candidate in a surprising place. It turns out that inflation already has an unsolved problem looking for a solution: theorists have not all agreed on what happens to the very tiniest quantum details when expansion occurs and magnifies the static of the vacuum.

Physicists lack a working theory that describes the world below the level of the so-called Planck length, an extremely minute distance where they expect the quantum side of gravity to appear. Proponents of inflation have typically had to assume that they can one day work those "trans-Planckian" details into it and that they will not make a big difference to any predictions. But how that step will happen remains an open question.

Vafa and Bedroya have given a simple answer: forget about it. Their new trans-Planckian censorship conjecture asserts that extremely tiny quantum fuzziness should always stay extremely tiny and quantum, despite the magnifying effect of expansion. If this idea is true, it implies limits on the amount of inflation that could happen, because too much of it would mean too much magnification of the trans-Planckian details.

So in a new twist for string theory, researchers can actually look to the sky for some answers. How much inflation is too much for the censorship conjecture? The situation is a bit complicated. Several different models for the actual process of inflation exist, and astrophysicists do not yet have data that confirm any one of them, or the basic idea as a whole, as the correct description of our universe. Researchers have begun working out the limits the new conjecture puts on the many versions of inflation. Some have a built-in way to hide trans-Planckian details, but Loverde says that many of the typical models conflict with the conjecture.

One clear conflict comes from "primordial" gravitational waves. These waves, which theorists expect arise during the inflationary phase, would have left behind a faint but distinct sign in the cosmic microwave background. So far they have not been seen, but telescopes are actively looking for them. The censorship conjecture would only allow a "ridiculously, unobservably small" amount, Loverde says—so small that any sign of these waves would mean the conjecture does not apply to our universe unless theorists can come up with a different explanation for them.

Does this conjecture really amount to a test of string theory? No, it is too early to say that, according to Vafa. The principles are still just conjectures—for now. "The more one connects these principles together—surprising, unexpected relations—the more it becomes believable why it's true," he says.

—Brendan Z. Foster

Antimatter Discovery Reveals Clues about the Universe's Beginning

New evidence from neutrinos points to one of several theories about why the cosmos is made of matter and not antimatter

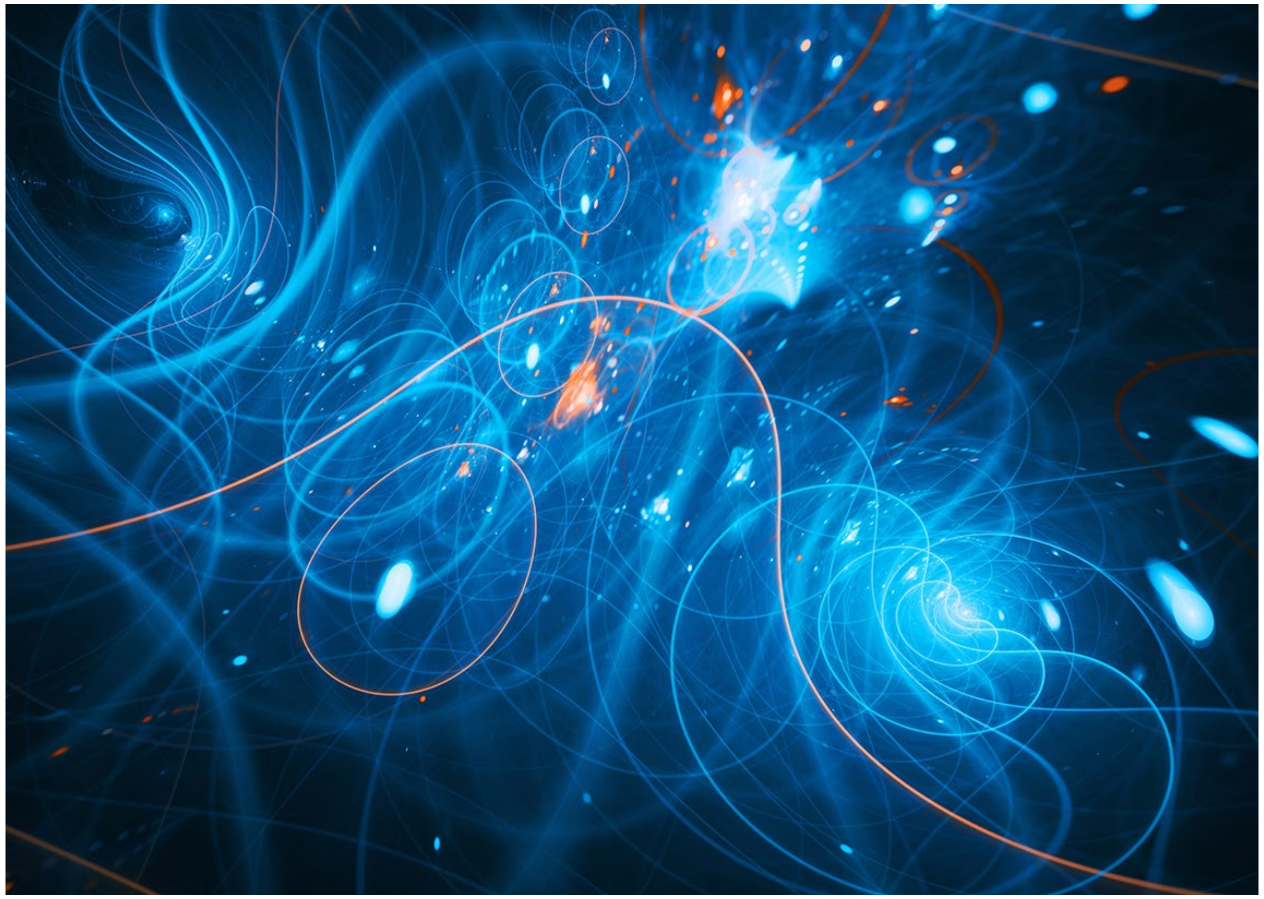
In the beginning, there was matter and antimatter, and then there was only matter. Why? This question is one of the defining mysteries of physics. For decades theorists have come up with potential solutions, most involving the existence of extra particles beyond the known species in the universe. In April scientists announced tantalizing findings that point toward one possible solution, but the data fall short of a definitive discovery. Whatever the final answer is, resolving the question may tell us more than just why we live in a universe of matter—it could expose secrets from the earliest epochs of the cosmos or even connect us to the invisible dark matter that eludes scientists.

Most of the theories about how matter got the upper hand over antimatter fall into two main camps. One, called electroweak baryogenesis, posits extra versions of the Higgs boson—the particle related to how everything else gets mass. If these Higgs cousins exist, they could have helped set off an abrupt phase transition, akin to the shift when water goes from liquid to gas, early in the universe that might have led to slightly more matter than antimatter in space. When matter and antimatter come into contact, they annihilate each other, so most of the stuff in the young universe would have been destroyed, leaving behind just a small surplus of matter to make the galaxies and stars and planets around us.

The other leading theory, called leptogenesis, stems instead from neutrinos. These particles are much, much lighter than quarks and pass through the cosmos ethereally, rarely stopping to interact with anything at all. According to this scenario, in addition to the regular neutrinos we know of, there are extremely heavy neutrinos that are so gargantuan that they could have been forged only from the tremendous energies and temperatures present just after the big bang, when the universe was very hot and dense. When these particles inevitably broke down into smaller, more stable species, the thinking goes, they might have produced slightly more matter than antimatter by-products, leading to the arrangement we see today.

TWO MYSTERIES FOR THE PRICE OF ONE

The recent announcement, which was made by scientists at the T2K (Tokai to Kamioka) experiment in Japan, offers hopeful signs for the leptogenesis concept. The experiment observes neutrinos as they travel through 300 kilometers underground and change among three types, or flavors—a peculiar ability of neutrinos called oscillation. The T2K researchers detected more oscillations in neutrinos than in antineutrinos, suggesting the two do not just act as mirror images of each other but, in fact, behave differently. Such a difference between a particle and its antimatter counterpart is termed CP violation, and it is a strong clue in the quest to understand how matter outran antimatter after the universe was born. “We don’t call it a discovery yet,” says T2K team member Chang Kee Jung of Stony Brook University. The experiment has now ruled out the possibility that neutrinos have zero CP violation with 95 percent confidence, and it shows hints that the particles might display the maximum possible amount of CP violation allowed. Yet more data, and probably future experiments, will be needed to precisely measure just how much neutrinos and antineutrinos differ.


GETTY IMAGES

Even if physicists make a definitive discovery of CP violation in neutrinos, they will not have completely solved the cosmic antimatter question. Such a finding would be “necessary but not sufficient” to prove leptogenesis, says Seyda Ipek, a theoretical physicist at the University of California, Irvine. Another requirement of the theory is that neutrinos and antineutrinos turn out to be the same thing. How is that seeming contradiction possible? Matter and antimatter are thought to be identical except for a reversed electrical charge. Neutrinos, having no charge, could be both at the same time.

If this possibility is the case, it could also explain why neutrinos are so light—perhaps less than one six-millionth of the mass of the electron. If neutrinos and antineutrinos are the same, they might gain mass not by interacting with the Higgs field (which is associated with the Higgs boson), as most particles do, but through another process called the seesaw mechanism. Their puny masses would be inversely proportional to those of the heavy neutrinos that arose in the early universe. “When one is up, the other is down, like a seesaw,” Ipek says.

“Leptogenesis is a very elegant way of explaining things,” says Jessica Turner, a theoretical physicist at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill. “First, you answer why there’s more matter than antimatter. And second, you explain why neutrinos have such small masses.” Evidence that neutrinos are their own antimatter counterparts could come from experiments searching for a theorized reaction called neutrinoless double beta decay, which could only occur if neutrinos were able to annihilate themselves as matter and antimatter do on contact. Even this finding, though, would not fully prove leptogenesis took place. “If you measure the most possible CP violation we can see, and if you observed that neutrinos were their own antiparticles, we would say that’s circumstantial evidence, not direct evidence,” Turner says.

CONNECTING TO THE DARK SECTOR

The other theoretical option on the table, electroweak baryogenesis, might be easier to investigate, physicists say. Whereas the creation of heavy neutrinos involved in leptogenesis would most likely be beyond the capabilities of particle accelerators, the extra Higgs bosons predicted by this theory just might show up at the Large Hadron Collider, says Marcela Carena, head of Fermilab’s theoretical physics department. Even if the machine does not make them directly, these Higgs relatives could subtly but detectably interact with the traditional Higgs bosons it produces.

Electroweak baryogenesis also requires additional CP violation in the universe but not specifically in neutrinos. In fact, CP violation has already been discovered in quarks, though in such small amounts that it does not explain the matter-antimatter imbalance. One place this theory’s missing CP violation might be hiding is the so-called dark sector—the realm of the invisible dark matter that is thought to make up most of the matter in space. Perhaps dark matter and dark antimatter behave differently, and this difference can explain our universe as we know it. “My line of work has been trying to connect the matter-antimatter imbalance in the universe to the idea that we know we need something we haven’t seen so far in order to explain dark matter,” Carena says.

Evidence for electroweak baryogenesis could come not just through detecting extra Higgs particles but also via the numerous experiments hunting for dark matter and the dark sector. Furthermore, if a cosmological phase transition occurred shortly after the big bang, as the theory supposes, it might have produced gravitational waves that could be found by future experiments, such as the Laser Interferometer Space Antenna (LISA), a space-based gravitational-wave detector due to launch in the 2030s.

Ultimately, though, the universe could surprise us. Perhaps neither leptogenesis nor electroweak baryogenesis occurred. “Those are not the only two options—the theory realm is very vast,” Ipek says. She recently worked on a model involving CP violation in the strong interaction of the quarks inside protons and neutrons, for instance, and theorists are looking into many other ideas as well. “I think we need to let ourselves explore all possibilities,” Turner says. “Nature unravels as it does; we can’t control that. We just try our best to understand it.”

In the meantime, a definitive measurement of CP violation in neutrinos, at least, is within sight. Upcoming projects such as the Deep Underground Neutrino Experiment (DUNE) and T2K’s successor Hyper-Kamiokande (Hyper-K) should have the sensitivity required for a precise accounting. “The T2K data look as interesting as they could look,” says DUNE co-spokesperson Ed Blucher of the University of Chicago. “It makes me very excited that there’ll be something interesting to study in the next generation of experiments that are coming.”

—Clara Moskowitz

This Black Hole Collision Just Made Gravitational Waves Even More Interesting

An unprecedented signal from unevenly sized objects gives astronomers rare insight into how black holes spin

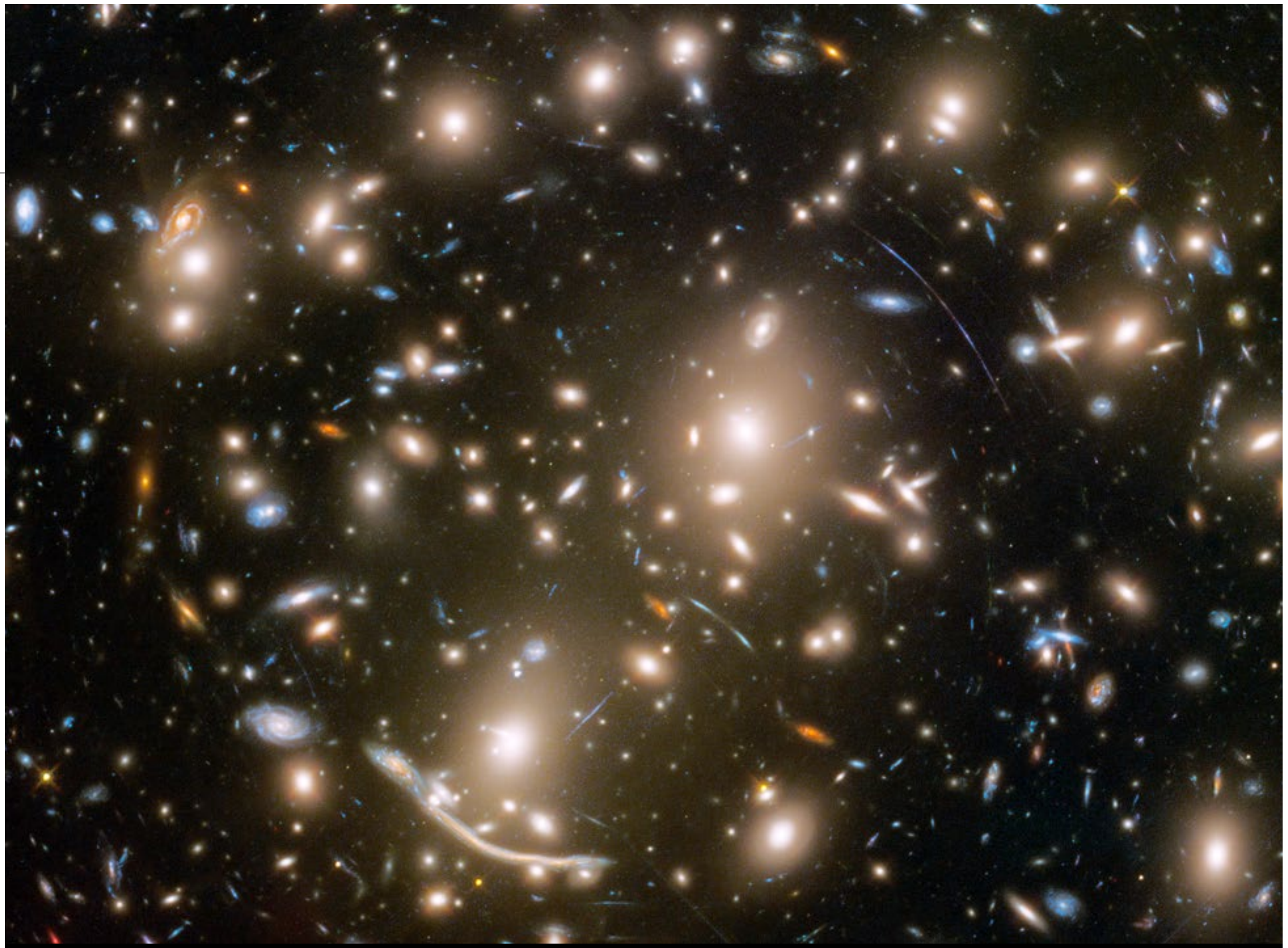
Gravitational-wave astronomers have for the first time detected a collision between two black holes of substantially different masses—opening up a new vista on astrophysics and on the physics of gravity. The event offers the first unmistakable evidence from these faint spacetime ripples that at least one black hole was spinning before merging, giving astronomers rare insight into a key property of these these dark objects.

"It's an exceptional event," said Maya Fishbach, an astrophysicist at the University of Chicago. Similar mergers on which data have been published all took place between black holes with roughly equal masses, so this new one dramatically upsets that pattern, she said. The collision was detected last year and was unveiled on April 18 by Fishbach and her collaborators at a virtual meeting of the American Physical Society, held entirely online because of the coronavirus pandemic.

The Laser Interferometer Gravitational-wave Observatory (LIGO)—a pair of twin detectors based in Hanford, Wash., and Livingston, La.—and the Virgo observatory near Pisa, Italy, both detected the event, identified as GW190412, with high confidence on April 12, 2019. The LIGO-Virgo collaboration, which includes Fishbach, posted its findings on the arXiv preprint server.

LIGO made the first discovery of gravitational waves in September 2015, detecting the spacetime ripples from two merging black holes. LIGO, later joined by Virgo, subsequently made 10 more detections in two observing runs that ended in 2017: nine more black hole mergers and one collision of two neutron stars, which helped to explain the origin of the universe's heavy chemical elements.

The third and most recent run started on April 1, 2019, and ended on March 27, 2020, with a month-



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

Universe Creates All Elements in the Periodic Table in 10 Minutes

Originally published in July 1948

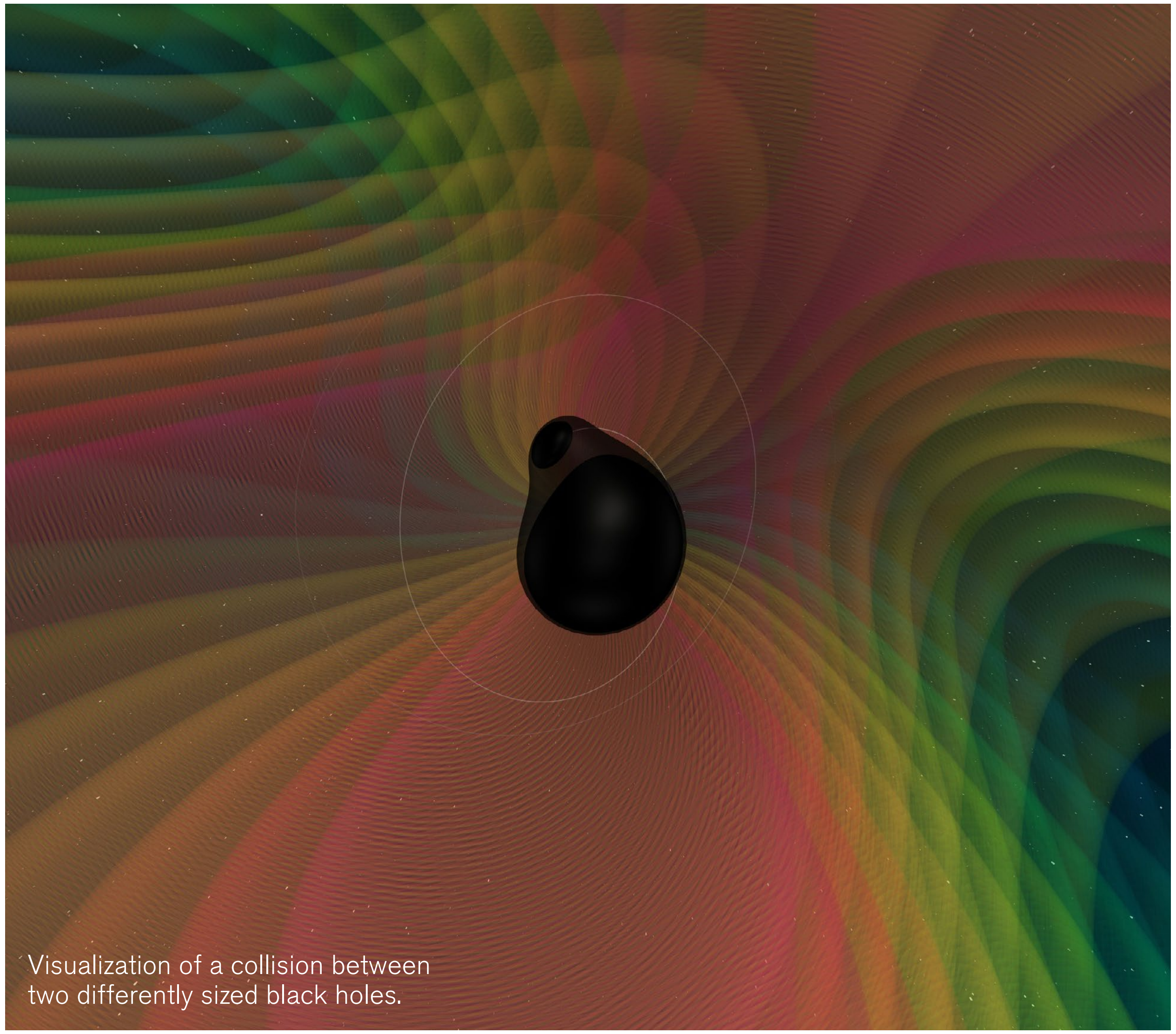
"Nineteen years after Edwin Hubble's discovery that the galaxies seem to be running away from one another at fabulously high speeds, the picture presented by the expanding universe theory—which assumes that in its original state all matter was squeezed together in one solid mass of extremely high density and temperature—gives us the right conditions for building up all the known elements in the periodic system. According to calculations, the formation of elements must have started five minutes after the maximum compression of the universe. It was fully accomplished, in all essentials, about 10 minutes later."

—*Scientific American*, July 1948
More gems from *Scientific American*'s first 175 years
can be found on our anniversary archive page.

long break in October. Greatly improved sensitivity enabled the network to accumulate around 50 more "candidate events" at a rate of roughly one per week. Until now, the international collaboration had unveiled only one other event from this observation period—a second merger between two neutron stars, dubbed GW190425, that was revealed in January.

DISTORTED SPACE

The latest event is unique. One of the two black holes that merged had an estimated mass of around eight solar masses, and the other was more than three times larger, at 31 solar masses. This imbalance made the larger black hole distort the space around it, so the other's trajectory deviated from a perfect spiral. This could be seen in the resulting gravitational waves, which were created as the objects spiraled into each other. All the other merger events that have been unveiled produced a wave that forms a similar "chirp" shape—which increases in both intensity and frequency up to the moment of collision. But GW190412 was different: its intensity didn't simply rise as in a chirp. "This makes this system very interesting, just looking at the morphology of the signal," Fishbach said.


Visualization of a collision between two differently sized black holes.

Physicists had eagerly awaited such "nonvanilla" events because they provide new, more precise ways of testing Albert Einstein's theory of gravity, the general theory of relativity. "We are in a new regime of testing general relativity," said Maximiliano Isi at the Massachusetts Institution of Technology, another LIGO member who was presenting at the meeting.

In particular, researchers were able to use these data to discern the "spin" of black holes. "We know with confidence that this heavier object had to be spinning," Isi said. Previous events had left researchers baffled: observations of black holes in the Milky Way suggested that black holes should have high spins, but this observation did not show up in gravitational-wave data from the first two runs.

Astrophysicists hope that detecting spins can shed light on how the black holes formed and came to orbit each other. The richer information in asymmetrical mergers helps to measure an event's distance from the Milky Way with better precision. Accumulating many such measurements could provide a new way to map the history of expansion of the universe.

The LIGO-Virgo collaboration will continue to publish more results from its vast trove of unpublished data, including individual events that are particularly interesting or exciting, says Virgo's Jo van den Brand, a physicist at the National Institute for Subatomic Physics in Amsterdam: "I think the harvest is quite good—let me put it like that."

—Davide Castelvecchi

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N. FISCHER, H. PFEIFFER, A. BUONANNO (MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS), SIMULATING EXTREME SPACETIMES (SXS) COLLABORATION

Do We Live in a Lopsided Universe?

A new study of galaxy clusters suggests that the cosmos may not be the same in all directions

By Lee Billings

Galaxy cluster glows with x-rays from hot gas (*shown here in purple*). Surveys of such clusters across the sky are revealing what may be curious anomalies in cosmic structure.

ESA AND XMM-NEWTON (*X-RAYS*); CFHTLS (*OPTICAL*); XXL SURVEY

Lee Billings is a senior editor for space and physics at *Scientific American*.

IF YOUR LIFE sometimes seems directionless, you might legitimately blame the universe.

According to the key tenets of modern physics, the cosmos is "isotropic" at multibillion-light-year scales—meaning it should have the same look and behavior in every direction. Ever since the big bang nearly 14 billion years ago, the universe ought to have expanded identically everywhere. And that expectation matches what astronomers see when they observe the smooth uniformity of the big bang's all-sky afterglow: the cosmic microwave background (CMB). Now, however, an x-ray survey of distances to galaxy clusters across the heavens suggests some are significantly closer or farther away than isotropy would predict. This finding could be a sign that the universe is actually "anisotropic"—expanding faster in some regions than it does in others. With apologies to anyone seeking a cosmic excuse for personal woes, maybe the universe is not so directionless after all.

This possible evidence for anisotropy comes from an international team led by astronomer Konstantinos Migkas of the University of Bonn in Germany. Moreover, it relies on new or archival data about nearly 850 galaxy clusters seen by NASA's Chandra X-ray Observatory, the European Space Agency's X-ray Multi-Mirror Mission (XMM-Newton) satellite and Japan's Advanced Satellite for Cosmology and Astrophysics.

The study, which appeared in the April edition of *Astronomy & Astrophysics*, treats each cluster a bit like a lighthouse—gauging their distances by how bright or dim each one appears. By measuring the kinds and amounts of x-rays emitted by the hot, rarefied gas suffusing a given cluster, the team could determine that gas's temperature. Doing so allowed the researchers to estimate the cluster's x-ray luminosity—and therefore its distance. Next, they calculated each cluster's luminosity via a separate technique that relied, in part, on preexisting determinations of the universe's expansion rate. Comparing the two independent cluster luminosity values allowed Migkas and his colleagues to probe potential deviations in the universe's rate of expansion across the entire sky, revealing two regions where clusters were some 30 percent brighter or fainter (and thus potentially closer or farther away) than expected.

"We managed to pinpoint a region that seems to expand slower than the rest of the universe and one that seems to expand faster," Migkas says. "There are many studies with optical supernovae and with infrared galaxies that have detected similar anisotropies toward the same directions as well. And there are many studies with similar data sets that do not show any anisotropies! Therefore, the situation is still vague. We do not argue to know the origin of the anisotropies, only that they are there."

AN ASTONISHING, DEPRESSING ANISOTROPY

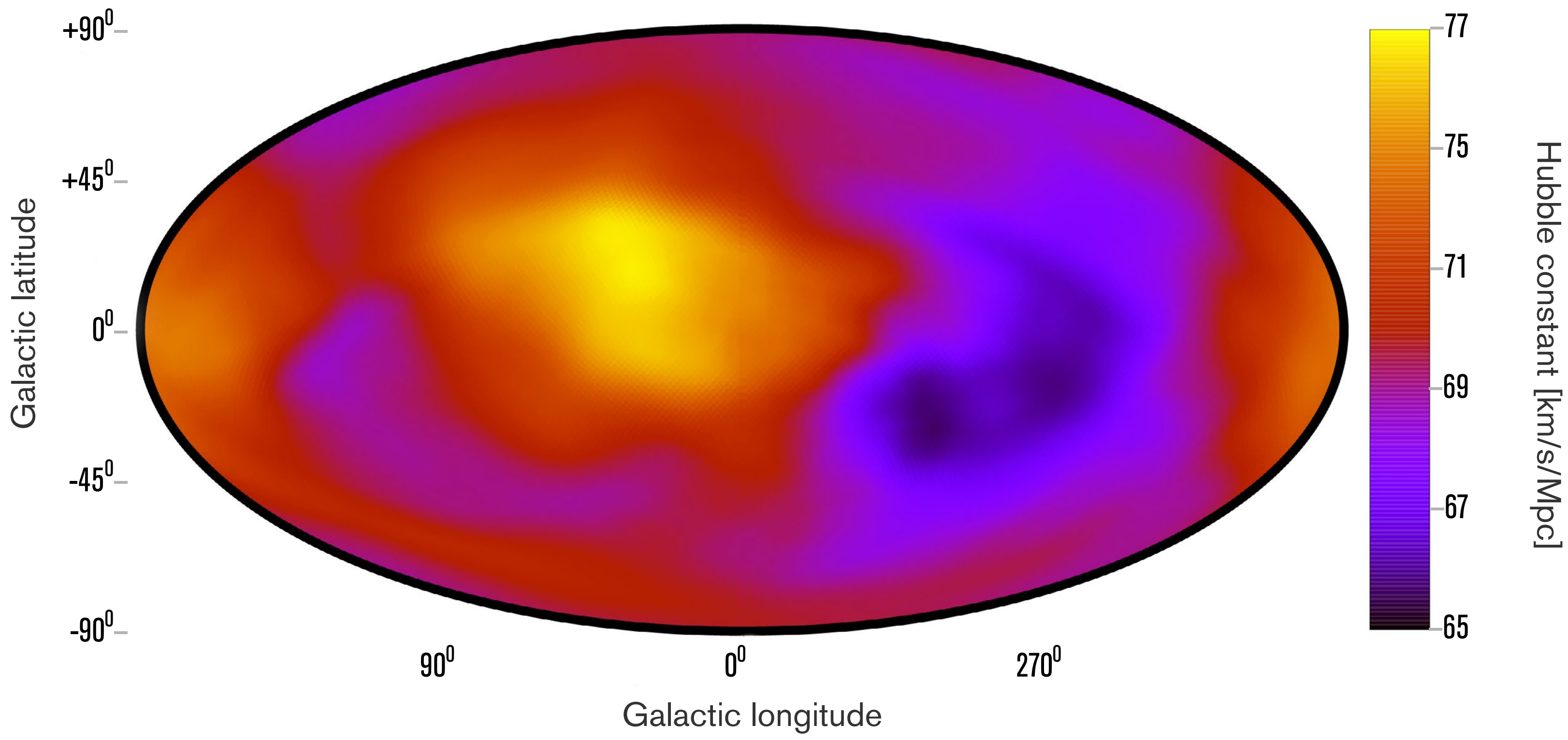
An anisotropic universe would shake the pillars of physics, demanding major revisions to current thinking about cosmic evolution. "If [the universe's growth] is indeed different in different directions, that brings a whole new wrinkle into a cosmological assumption about homogeneity of the expansion over sufficiently large regions of space," says Megan Donahue, a Michigan State University astrophysicist, who was not involved in the study. A lopsided expansion "would be astonishing and depressing," she adds, because it would suggest our understanding of the universe's large-scale structure and evolution is profoundly—perhaps permanently—incomplete.

To explain such a thing—and to reconcile it with the nearly perfect isotropy seen in the CMB—cosmologists could turn to dark energy, the mysterious force driving an acceleration to the universe's growth. Perhaps, somewhere in the intervening eons between the CMB's picture of the "early" universe and the "late" one of the past several billion years, dark energy's effects became stronger in some select parts of the cosmos, creating a lopsided expansion.

"It would be remarkable if dark energy were found to have different strengths in different parts of the universe," said study co-author Thomas Reiprich of the University of Bonn in a recent statement. "However, much more evidence would be needed to rule out other explanations and make a convincing case."

Alternatively, the universe might not be lopsided at all: the aberrant galaxy clusters could be caught up in a "bulk flow," pulled out of place by the gravitational grip of even bigger and more distant clusters, a bit like boats swept along in a river's swift currents. But most cosmologists have not expected bulk flows to occur across the extremely large scales probed by the study, which made measurements out to roughly five billion light-years.

"It could very well be a bulk flow," Migkas says. "Nevertheless, this would be very important as well, simply because most studies do not take that into account! Any existing bulk flows could heavily affect our results and measurements if people do not correct for these motions appropriately."



All-sky map showing what may be a lopsided expansion of the universe, based on x-ray surveys of hundreds of galaxy clusters. Orange-yellow hues indicate a faster-than-expected expansion rate. Purple-black colors correspond to slower-than-expected expansion.

K. MIGKAS ET AL. 2020 (CC BY-SA 3.0 IGO)

COSMIC BLIND SPOTS

The most obvious explanation, of course, would be that the apparent asymmetries in cluster spacing are because of flaws in the data or their analysis. Yet that scenario could still demand updates to scientists' understanding of how errors creep into their best reckonings of cosmic distances.

"Studies using clusters as probes of cosmology have been giving screwy results for a while," says Adam Riess, an astronomer at Johns Hopkins University, who is unaffiliated with Migkas's team, citing recent analyses by other researchers that highlight inconsistencies between cluster-based work and other measurement techniques. Such inconsistencies suggest correlations between a galaxy cluster's x-ray temperature and its luminosity are not as clear-cut as researchers would prefer. Furthermore, Riess says, there are other potential problems to deal with right here in the Milky Way: namely, our galaxy's gas- and dust-filled disk, which obscures astronomers' views of the wider cosmos in various vexing ways. It may not be coincidental, he says, that the region of greatest apparent cosmic anisotropy identified by Migkas and his colleagues borders the place where the Milky Way's x-ray-absorbing gas and dust are thickest. "They are claiming the weird direction of the universe is right in our blind spot," Riess adds. "That seems suspicious!"

David Spergel, a cosmologist at Princeton University and the Flatiron Institute in New York City, also suspects faults in the cluster-based measurements—in part because so many other techniques provide fundamentally conflicting results. "This is a paper that is very important if [it is] true but very unlikely to be true," he says. "We have many much more accurate tests of anisotropy based on observations of [the CMB] and of large-scale structure. These observations are simpler, cleaner, and have been reproduced in multiple different ways." Anisotropies of the scale suggested by the new study, he says, would lead to fluctuations in the CMB that were 1,000 times brighter than what astronomers have observed.

Even so, Migkas and his colleagues argue that decisively ruling against—or for—a lopsided universe requires additional, more comprehensive probes of large-scale cosmic structure. They are now looking for further hints of galaxy-cluster anisotropy within maps of the CMB and seeking to validate their x-ray-based cluster studies with complementary infrared observations. Conclusive results could ultimately come from new space telescopes—such as eROSITA, a German-Russian x-ray observatory, or the European Space Agency's upcoming Euclid mission—that will perform deeper and broader surveys of clusters across the entire sky.

"Generally, we believe that more and more people should look into the isotropy of the universe—finding new methods and tools to do so—considering the enormous significance this has for standard cosmology," Migkas says. "It would be great if we knew, once and for all, if the late universe looks isotropic or not."

Milky Way Dark Matter Signals in Doubt after Controversial New Papers

New analyses question whether mysterious gamma-ray and x-ray light in the galaxy actually stems from an invisible mass

By Clara Moskowitz

Decaying dark matter should produce a bright and spherical halo of x-ray emission around the center of the Milky Way that could be detectable when looking in otherwise blank regions of the galaxy.

CHRISTOPHER DESSERT, NICHOLAS RODD, BENJAMIN SAFDI, ZOSIA ROSTOMIAN, FERMI LARGE AREA TELESCOPE

Clara Moskowitz is a senior editor at *Scientific American*.
She covers space and physics.

WE KNOW IT'S THERE, BUT WE DON'T KNOW WHAT IT IS: this invisible stuff is dark matter. Scientists are fairly certain it dominates the cosmos, yet its ingredients are unclear. For a while astrophysicists have been excited by two potential signals of dark matter in space: an unexplained excess of gamma-ray light in the center of the Milky Way and a mysterious spike in x-ray light spotted in some other galaxies and galaxy clusters. The signals have been interpreted as possible evidence of dark matter annihilating itself and decaying into different particles, respectively, but two new papers seem to dampen both hopes. Some say it is time to look for different routes to dark matter. Other researchers, however, maintain that either of these signals could still turn out to be the answer.

The x-ray spike, seen as a bright line of emission at an energy of 3,500 electron volts (3.5 KeV), was first spotted in 2014 and has now been identified in numerous galaxy clusters, as well as in our neighboring galaxy Andromeda. The excitement here stems from the fact that one promising dark matter candidate, a brand of particle known as a sterile neutrino, is expected to naturally decay into ordinary matter and produce just this kind of emission line. Recently Benjamin Safdi of the University of Michigan and his colleagues decided to look for this line in our own galaxy by analyzing a massive amount of data from the X-ray Multi-Mirror Mission (XMM-Newton) telescope. The team took images of various objects gathered for other purposes and blocked them out to instead look in the dark "empty space" off to the side for the 3.5-KeV light. After amassing what amounts to a total exposure time of about a year, the researchers saw no sign of the spike. Their findings came out in March in *Science*. "Unfortunately, we saw nothing," Safdi says, "and the result is that the dark matter interpretation of this line is ruled out by many orders of magnitude."

Case closed? Not exactly. Numerous x-ray astronomers take issue with the researchers' methods and say this feature is very likely to be present in our galaxy and is still a strong contender for dark matter. "I have several reservations about the technical part of the paper," says Nico Cappelluti of the University of Miami. "The technique they use is not standard. And so I think the conclusions they draw are a bit rushed." Another physicist, Alexey Boyarsky of Leiden University in the Netherlands, puts it more bluntly. "Most of the experts I know believe the main result of the paper is wrong," he says. "I do not see how they can claim that this line does not exist in the data."

Boyarsky and his collaborators also examined XMM-Newton data for the x-ray line and released a preprint paper in December 2018 claiming they detected it in the Milky Way with strong statistical significance. The difference, he says, is that Safdi's team analyzed too narrow an energy range and therefore could not accurately separate the background radiation inherent in all of the telescope's data from the spike in question. Safdi counters that his analysis technique, though new to x-ray astronomy, has proved itself in particle physics research, including searches for dark matter at the Large Hadron Collider (LHC) at CERN near Geneva. "Every time you bring a new analysis framework to a field, there's a lot of conversation about the merits of it. Are you missing anything?" he says. "Our opinion is that it is a more robust way of analyzing the data, which makes it less likely that you're fooling yourself into seeing something that isn't actually there." Of Boyarsky and his colleagues' results, Safdi says, "my best guess is that what they see in their analysis is either a statistical fluctuation or a systematic issue."

Still, many scientists say the x-ray signal remains a promising path toward dark matter. "I think, for the 3.5-KeV line, to say something meaningful, we need new technology," says Esra Bulbul of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, who, with her colleagues, first detected the line in the Perseus galaxy cluster in 2014. The X-ray Imaging and Spectroscopy Mission (XRISM), led by the Japan Aerospace Exploration Agency and due to launch in 2022, should provide definitive evidence on whether this signal exists and matches the characteristics expected of dark matter. "Before that, I will not be convinced that the dark matter origin of the line is excluded," Bulbul says.

DARK MATTER DESTRUCTION

The other potential link to the dark side, the unexplained gamma-ray light at the center of our galaxy, suggests not dark matter decay but destruction. In this scenario, the mysterious substance might be both matter and antimatter. Thus, when two dark matter particles meet, they could annihilate each other, creating gamma rays in the process. The gamma-ray signal was first seen in 2009 in data from the Fermi Gamma-ray Space Telescope, and scientists have debated its provenance ever since. Though the light fits with dark matter models, it could be more mundane, perhaps created by many spinning neutron stars called pulsars at the heart of the Milky Way.

A new study led by Ryan E. Keeley of the Korea Astronomy and Space Science Institute and Oscar Macias of the Kavli Institute for the Physics and Mathematics of the Universe at the University of Tokyo closely analyzed the pattern of the gamma rays in terms of both their spatial spread and their energy. The researchers found that the light matches the shape of the regular stars, gas and galactic emission from the "bulge" at the center of our galaxy better than it does models of how dark energy by-products would act. "With that, since we have a better fit, the question is: How much room is left for dark matter?" says Kevork Abazajian of the University of California, Irvine, who contributed to the paper, which has been submitted to *Physical Review D* and posted to the preprint server arXiv.org. The answer, they found, is not much. "We've put the strongest constraints on dark matter annihilation yet."

> **"We don't see them in the lab, we don't see them in the LHC, and we don't see them in the sky. There's a kind of existential crisis in particle physics."**
> ***—Kevork Abazajian***

Here, too, though, scientists are not ready to throw in the towel. "The paper does bring up some new interesting evidence that should be taken into account," Cappelluti says. "This is another very complicated measurement. It's definitely something we shouldn't abandon, and we should keep investigating." Tracy Slatyer, a physicist at the Massachusetts Institute of Technology, agrees. "This is a really nice analysis, but it's conditional on whether the galactic background and signal models we have are good enough," she says. "I do worry that these models may not be good enough to make these conclusions."

In recent years other studies have found that the Milky Way's gamma-ray excess seems more likely to come from individual "point sources" of light—such as those that might be produced by pulsars—rather than from a smooth spread of emission—as would be created by dark matter. Slatyer and her M.I.T. colleague Rebecca Leane, however, found that a systematic effect could be biasing these searches toward that answer and that pulsars are not necessarily more favored than dark matter. "This effect can fake a strong preference for exactly the kinds of bright point sources that the previous analyses were finding," Slatyer says. "That doesn't mean there can't be any point sources in the excess, and it doesn't mean the excess is dark matter. But we should be cautious of any previous analyses that have said it must be point sources."

EXISTENTIAL CRISIS

Ultimately scientists are left scratching their head at the extremely odd behavior of 85 percent of the mass in the universe. Do the new studies discrediting the supposed signals of dark matter in our galaxy make them doubt dark matter exists? "No," Abazajian says, "particle dark matter is so consistent with what's been observed, from the subgalaxy scale out to the horizon of the cosmos, that it is, basically, without a doubt, there."

Even though their faith in the existence of dark matter is unshaken, scientists' hope of finding it may be diminished. Not only is astrophysical evidence elusive, but direct detection experiments aiming to capture the particles responsible have so far failed. And searches at the LHC have also come up empty. "We don't see them in the lab, we don't see them in the LHC, and we don't see them in the sky," Abazajian bemoans. "There's a kind of existential crisis in particle physics."

And scientists' inability to find dark matter makes its true identity more uncertain than ever. The once leading candidates for dark matter, weakly interacting massive particles (WIMPs), are practically ruled out by their failure to show up in direct detection experiments—and possibly by the new limits Abazajian's paper calculates. "A lot of the standard models for what people thought dark matter would be have been taken off the table," Safdi says. "A lot of people thought WIMPs would almost certainly exist. In some sense, it's a discouraging time. But in another sense, it's very exciting because it means we're all brainstorming, going back to the basics, thinking about what dark matter can be."

Powerful magnetic and electric fields whip charged particles around, in a computer simulation of a spinning neutron star.

The Strange Hearts of Neutron Stars

Space observations are poised to reveal more about the center of one of the universe's most enigmatic objects

By Adam Mann

NASA'S GODDARD SPACE FLIGHT CENTER

Adam Mann is a journalist specializing in astronomy and physics. His work has appeared in *National Geographic*, the *Wall Street Journal*, *Wired,* and elsewhere.

WHEN A MASSIVE STAR DIES IN A SUPERNOVA, THE EXPLOSION IS ONLY THE BEGINNING OF the end. Most of the stellar matter is thrown far and wide, but the star's iron-filled heart remains behind. This core packs as much mass as two suns and quickly shrinks to a sphere that would span the length of Manhattan. Crushing internal pressure—enough to squeeze Mount Everest to the size of a sugar cube—fuses subatomic protons and electrons into neutrons.

Astronomers know that much about how neutron stars are born. Yet exactly what happens afterward, inside these ultradense cores, remains a mystery. Some researchers theorize that neutrons might dominate all the way down to the center. Others hypothesize that the incredible pressure compacts the material into more exotic particles or states that squish and deform in unusual ways.

Now, after decades of speculation, researchers are getting closer to solving the enigma, in part thanks to an instrument on the International Space Station called the Neutron Star Interior Composition Explorer (NICER).

Last December this NASA space observatory provided astronomers with some of the most precise measurements ever made of a neutron star's mass and radius, as well as unexpected findings about its magnetic field. The NICER team plans to release results about more stars in the next few months. Other data are coming in from gravitational-wave observatories, which can watch neutron stars contort as they crash together. With these combined observations, researchers are poised to zero in on what fills the innards of a neutron star.

For many in the field, these results mark a turning point in the study of some of the universe's most bewildering objects. "This is beginning to be a golden age of neutron star physics," says Jürgen Schaffner-Bielich, a theoretical physicist at Goethe University in Frankfurt, Germany.

Launched in 2017 on board a SpaceX Falcon 9 rocket, the $62-million NICER telescope sits outside the space station and collects x-rays coming from pulsars—spinning neutron stars that radiate charged particles and energy in enormous columns that sweep around like beams from a lighthouse. The x-rays originate from million-degree hotspots on a pulsar's surface, where a powerful magnetic field rips charged particles off the exterior and slams them back down at the opposing magnetic pole.

NICER detects these x-rays using 56 gold-coated telescopes and time-stamps their arrival to within 100 nanoseconds. With this capability, researchers can precisely track hotspots as a neutron star whips around at up to 1,000 times per second. Hotspots are visible as they swing across the object. But neutron stars warp spacetime so strongly that NICER also detects light from hotspots facing away from Earth. Einstein's general theory of relativity provides a way to calculate a star's mass-to-radius ratio through the amount of light bending. That and other observations allow astrophysicists to pin down the masses and radii of the deceased stars. Those two properties could help in determining what is happening down in the cores.

DEEP, DARK MYSTERY

Neutron stars get more complicated the deeper one goes. Beneath a thin atmosphere made mostly of hydrogen and helium, the stellar remnants are thought to boast an outer crust just a centimeter or two thick that contains atomic nuclei and free-roaming electrons. Researchers think that the ionized elements become packed together in the next layer, creating a lattice in the inner crust. Even farther down, the pressure is so intense that almost all the protons combine with electrons to turn into neutrons, but what occurs beyond that is murky at best.

"It's one thing to know the ingredients," says Jocelyn Read, an astrophysicist at California State University, Fullerton. "It's another to understand the recipe and how those ingredients are going to interact with each other."

Physicists have some idea of what happens, thanks to particle accelerators on Earth. At facilities such as Brookhaven National Laboratory in Upton, N.Y., and CERN's Large Hadron Collider near Geneva, researchers have smashed together heavy ions, such as those of lead and gold, to create brief collections of monumentally dense material. But these kinetic experiments generate billion- or even trillion-degree flashes, in which protons and neutrons dissolve into a soup of their constituent quarks and gluons. Terrestrial instruments have a hard time probing the relatively mild millions-of-degrees conditions inside neutron stars.

There are multiple ideas about what might occur. It could be that quarks and gluons roam freely. Or the extreme energies could lead to the creation of particles called hyperons. Like neutrons, these particles contain three quarks. But whereas neutrons contain the most basic and lowest-energy quarks, known as up and down quarks, a hyperon has at least one of those replaced with an exotic “strange” quark. Another possibility is that the center of a neutron star is a Bose-Einstein condensate, a state of matter in which all subatomic particles act as a single quantum-mechanical entity. And theorists have dreamed up even more outlandish prospects.

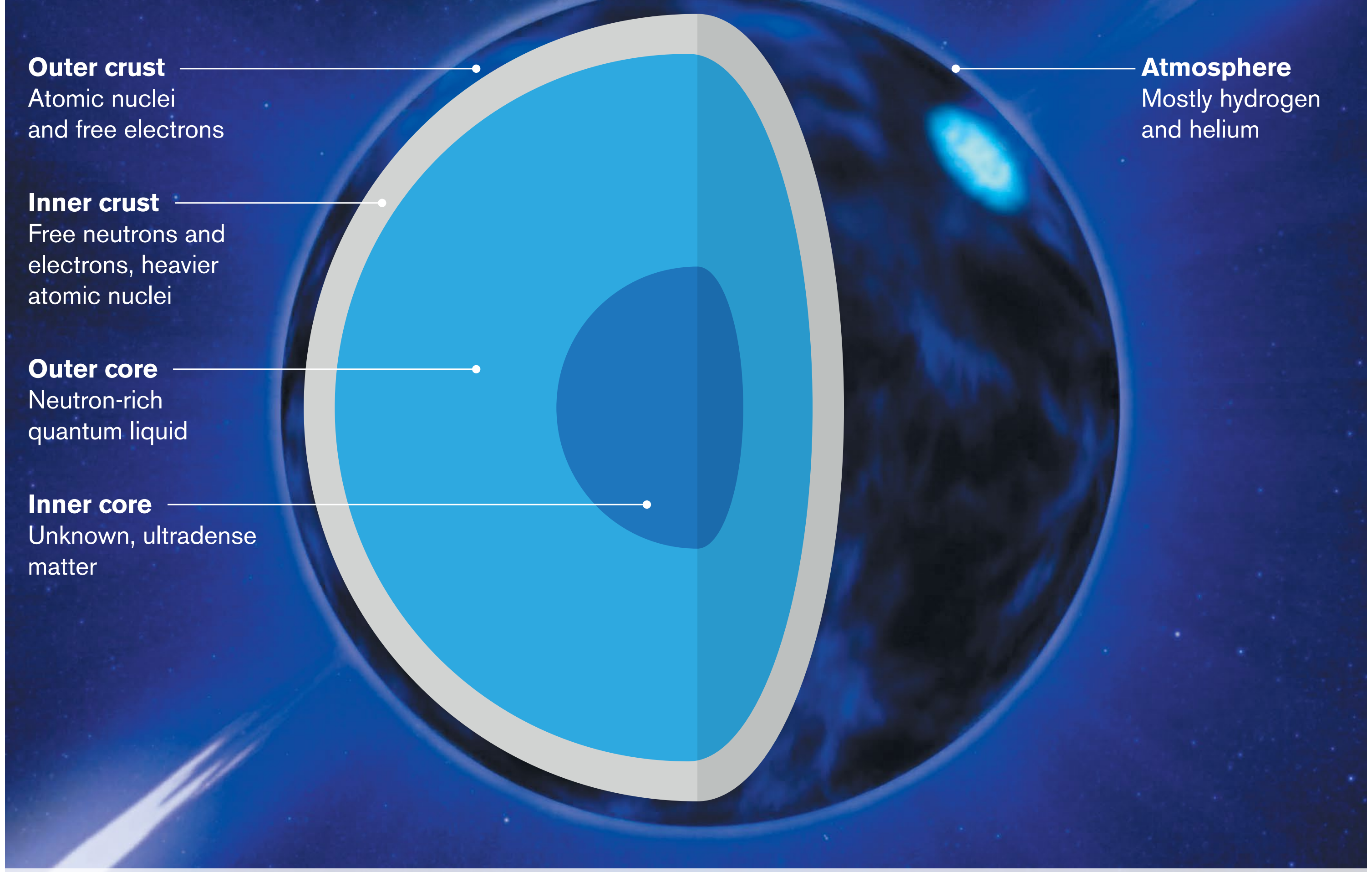
Crucially, each possibility would push back in a characteristic way against a neutron star’s colossal gravity. Each would generate different internal pressures and therefore a larger or smaller radius for a given mass. A neutron star with a Bose-Einstein condensate center, for instance, is likely to have a smaller radius than one made from ordinary material such as neutrons. One with a core made of pliable hyperon matter could have a smaller radius still.

“The types of particles and the forces between them will affect how soft or squashy the material is,” says Anna Watts, who is a NICER team member at the University of Amsterdam.

Differentiating between the models will require precise measurements of the size and mass of neutron stars, but researchers have not yet been able to push their techniques to fine-enough levels to say which possibility is most likely. They typically estimate masses by observing neutron stars in binary pairs. As the objects orbit, they tug gravitationally on one another, and astronomers can use this to determine their masses. Roughly 35 stars have had their masses measured in this way, although the figures can contain error bars of up to one solar mass. A mere dozen or so have also had their radii calculated, but in many cases, the techniques cannot determine this value to better than a few kilometers—as much as one fifth of the size of a neutron star.

DENSE MATTER

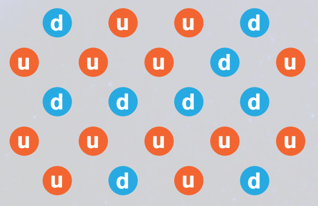
Neutron stars get denser with depth. Although researchers have a good sense of the composition of the outer layers, the ultradense inner core remains a mystery.



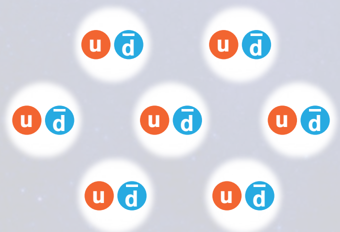
Core scenarios

A number of possibilities have been suggested for the inner core, including these three options.

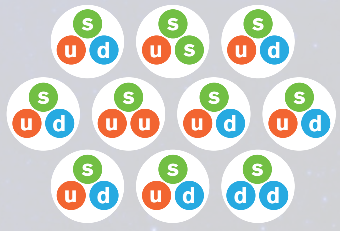
u Up quark
d Down quark
s Strange quark
d̄ Anti-down quark



Quarks
The constituents of protons and neutrons—up and down quarks—roam freely.



Bose-Einstein condensate
Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.



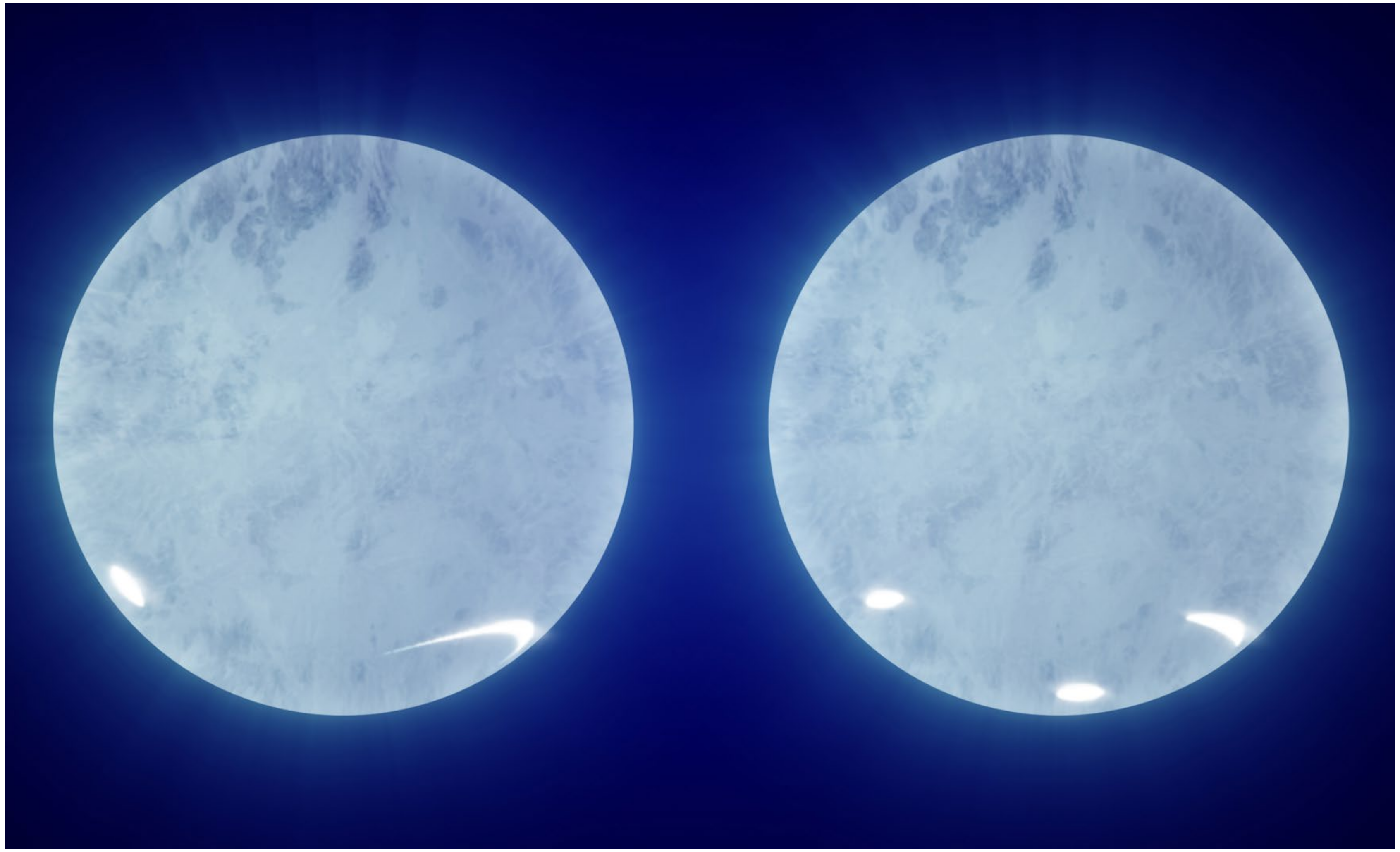
Hyperons
Particles called hyperons form. Like protons and neutrons, they contain three quarks but include “strange” quarks.

NATURE

NICER's hotspot method has been used by the European Space Agency's X-ray Multi-Mirror Mission (XMM-Newton) satellite, which launched in 1999 and is still in operation. NICER is four times more sensitive and has hundreds of times better time resolution than XMM-Newton. Over the next two to three years, the team expects to be able to use NICER to work out the masses and radii of another half a dozen targets, pinning down their radii to within half a kilometer. With this precision, the group will be well placed to begin plotting out what is known as the neutron-star equation of state, which relates mass to radius or, equivalently, internal pressure to density.

If scientists are particularly lucky and nature happens to serve up especially good data, NICER might help eliminate certain versions of this equation. But most physicists think that, on its own, the observatory will probably narrow down rather than completely rule out models of what happens in the mysterious objects' cores.

"This would still be a huge advance on where we are now," Watts says.



Hotspots rotate in two scenarios for the pulsar J0030+0451, based on analysis of NICER data.

FIELD LINES

NICER's first target was J0030+0451, an isolated pulsar that spins roughly 200 times per second and is 337 parsecs (1,100 light-years) from Earth, in the constellation Pisces.

Two groups—one based primarily at the University of Amsterdam and another led by researchers at the University of Maryland at College Park—separately sifted through 850 hours of observations, serving as checks on each other.

Because the hotspot light curves are so complex, the groups needed supercomputers to model various configurations and work out which ones best fit the data. But both came up with similar results, finding that J0030 has a mass that is 1.3 or 1.4 times that of the sun and a radius of roughly 13 kilometers.

Those results are not definitive: they could be used to support either the mundane or the otherworldly predictions for what is inside the guts of neutron stars. "There's no requirement for anything funky or crazy or exotic yet," says Andrew Steiner, a nuclear astrophysicist at the University of Tennessee.

Researchers got a bigger surprise with findings about the shape and position of the hotspots. The canonical view of neutron stars has their magnetic field lines looking like those surrounding a bar magnet, with north and south sides emerging from circular spots at opposing ends of the star. In contrast, the Dutch supercomputer simulations implied that both of J0030's hotspots are in its southern hemisphere and that one of them is long and crescent-shaped. The Maryland team also came up with the possibility of a three-hotspot solution: two southerly oval-shaped ones and a final circle near the rotational south pole.

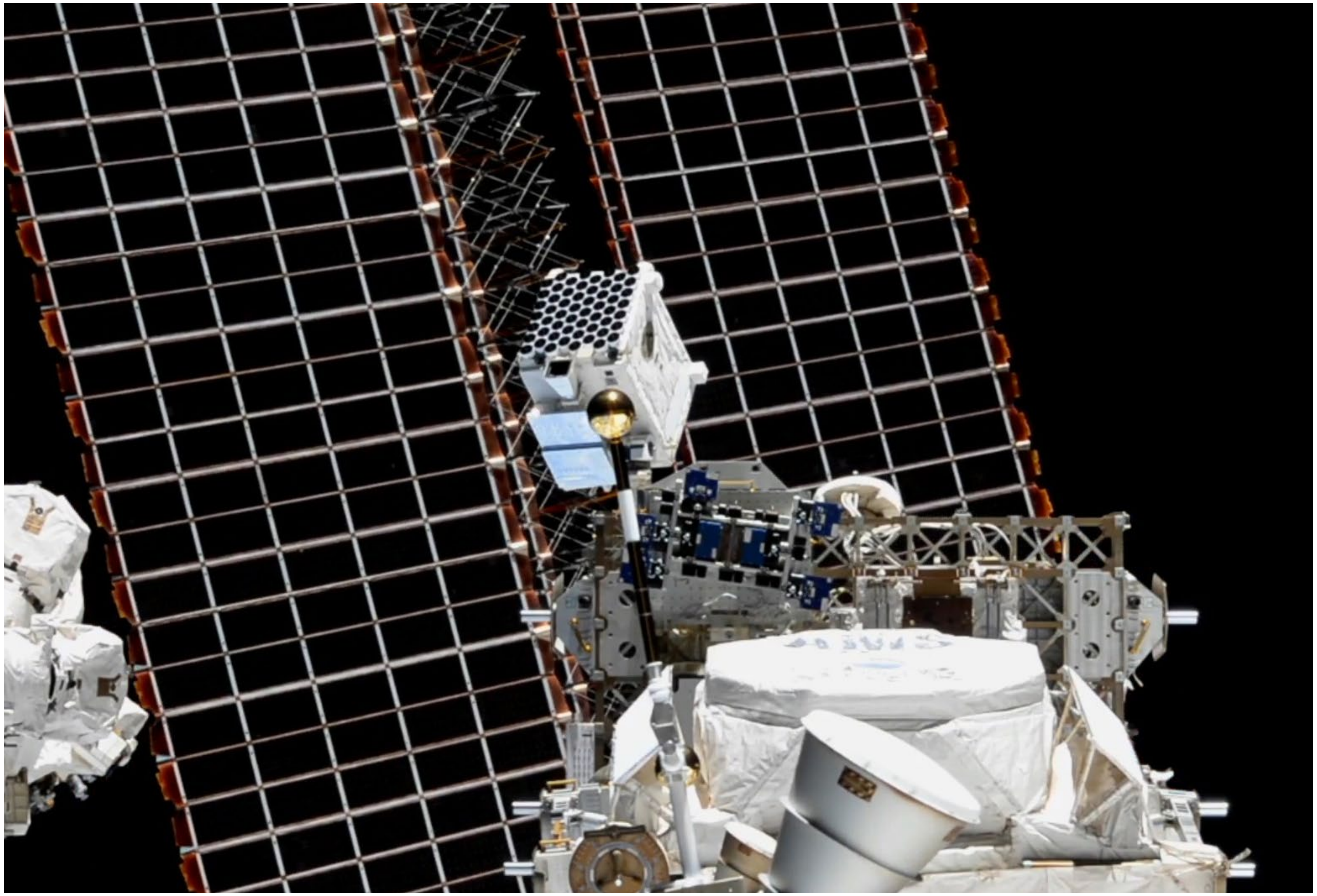
"It looks like they might have made the first real detection of a pulsar where the beams are not 180 degrees separated," says Natalie Webb, an astrophysicist at the Institute for Research in Astrophysics and Planetology in Toulouse, France, who has modeled such possibilities. "That's fantastic if true."

The results would bolster previous observations and theories suggesting that neutron stars' magnetic fields, which are one trillion times stronger than the sun's, can be more complex than generally assumed. After they first form, pulsars are thought to slow their rotation over millions of years. But if they have a companion star orbiting around them, they might steal material and angular momentum from this partner, boosting their spinning to superfast speeds. As the matter gets deposited on the star's exterior, some theorists suggest it could affect a fluidlike layer of subsurface neutrons, generating gigantic vortices that twist the neutron star's magnetic field into odd arrangements. The companion might ultimately be consumed or lose so much mass that it becomes gravitationally unbound and flies away, as could have been the case with the now solitary J0030.

WORK IN PROGRESS

NICER is continuing to observe J0030 to further improve the precision of its radius measurements. At the same time, the team is beginning to analyze data from a second target, a slightly heavier pulsar with a white dwarf companion. Other astronomers have used observations of this pair's orbital dance to determine the pulsar's mass, which means NICER researchers have an independent measurement that they can use to validate their findings.

Among NICER's targets, the team plans to include at least a couple of high-mass pulsars, including the current record-holder for most massive neutron star—a behemoth with a mass 2.14 times that of the sun. That should allow the researchers to probe an upper limit: the point at which a neutron star collapses into a black hole. Even the 2.14-solar-mass object is challenging for theorists to explain. Several researchers have also suggested that NICER might be able to find two neutron stars with the same mass but different radii. That would suggest the presence of a transition point, at which slight differences create two distinct cores. One might contain mostly neutrons, for example, and the other might be composed of more exotic material.



NICER, which picks up x-rays using 56 gold-coated telescopes, is installed on the exterior of the International Space Station.

NASA

Although NICER is at the vanguard, it is not the only instrument plumbing pulsars' depths. In 2017 the Laser Interferometer Gravitational-wave Observatory (LIGO), along with the Virgo detector in Italy, picked up the signal from two neutron stars crashing and merging together. As the objects rotated around each other before the crash, they emitted gravitational waves that contained information about the stars' size and structure. Each star's colossal gravitational influence tugged on and deformed its partner, contorting both from spheres into teardrop shapes. The amount of distortion in those final moments gives physicists clues about the malleability of the material inside the neutron stars.

LIGO's facility in Livingston, La., picked up a second neutron star smash-up last April, and more events could be spotted at any time. So far the two mergers have only hinted at the properties of neutron star interiors, suggesting that they are not particularly deformable. But the current generation of facilities cannot observe the crucial final moments, when the warping would be greatest and would display internal conditions most clearly.

The Kamioka Gravitational Wave Detector in Hida, Japan, is expected to come online later this year, and the Indian Initiative in Gravitational-wave Observations near Aundha Naganath, Marathwada, in 2024. In combination with LIGO and Virgo, they will improve sensitivity, potentially even capturing the details of the moments leading up to a crash.

Looking further into the future, several planned instruments could make observations that elude NICER and current gravitational-wave observatories. A Chinese-European satellite called the enhanced X-ray Timing and Polarimetry mission, or eXTP, is expected to launch in 2027 and study both isolated and binary neutron stars to help determine their equation of state. Researchers have also proposed a space-based mission that could fly in the 2030s called the Spectroscopic Time-Resolving Observatory for Broadband Energy x-rays, or STROBE-X. It would use NICER's hotspot technique, pinning down the masses and radii of at least 20 more neutron stars with even more precision.

The hearts of neutron stars will probably always retain some secrets. But physicists now seem well placed to begin peeling back the layers. Read, who is a member of the LIGO team, says that she has collaborated on a project to imagine what scientific questions gravitational-wave detectors would be able to tackle in the 2030s and 2040s. In the process, she realized that the landscape for neutron star research—in particular, the question of the equation of state—should look very different by then.

"It's been this long-standing puzzle that you figure will always be there," Read says. "Now we're at a point where I can see the scientific community figuring out the neutron star structure puzzle within this decade."

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Apollo 13 at 50 Years:

LOOKING BACK AT THE MISSION'S LOST LUNAR SCIENCE

Its commander Jim Lovell and pilot Fred Haise reflect on their fateful, flawed voyage to the moon

By Robert Z. Pearlman

Crew members of *Apollo 13* exit a helicopter onto the USS *Iwo Jima* shortly after their successful return to Earth on April 17, 1970. *From left:* Lunar module pilot Fred Haise, commander Jim Lovell and command module pilot Jack Swigert.

NASA

Robert Z. Pearlman is a space historian, journalist and the founder and editor of the space history news publication collectSPACE.com. His writing often focuses on the intersection between space exploration and pop culture.

Had all gone to plan, NASA's third mission to land astronauts on the moon would have deployed a pallet of science instruments and brought back samples from humanity's first visit to the lunar uplands. Instead, 50 years ago this, *Apollo 13* "had a problem."

An oxygen tank that had been unknowingly damaged before it left the ground exploded en route to the moon, crippling the spacecraft with astronauts Jim Lovell, Fred Haise and Jack Swigert onboard. In an instant, the April 1970 mission's priority switched from extending knowledge about Earth's natural satellite to safely returning the crew home.

"We said, 'Oh, my God, the moon landing is off,'" recalls Lovell, *Apollo 13*'s commander. "We still had one good fuel cell, and it was providing enough electrical power to get us back to Earth. But the oxygen needed for the fuel cell was being spewed out the back end of our spacecraft."

Quickly assessing the situation

Group of flight controllers gather to discuss the challenge of bringing the crew of the crippled *Apollo 13* spacecraft safely home.

NASA

and following the guidance of a team of engineers on the ground, the crew went to work on shutting down the command module and powering up the lunar lander to serve as a lifeboat.

"Before you go on one of these missions, you assume, necessarily, you're not going to get back," says Haise, *Apollo 13*'s lunar module pilot. "I had no idea about the percentage—what odds there were. It was a matter of working through it with a number of the challenges and [hoping] that someone on the ground, working at mission control, would find the answers."

Using something that was still operating on the spacecraft—namely, the rocket engine that would have landed Lovell and Haise on the moon—*Apollo 13* was put on a "free return" trajectory. Looping around the far side, the moon's gravity would provide the acceleration needed to get the astronauts back to Earth.

Lovell had been to the moon before—he was among the first three people to enter its orbit on the *Apollo 8* mission two years earlier—but this journey was the first time Haise and Swigert saw the cratered surface up close. As command module pilot, Swigert had trained to photograph the

Tsiolkovsky Crater, photographed by the *Apollo 13* astronauts as they looped around the far side of the moon.

NASA

natural satellite from high above, including using a new large-format topographic camera that had not been flown before. But with the crew members' survival weighing heavily on everyone's mind, the mission's science objectives were not a priority.

"The flight plan was in the wastebasket. Jack and I both pulled out our cameras and shot a lot of pictures. We shot them mostly out of interest as a tourist," Haise says. "Looking down at the moon, we could view Fra Mauro, our site where we planned to land."

Unlike the sites chosen for the *Apollo 11* and *Apollo 12* landings, which had both been on the flat basaltic plains of the moon's maria, or "seas," the Fra Mauro highlands were characterized by low ridges and large hills, offering brand-new varieties of lunar terrain to explore. The area was of particular interest to geologists, because it was anticipated that much of the material on the surface had been excavated and ejected from the nearby Cone Crater.

Haise's first view of Fra Mauro should have been a moment of excitement: under normal circumstances, it would have been a glimpse of things to come. Instead the view was immediately a reminder of what he would not get to achieve. "It wasn't an overwhelming kind of emotion at that point. It was just a continuation of the feeling of disappointment that we were not going to be able to do as we trained and set out to do," he says.

Had there not been an explosion, Lovell and Haise would have touched down on the lunar surface and made two moon walks, including a trek to the rim of Cone Crater. The two astronauts had undergone extensive training not just to pick up moon rocks and traverse their landing site but also to deploy instruments in order to "gather and relay long-term scientific data to Earth for at least year on the moon's physical and environmental properties," as NASA's preflight press kit read.

Some of the hardware was of the same design that had flown on the two prior moon landings. For example, both *Apollo 11* and *Apollo 12* had left behind seismometers to measure meteoroid impacts and "moonquakes." (*Apollo 12*'s seismometer, like *Apollo 13*'s, was powered by a nuclear radioisotope thermoelectric generator, or RTG, that led to a disposal concern at the end of the latter mission.) Others science tools were planned to be used for the first time.

Clad in spacesuits during a training exercise in January 1970, *Apollo 13* astronauts Lovell (*at left*) and Haise train with an electric drill in preparation for their ill-fated mission to the lunar surface.

NASA

"The unique one that we had on our flight, which was not flown again until *Apollo 15*, was the electric drill," Haise says, referring to part of a heat-flow experiment that called for boring a few meters into the moon's surface to collect core samples. (As it turned out, Haise might have run into the same difficulty that the *Apollo 15* crew later did, given the tendency for the lunar regolith, or soil, to clog up the drill.)

The other lunar science packages on *Apollo 13* included a charged-particle experiment that would have measured the effects of the solar wind in the moon's environment; a cold-cathode-gauge experiment to quantity the density and temperature variations in its thin atmosphere and a dust detector. "I think if we had landed, and if we never had the problem in the first place, I think the science work we had trained for would have been achieved," Lovell says.

In the end, the crew did get home safely (Swigert later died of cancer in 1982). Without the opportunity to survey the Fra Mauro region and deploy the lunar-surface experiments, NASA's program director recommended the *Apollo 13* mission be considered "unsuccessful." But not all of its science was lost.

As the astronauts were returning home, the segment of their rocket that boosted them away from Earth was purposely directed to collide with the moon. The resulting impact, as measured by a seismometer deployed during *Apollo 12*, walloped the surface with an energy equivalent of more than 10 metric tons of TNT. The data that were collected provided new insight into the composition of the natural satellite, which, in turn, informed future moon-landing missions and their experiment packages.

After having set aside all of their training and science objectives, the news from mission control that the booster's impact had been successfully recorded inspired Lovell to respond. "Well, at least something worked on this flight," he radioed back to Earth.

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SPACE

A Sobering Astronomical Reminder from COVID-19

We should be grateful for the conditions that allow us to exist at all, because they won't last forever

Mother Nature has its nuanced way of educating us. Following a century of scientific and technological advances that triggered unprecedented economic growth, our civilization perceived its superiority over nature as undisputed.

Like corrections to irrationally exuberant stock markets, however, COVID-19 is a correction to human hubris. Nature is teaching all humans, rich and poor, to be humble. Although we thought we can manipulate nature at our will, here comes a primitive coronavirus with negligible information content relative to our brain, threatening to kill us and wreck our economy, causing as much damage from the side effects triggered by our societal reaction to it as from its direct medical impact.

Personally, I practiced social distancing long before

ARTUR DEBAT *GETTY IMAGES*

it became trendy. In my mind, it was evident before the appearance of COVID-19 that we are fundamentally "monads" as envisioned by philosopher Gottfried Leibniz, despite illusive notions of empowerment that stem from groupthink. Social distancing benefits free thinking. Isaac Newton did his best scientific work while staying home with his parents at Woolsthorpe during the Great Plague of London in 1665–66, when the University of Cambridge closed down. Over a year of independent work, he developed calculus, optics and realized the nature of gravity.

But there is another lesson to be learned. A few years earlier Newton wrote a document that, among other things, listed the sins he had committed "Before Whitsunday 1662." Number 13 on the list: "Threatening my father and mother Smith to burne them and the house over them."

As a student of history, I am doing my best to be nice to my daughters during the COVID-19 lockdown.

Beyond existential lessons, however, COVID-19 has sparked international scientific collaborations demonstrating that science has no borders when it comes to promoting a better common future for our civilization. Just as the novel coronavirus can infect everyone, a successful vaccine can benefit everyone. Scientific triumphs are for all of us to share. Science is not a zero-sum, but rather an infinite-sum, game. Here is hoping that in the wake of COVID-19, international scientific collaborations will lead to more goodwill among nations and better political collaboration across the globe in our future.

The most fundamental lesson is simple. We must treasure all the good that nature gives us rather than take it for granted, because it can easily disappear. Over the next century trillions of dollars could be lost not just from pandemics like COVID-19 but also from major solar flares or asteroid impacts. We had better prepare protections for those before they hit us.

On longer timescales, even bigger catastrophes might occur, such as explosions of nearby stars or a brightening of the sun that will boil off our oceans less than a billion years from now.

As I told students over Zoom in my freshman seminar in April at Harvard University, life as we know it is merely an afterthought in the global scheme of the cosmos. The universe started off consisting mainly of hydrogen and helium. Heavy elements like carbon and oxygen, which enable the chemistry of life, are the "ashes" from nuclear burning in the hot cores of stars. Our transient existence has lasted for less than 10 one-billionths of cosmic history so far on a tiny rock we call Earth, surrounded by a vast lifeless space. We should be thankful for the fortuitous circumstances that allow us to exist, because they will surely go away one day, with or without COVID-19.

The Hubble Space Telescope needs no introduction.

SPACE

A Birthday Message from the Hubble Telescope

I'm turning 30, and it's been an amazing journey so far


NASA

I have seen 160,000 sunrises and sunsets, more than anyone could hope for. Circling hundreds of miles above the surface of our big blue marble for 30 years, I've had a remarkable view of the universe. I haven't always been comfortable up here, but thanks to many of you I have outgrown a host of problems and found a purpose far more expansive and satisfying than anything my creators envisioned.

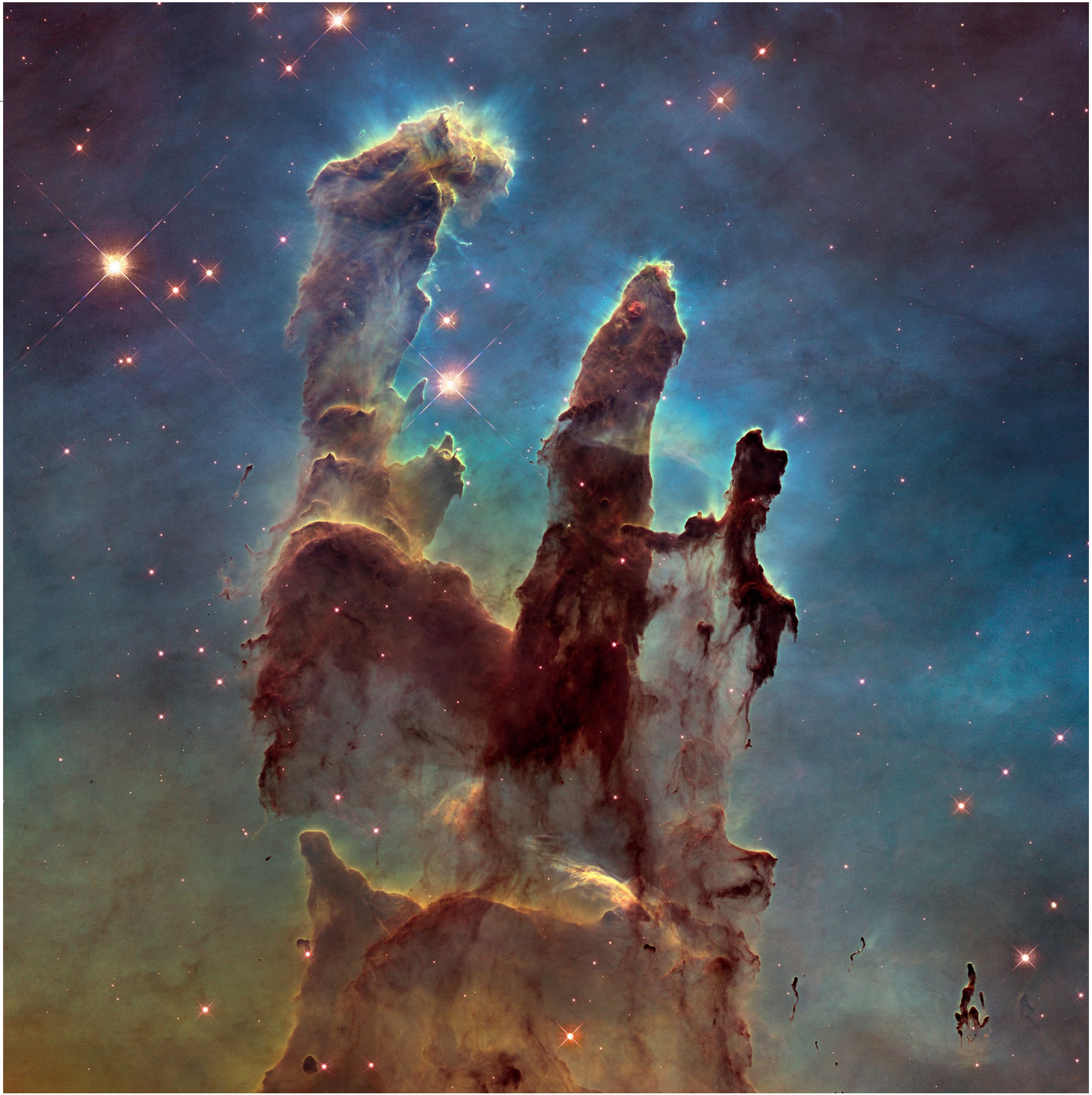
I've come to appreciate the perspective that one develops when falling endlessly yet always hovering above Earth's atmosphere. Unencumbered by air currents or clouds, the seeing is superb, and the sky is dark. I have never seen alligator lizards in the air, as I don't look down at clouds very often. But I have seen far distant cosmic tarantulas and eagles and butterflies and lagoons of brilliant colors in exquisite detail.

The best part of exploring the universe is that I've been able to share those images with you. I can see only a narrow range of colors at a time, but graphic artists and scientists on the ground combine the pictures I take into glorious multicolor compositions that inspire me to peer deeper, look longer and try new things. I know they've inspired some of you, too.

I've made many friends over the years, most of whom I've never met in person but cherish all the same. I consider myself to be the luckiest scope in the world. You have made me what I am—your telescope, your window on the universe.

Together we've peered into the depths of time and witnessed colossal collisions, brilliant explosions, cosmic rhythms and wisps of the fleeting past. We've seen stars forming in stellar nurseries and stars disappearing into black holes. Oh!—there are so many stars up here. I wish I could see them all, but I'd need a much larger field of view for that. For now I'm content looking at new worlds and blazing new horizons for others to explore.

Speaking of others, it's been a long time since anyone has visited me! That's actually a good thing, I guess, as I've been healthy and productive for the past 10 years since my last instrument transplant. The Hubble team—they're the best—tells me that approaching 30 years is by no means the final countdown for me. My best years are still ahead, so I'm eagerly



"Pillars of Creation" in the Eagle Nebula

NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

anticipating all the new observing plans and looking forward to what's yet to come.

Astronomers are a clever bunch. They like to try new things and present new challenges to my schedulers, which keeps me motivated to do the best I can. I'm not always as efficient or as steady as I'd like to be, but that's okay. Together we've been learning how to get through the rough patches. When I get cranky, they change my attitude, and when I need a bit of a reset, they patiently give me time to reboot.

Some have said that I'm the most productive science instrument of all time. That's a big claim to live up to. I'm certainly proud of the accomplishments I've helped make possible, but the real work is done down there on Earth. Based on my observations, scientists published more than 1,000 scientific papers in the peer-reviewed astronomical literature this past year alone. It takes clever, dedicated people to turn great ideas into science, and a lot of public support for those efforts. I'm hopeful that continues well into the future, even after I'm retired.

One of the things I'm most excited

Lagoon Nebula

NASA, ESA, AND STSCI

about is working with my younger sibling, James. I can hardly wait to see what the first stars and galaxies look like or what all those glorious star-forming regions I've seen over the years look like to James with infrared vision. Sometime next year James will speed past me off to a new home about a million miles away. That seems like a long way, but it's only about four times farther than the moon. Oddly, it's far enough and yet close enough that I can't get a good look at James from my vantage point here while whizzing around Earth at 17,000 miles per hour. Like me, James has an amazing team of engineers, technicians, scientists and skilled professionals doing everything they can to ensure mission success.

Looking forward even further, I hope that I've inspired the next generation of scientists to strike out in bold, visionary directions. The space telescopes envisioned for the 2020s and 2030s make me feel small, but they are so powerful that I can't help but believe we'll see a universe far beyond my ken. You've seen all I've done, but my technology is decades old. With new instrumentation we'll be able to determine the

Butterfly Nebula

NASA, ESA, AND THE HUBBLE SM4 ERO TEAM

fate of the cosmos, resolve the structure of galaxies anywhere in the universe, and study Earth-like worlds in other solar systems. Who knows, we may even find evidence for life on some of those planets, something I'll probably never be able to do. If that isn't inspiring, I don't know what is. It won't be easy, and at times it may seem impossible. But I've shown you what is possible when you persist. I've laid the groundwork, now go out there and explore!

I am humbled that so many of you are thinking of me today and wishing me well. Some of you are even baking me cakes and sending me birthday cards. I truly appreciate your support, as I would not be here without you. For me, the connection I have with you is both my greatest success and my ultimate purpose. In gratitude, I snapped a new view of a little corner of the universe dubbed the "Cosmic Reef."

I share with you my birthday wish for a healthy, peaceful world full of wonder.

Thank you for listening!

—The Hubble Space Telescope

NASA, ESA, AND D. LENNON (ESA/STSCI)

NASA, ESA, AND STSCI

Tarantula Nebula (*top*), "Cosmic Reef" (*botttom*): The giant nebula NGC 2014 and its neighbor NGC 2020, which together form part of a vast star-forming region in the Large Magellanic Cloud

Wade Roush is the host and producer of Soonish, a podcast about technology, culture, curiosity and the future. He is a co-founder of the podcast collective Hub & Spoke and a freelance reporter for print, online and radio outlets, such as MIT Technology Review, Xconomy, WBUR and WHYY. His new book, *Extraterrestrials*, is published by the MIT Press.

SPACE

Life as We Don't Know It

If we're going to find extraterrestrials, we need to stop assuming they'll think like humans

DAVID WALL *GETTY IMAGES*

In 1985, when I was a baby journalist writing my first college newspaper story, I covered a symposium at Harvard University inaugurating the Megachannel Extraterrestrial Assay (META), a computer system designed by physicist Paul Horowitz to sift through millions of narrow radio channels for signals from other civilizations.

Carl Sagan was on hand that weekend to represent the Planetary Society, which had helped fund the project. So was Steven Spielberg, who had written a $100,000 check. Having grown up on Sagan's *Cosmos* and Spielberg's *Close Encounters of the Third Kind* and *E.T.: The Extraterrestrial*, I was star-struck. But I was also thrilled to witness what felt like the launch of a voyage that would finally turn science fiction into science reality.

No one at the symposium was rash enough to predict whether or when Horowitz's project would succeed. But if you'd told the assembled scientists that 35 years would go by without META or any of its successors detecting even a hint of a signal, they'd have reacted with disappointment and disbelief. The aliens ought to be out there; they ought to be broadcasting; we ought to be able to hear them. But a 2020 *Astronomical Journal* paper detailing a search of 1,327 nearby stars at the highest sensitivity to date found zero candidate signals. So how is it that the Great Silence—to use the title phrase from astronomer Milan Cirkovic's 2018 book— continues?

Well, having just written my own book about the

> **“So far in our quest to find ET, we have only been searching for other versions of ourselves.”**
> ***—Nathalie Cabrol***

history of that question (*Extraterrestrials*, MIT Press, April 2020), I’ve come to suspect that there’s something missing in our approach to the search for off-world intelligence. This search is built around the hope that if technological societies are out there, they’re communicating (1) using the parts of the electromagnetic spectrum we can most easily scan from Earth’s surface, namely radio and optical frequencies, and (2) using encoding schemes such as pulse modulation that we can easily recognize. Those assumptions made sense in the early days of SETI in the 1960s, when the field was still a quirky offshoot of radio astronomy.

But today they seem fatally Earth-centric and human-centric. As Nathalie Cabrol of the SETI Institute wrote in a paradigm-busting 2016 *Astrobiology* paper, “[S]o far in our quest to find ET, we have only been searching for other versions of ourselves.”

What we didn’t know in the 1960s is that there are planets around most stars—and that while many are in the “habitable zones” of their systems, where surface water would neither boil nor freeze, few of them precisely resemble Earth. We also didn’t understand how hardy and adaptable life can be: We’ve found it in places with crushing pressures and scalding temperatures, in Antarctic lakes cut off from the sun for thousands of years, and even inside nuclear reactors, where it feeds on radiation. And we didn’t appreciate the dazzling variety of communication styles among the sentient beings we do know—the other animals who share Earth.

Cabrol is right: it’s time to move beyond the idea that extraterrestrials would think like us or use technologies like ours. Sure, let’s keep listening for technosignatures such as radio signals. As SETI Institute founder Jill Tarter has pointed out, our search so far amounts to sampling a single glass of water from the ocean. But let’s also look for biosignatures, such as signs of industrial activity in the atmospheres of exoplanets—data that we’ll soon be able to gather using NASA’s James Webb Space Telescope. Let’s expand the search beyond familiar sunlike stars and red dwarfs. Let’s look at planets where exotic biochemistry might reign. Let’s use our computers to model how the universe might look to beings who evolved in different environments and might have very different sense organs and neural systems. And then let’s build new observing and filtering systems to look for the kinds of messages they might be sending.

Maybe we’ll get lucky and detect a radio signal tomorrow that says “hello” in simple mathematical code, the way Sagan predicted in his 1985 novel *Contact*. But more likely, if we want to find what Cabrol calls “life as we do not know it,” we’ll have to get outside our own heads and think more like aliens.

Graham Farmelo is a Fellow of Churchill College, University of Cambridge; a frequent Director's Visitor at the Institute for Advanced Study; and author of *The Universe Speaks in Numbers* (Basic Books).

PHYSICS

Remembering Freeman Dyson

In our conversations, he ventured far and wide across science, literature and politics, offering unorthodox ideas with a bracing self-confidence

NADINE RUPP *GETTY IMAGES*

Freeman Dyson was incapable of speaking a dull sentence. For more than 60 years he was one of the world's most accomplished living mathematical physicists, and in his later decades he earned a literary reputation as one of the few great scientists who wrote as clearly as he thought.

Before I first met him 16 years ago, I imagined that he would be a commanding figure with a voice to match. I was therefore surprised to shake hands with a physically small and slender man, formally dressed in a way that would have been fashionable in the 1950s. Although he had lived in the U.S. for more than five decades and been an American citizen since 1957, he spoke with a strong English accent, in a manner that was direct, unassuming and cautiously friendly. In his peremptory way, he told me: "I have only two talents—doing calculations and writing essays."

In our subsequent conversations, he ventured far and wide across science, literature and politics, almost always taking a counterorthodox line, articulated with a bracing self-confidence, in language studded with aphorisms (this is partly why he was a dream interviewee). Often described as a contrarian, he preferred to think of himself as a rebel. When I put it to him that he would rather be interesting than right—a common description of him in Princeton circles—he replied, "Yes, there is some truth in that." After I quoted the late journalist Malcolm Muggeridge's line that "Only dead fish swim with the sea," Dyson painstakingly wrote it in a note-book, smiling broadly and muttering, "I like it."

Among Dyson's favorite themes was the search for patterns. He loved to quote the famous maxim of mathematician G. H. Hardy that mathematicians make enduring patterns out of ideas. For Dyson, science was about understanding the order in the natural world—the abstract patterns that underlie the workings of the universe. Even when he was considering complicated topics, he could not resist organizing them into a handful of neat categories (too neat, some would argue). Most famously, he classified leading physicists and mathematicians as either birds or frogs. For him, Albert Einstein was the archetypal bird—flying high, surveying broad vistas out to the horizon—while Dyson regarded himself as a frog, hopping from one problem to another. He allowed few exceptions to his categories, but he did concede that his friend Richard Feynman was "a frog who wanted to be a bird."

Dyson was born in Berkshire, England, in 1923 to well-off parents, his mother a law graduate, his father a well-known composer (later a knight). It was soon clear that Freeman was a mathematical prodigy. In later life, he recalled trying to calculate the sum of an infinite series of numbers when he was still sleeping in a cot. Dyson was only 17 years old when he began to study at Trinity College, Cambridge, where he was taught mainly 19th-century mathematics by several top-class practitioners, including Abram Besicovistch. It was Besicovistch, Dyson told me, who led him to regard mathematics as the art of problem-solving. After he graduated in 1943, he worked at the Royal Air Force's Bomber Command, using mathematics to assist the military "to kill as many German civilians as possible," as he later ruefully described it.

After the conflict, having understood that he was ill equipped to shine in formidably abstract modern mathematics, he switched to theoretical physics, believing he could use his mathematical skill to address some of the challenges of making sense of a theory of electromagnetic interactions that is consistent with both quantum mechanics and Einstein's basic theory of relativity. It was a wise move. At Birmingham University, the German-born theorist Rudolf Peierls became Dyson's mentor. Dyson quickly became a star and never studied for a Ph.D., a qualification that he regarded as worthwhile only for students destined to be college professors.

In the late 1940s and early 1950s he made his most profound contribution to physics: he demonstrated that three versions of the quantum theory of electromagnetic interactions were equivalent and that the theory could be used to make predictions of arbitrarily high accuracy. Of the four leading pioneers of this subject, only Dyson did not win a Nobel Prize, leading many of his peers to regard him as the most accomplished living theorist not to be given that honor. He denied that he was disappointed to have been passed over: "I didn't deserve it," he often told me.

> **"I have spent my life befriending my enemies."**
> ***—Freeman Dyson***

Dyson had become "a big shot with a vengeance," as he told his parents. He was soon bustling at the frontiers of theoretical physics with its quantum royalty, including Niels Bohr, Werner Heisenberg, Max Born and Paul Dirac. These conversations later furnished him with a rich store of anecdotes that enabled him to become an accomplished raconteur and an Olympic-class name-dropper.

By the time he was 29 years old, he had been elected Fellow of the Royal Society and had been appointed to the Faculty of the Institute for Advanced Study, recruited by its director Robert Oppenheimer. "I was thrilled to get a job at the Institute," Dyson told me, "partly because I was not required to do any teaching." Einstein was then an emeritus professor, but Dyson did not try to meet him and never regretted having done so. "He avoided us, and we avoided him," he told me.

Oppenheimer was "a good but undistinguished physicist," in Dyson's view, but had "a blind spot for mathematics" and a snobbish disdain for any physics he did not regard as fundamental. Plus, Dyson, thought, Oppenheimer was deeply unlikable: "You never knew where you were with him." Oppenheimer made no secret of his disappointment when Dyson turned his attention away from particle physics towards other topics, less fashionable among their peers.

Dyson repeatedly demonstrated his prodigious talent for imaginative problem-solving and in a wide variety of fields, while continuing to do mathematics “as a recreation,” as he put it. Among his contributions to science, one of his favorites was the speculative idea that there might be solar systems in which a star is surrounded by a giant structure—a “Dyson Sphere”—that captures much of its power output. Using such a structure, an advanced civilization might prolong its existence in a universe heading toward heat death.

His inventiveness was underpinned by his breathtaking mathematical virtuosity and immense technical skill. Among his most impressive mathematical contributions was his work on random matrices (arrays of quantities of which at least some of the elements are random). These innovations have been successful in a wide range of topics from nuclear physics to neuroscience.

Dyson’s imagination ventured far beyond physics. In the latter part of his career, he brought an unconventional perspective to the life sciences. This often landed him in trouble with leading experts, notably when he repeatedly dismissed computer models of Earth’s climate and the growing consensus that climate change was a crisis for humanity.

Around 1970, before he was 50 years old, Dyson switched his focus from research to writing (“I just couldn’t keep up with the guys along the corridor,” he told me, modestly). In a style that was both silky and muscular, he wrote dozens of articles, many of them for the *New York Review of Books,* where his pieces often focused less on the books he was discussing than on his own experiences and perspectives on their subject matter.

He had no interest in writing definitive texts but was most at home as the author of memoirs—first, the wonderfully entertaining *Disturbing the Universe,* published in 1979, and later the equally compelling *Maker of Patterns,* an autobiography told through selected letters he had written to family members (mostly his parents) over almost four decades, from 1941 to 1978. Published in 2018, its enthusiastic reception gave him enormous pleasure. It was a literary masterpiece, in my opinion, perhaps the first to be written by an author in their 90s.

I last spoke with Dyson in August 2019. He was sitting in his office, which was almost bare; almost all his books and papers had been taken away for cataloguing. “I feel like Ludwig Wittgenstein,” he said, alluding to Dyson’s awkward visit in the late 1940s to the great philosopher’s study, where the bookshelves were “as empty as his ideas.”

A few days before, Dyson had told me over lunch for the first time that he had “hated” Robert Oppenheimer. I was shocked to hear the good-natured Dyson admit to bearing a supposed friend such an intense dislike, especially as he often described even acquaintances as “friends.” To my surprise, he confirmed that “hatred” was indeed the right word, before he dropped the last zinger I was to hear him deliver: “I have spent my life befriending my enemies.”

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