SCIENTIFIC AMERICAN Space & Physics

ISSUE No.5

December 2018—January 2019

On a New Moon Far, Far Away

GLIMPSES OF AN EXOMOON ORBITING A PLANET 8,000 LIGHT-YEARS FROM EARTH

Also:

THE FIRST FEMALE PHYSICS LAUREATE IN 55 YEARS

FIXING OUR SPACE JUNK PROBLEM

A NEW WAY OF SEEING QUANTUM MECHANICS

WITH COVERAGE FROM nature

LIZ TORMES

A Universe of Possibilities

Astronomers estimate that every star in the universe has about one planet in orbit, on average. Given that there are somewhere in the neighborhood of 250 billion (yes, with a "b") stars in the Milky Way alone, the number of potential planets out there is staggering. Despite this apparent plethora, researchers have yet to conclusively observe any moons orbiting one of these faraway worlds. As Lee Billings writes in "Astronomers Tiptoe Closer to Confirming First Exomoon," Columbia University investigators have reported compelling data that a Neptune-size exomoon is circling a planet around the sunlike star called Kepler 1625 b, about 8,000 light-years from Earth.

Elsewhere in this issue, Alexandra Witze covers the latest efforts to clean up the 20,000 junk items that humans have littered in space (see "The Quest to Conquer Earth's Space Junk Problem"). And fascinating new research is focused on the human eye to get at one of the unresolved issues in quantum mechanics: the measurement problem (see "The Human Eye Could Help Test Quantum Mechanics"). From moons to single photons, astronomy and physics never fail to stagger the mind and the imagination.

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On the Cover

An artist's rendition of the moon (in the distance) from the planet that orbits Kepler 1625 b.

RON MILLERW

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WHAT'S INSIDE

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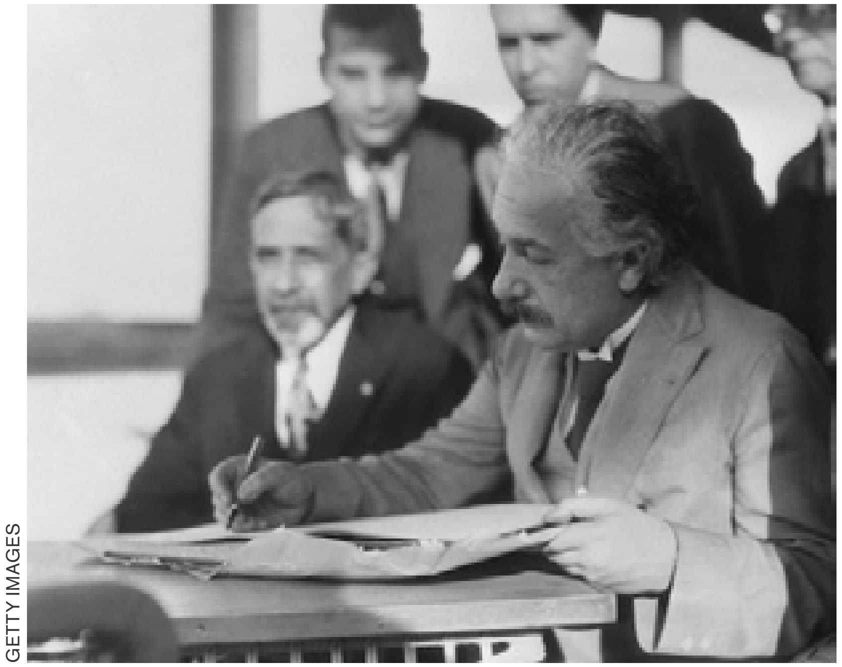

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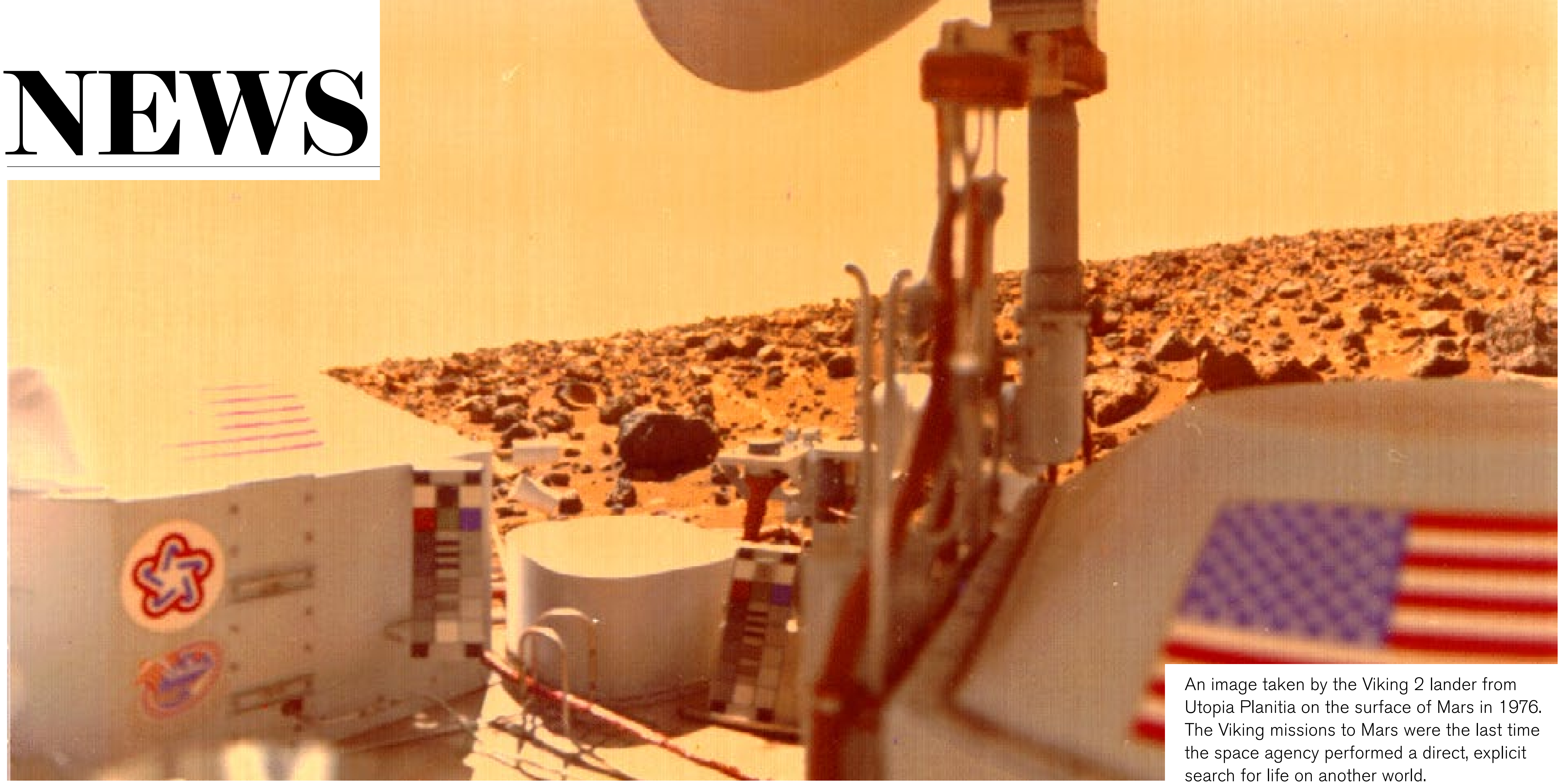


An image taken by the Viking 2 lander from Utopia Planitia on the surface of Mars in 1976. The Viking missions to Mars were the last time the space agency performed a direct, explicit search for life on another world.

NASA

Search for Alien Life Should Be a Fundamental Part of NASA, New Report Urges

A blue-ribbon committee finds the science of astrobiology is worthy of deep integration into the space agency's exploration efforts

FOR DECADES MANY researchers have tended to view astrobiology as the underdog of space science. The field—which focuses on the investigation of life beyond Earth—has often been criticized as more philosophical than scientific, because it lacks in tangible samples to study.

Now that is all changing. Whereas astronomers once knew of no planets outside our solar system, today they have thousands of examples. And although organisms were previously thought to need the relatively mild surface conditions of our world to survive, new findings about life's ability to persist in the face of extreme darkness, heat, salinity and cold have expanded researchers' acceptance that it might be found anywhere from Martian deserts to the ice-covered oceans of Saturn's moon Enceladus.

Highlighting astrobiology's increasing maturity and clout, a new congressionally mandated report from the National Academy of Sciences (NAS) urges NASA to make the search for life on other worlds an integral, central part of its exploration efforts. The field is now well set to be a major motivator for the agency's future portfolio of missions, which could one day let humanity know whether or not we are alone in the universe. "The opportunity to really address this question is at a critically important juncture," says Barbara Sherwood Lollar, a geologist at the University of Toronto and chair of the committee that wrote the report.

The astronomy and planetary science communities are currently gearing up to each perform their decadal surveys—once-every-10-year efforts that identify a field's most significant open questions—and present a wish list of projects to help answer them. Congress and government agencies such as NASA look to the decadal surveys to plan research strategies; the decadals, in turn, look to documents such as the new NAS report for authoritative recommendations on which to base their findings. Astrobiology's reception of such full-throated encouragement now may boost its odds of becoming a decadal priority.

Another NAS study released in September could be considered a second vote in astrobiology's favor. This "Exoplanet Science Strategy" report recommended NASA lead the effort on a new space telescope that could directly gather light from Earth-like planets around other stars. Two concepts, the Large Ultraviolet/Optical/Infrared (LUVOIR) telescope and the Habitable Exoplanet Observatory (HabEx), are current contenders for a multibillion-dollar NASA flagship mission that would fly as early as the 2030s. Either observatory could use a coronagraph, or "starshade"—objects that selectively block starlight but allow planetary light through—to search for signs of habitability and of life in distant atmospheres. But either would need massive and sustained support from outside astrobiology to succeed in the decadal process and beyond.

There have been previous efforts to back large, astrobiologically focused missions such as NASA's Terrestrial Planet Finder concepts—ambitious space telescope proposals in the mid-2000s that would have spotted Earth-size exoplanets and characterized their atmospheres (if these projects had ever made it off the drawing board). Instead, they suffered ignominious cancellations that taught astrobiologists several hard lessons. There was still too little information at the time about the number of planets around other stars, says Caleb Scharf, an astrobiologist at Columbia University, meaning advocates could not properly estimate such a mission's odds of success. His community had yet to realize that in order to do large projects it needed to band together and show how its goals aligned with those of astronomers less professionally interested in finding alien life, he adds. "If we want big toys," he says. "We need to play better with others."

There has also been tension in the past between the astrobiological goals of solar system exploration and the more geophysics-steeped goals that traditionally underpin such efforts, says Jonathan Lunine, a planetary scientist at Cornell University. Missions to other planets or moons have limited capacity for instruments, and those specialized for different tasks often end up in ferocious competitions for a slot onboard. Historically, because the search for life was so open-ended and difficult to define, associated instrumentation lost out to hardware with clearer, more constrained geophysical research priorities. Now, Lunine says, a growing understanding of all the ways biological and geologic evolution are interlinked is helping to show that such objectives do not have to be at odds. "I hope that astrobiology will be embedded as a part of the overall scientific exploration of the solar system," he says. "Not as an add-on, but as one of the essential disciplines."

Above and beyond the recent NAS reports, NASA is arguably already demonstrating more interest in looking for life in our cosmic backyard than it has for decades. This year the agency released a request for experiments that could be carried to another world in our solar system to directly hunt for evidence of living organisms—the first such solicitation since the 1976 Viking missions that looked for life on Mars. "The Ladder of Life Detection," a paper written by NASA scientists and published in *Astrobiology* in June, outlined ways to clearly determine if a sample contains extraterrestrial creatures—a goal mentioned in the NAS report. The document also suggests NASA partner with other agencies and organizations working on astrobiological projects, as the space agency did last month when it hosted a workshop with the nonprofit SETI Institute on the search for "techno-signatures," potential indicators of intelligent aliens. "I think astrobiology has gone from being something that seemed fringy or distracting to something that seems to be embraced at NASA as a major touchstone for why we're doing space exploration and why the public cares," says Ariel Anbar, a geochemist at Arizona State University in Tempe.

All this means is astrobiology's growing influence is helping bring what once were considered outlandish ideas into reality. Anbar recalls attending a conference in the early 1990s, when then NASA administrator Dan Goldin displayed an Apollo-era image of Earth from space and suggested the agency try to do the same thing for a planet around another star.

"That was pretty out there 25 years ago," he says. "Now it's not out there at all."

—Adam Mann

India's "Vyomanauts" Seek to Join the Elite Club of Spacefaring Nations by 2022

Based on more than a decade of preparations, the nation's ambitious time line for human spaceflight seems feasible to many senior space scientists

During a speech on August 15, 2018, Indian Prime Minister Narendra Modi announced the nation's plan to send humans into space by 2022.

GETTY IMAGES

INDIA'S PRIME MINISTER Narendra Modi has announced a plan to send humans to space by 2022, when the nation will celebrate the 75th anniversary of its independence. If successful, India will join Russia, the U.S. and China in the elite club of countries to achieve homegrown human spaceflight. India's only citizen to travel to space as yet has been Rakesh Sharma, a pilot in the country's air force who orbited Earth in 1984 as part of the Soviet Union's space program.

The planned Gaganyaan (Sanskrit for "sky craft") mission aims to send a three-person crew to low Earth orbit for up to a week. In keeping with the localized naming traditions set by U.S. astronauts, Russia's cosmonauts and China's taikonauts, Gaganyaan crew members will be called "vyomanauts"—a moniker derived from *vyoma*, the Sanskrit word for "space."

Kailasavadivoo Sivan, chairman of the Indian Space Research Organization, or ISRO, is confident about the 2022 deadline. "Most critical technologies required for the Gaganyaan program have been developed by ISRO engineers," he says. "ISRO has also successfully demonstrated the prototype of the crew module, a capsule to take humans to space, as well as a launch-abort system, which is needed to eject the crew in case of a failure." Next, Sivan says, come the more intricate aspects of the program: ensuring the rocket and crew module meet stringent safety requirements, developing life-support systems and heat shields for atmospheric reentry, and constructing communications and crew-training facilities. The program's entire cost, Sivan says, will be less than the equivalent of $1.4 billion.

From humble beginnings in the 1960s and 1970s—when India began developing its first rockets and satellites—the nation's space program has blossomed. Besides partnering with other spacefaring countries on a variety of missions, India has also launched scores of satellites and even two farther-flung craft: Chandrayaan 1, its lunar orbiter, operated at the moon from 2008 to 2009; its Mars orbiter, Mangalyaan, reached the Red Planet in 2013. Specific plans for a crew to fly date back to at least 2006, according to G. Madhavan Nair, a space scientist who served as ISRO's chairman from 2003 to 2009. That was the year the agency completed a study advocating such a project as the next logical step for India's burgeoning space program, and began lobbying the government for formal approval and further funding.

But this series of successes has been accompanied by setbacks typical of any country striving to advance in spaceflight, such as occasional launch failures and faulty satellites. The launch of India's next high-profile space science effort, Chandrayaan 2—which aims to orbit the moon and place a lander at the lunar south pole—has been delayed twice in the past year and is now slated for January 2019.

Even so, A. S. Kiran Kumar, former ISRO chairman and one of the masterminds behind Chandrayaan 1 and Mangalyaan, is ebullient about the 2022 deadline for India's human mission. ISRO, he notes, has for many years been diligently advancing the core technologies for human spaceflight. The nation has selected its newest, heaviest and most powerful rocket, the GSLV Mk III, to carry its crews to orbit, and Kumar says multiple test flights in the next few years should further refine the rocket's capabilities. Nair shares Kumar's optimism about the GSLV Mk III as well as meeting the 2022 deadline, but he worries "India hasn't yet started the process of selecting and training astronauts for the mission"—a task that is time-consuming. To accelerate the crew selection process, Nair says, ISRO may seek collaborations with the U.S. or Russian space agencies.

Also, not every Indian aerospace expert is so sanguine about the nation's rocketry being ready in time. Ajey Lele, a senior fellow in the Institute for Defense Studies and Analyses in New Delhi, says "the major problem is going to be the availability of the rocket for the mission. ISRO needs to make the GSLV Mk III operational—fast."

A more fundamental (and political) concern facing India's pursuit of a domestic human spaceflight program may be balancing such aspirations against its goals of continuing its economic development and lifting more of its citizens out of poverty. Kumar, however, sees India's space program not as a frivolous distraction from this goal but rather as an affordable necessity that will create new jobs and lead to technological spin-offs, which enhance and stimulate development. "It is necessary to meet the growing needs of the economy," he says. "Space has become the fourth frontier after land, air and water."

ISRO's total budget since its establishment, he notes, is less than what NASA now spends in a single year; this is in keeping with India's major space successes being achieved at remarkably low costs compared with its global counterparts. At $78 million, its Mars mission cost less than the production and marketing of a typical Hollywood movie. And if ISRO's budgetary projections hold, its first human spaceflight will consume roughly one seventh of what NASA is spending on a single space observatory, the $9.6-billion James Webb Space Telescope.

–Shekhar Chandra

Reimagining of Schrödinger's Cat Breaks Quantum Mechanics–and Stumps Physicists

In a multi-"cat" experiment the textbook interpretation of quantum theory seems to lead to contradictory pictures of reality, physicists claim

IN THE WORLD'S most famous thought experiment, physicist Erwin Schrödinger described how a cat in a box could be in an uncertain predicament. The peculiar rules of quantum theory meant that it could be both dead and alive, until the box was opened and the cat's state measured. Now, two physicists have devised a modern version of the paradox by replacing the cat with a physicist doing experiments—with shocking implications.

Quantum theory has a long history of thought experiments, and in most cases these are used to point to weaknesses in various interpretations of quantum mechanics. But the latest version, which involves multiple players, is unusual: it shows that if the standard interpretation of quantum mechanics is correct, then different experimenters can reach opposite conclusions about what the physicist in the box has measured. This means that quantum theory contradicts itself.

The conceptual experiment has been debated with gusto in physics circles for more than two years—and has left most researchers stumped, even in a field accustomed to weird concepts. "I think this is a whole new level of weirdness," says Matthew Leifer, a theoretical physicist at Chapman University in Orange, Calif.

The authors, Daniela Frauchiger and Renato Renner of the Swiss Federal Institute of Technology (ETH) in Zurich, posted their first version of the argument online in April 2016. The final paper appeared in *Nature Communications* in September. (Frauchiger has now left academia.)

WEIRD WORLD

Quantum mechanics underlies nearly all of modern physics, explaining everything from the structure of atoms to why magnets stick to each other. But its conceptual foundations continue to leave researchers grasping for answers. Its equations cannot predict the exact outcome of a measurement—for example, of the position of an electron—only the probabilities that it can yield particular values.

Quantum objects such as electrons therefore live in a cloud of uncertainty, mathematically encoded in a wave function that changes shape smoothly, much like ordinary waves in the sea. But when a property such as an electron's position is measured, it always yields one precise value (and yields the same value again if measured immediately after).

The most common way of understanding this was formulated in the 1920s by quantum-theory pioneers Niels Bohr and Werner Heisenberg, and is called the Copenhagen interpretation, after the city where Bohr lived. It says that the act of observing a quantum system makes the wavefunction collapse from a spread-out curve to a single data point.

The Copenhagen interpretation left open the question of why different rules should apply to the quantum world of the atom and the classical world of laboratory measurements (and of everyday experience). But it was also reassuring: although quantum objects live in uncertain states, experimental observation happens in the classical realm and gives unambiguous results.

Now, Frauchiger and Renner are shaking physicists out of this comforting position. Their theoretical reasoning says that the basic Copenhagen picture—as well as other interpretations that share some of its basic assumptions—is not internally consistent.

WHAT'S IN THE BOX?

Their scenario is considerably more involved than Schrödinger's cat—proposed in 1935—in which the feline lived in a box with a mechanism that would release a poison on the basis of a random occurrence, such as the decay of an atomic nucleus. In that case, the state of the cat was uncertain until the experimenter opened the box and checked it.

In 1967, the Hungarian physicist Eugene Wigner proposed a version of the paradox in which he replaced the cat and the poison with a physicist friend who lived inside a box with a measuring device that could return one of two results, such as a coin showing heads or tails. Does the wavefunction collapse when Wigner's friend becomes aware of the result? One school of thought says that it does, suggesting that consciousness is outside the quantum realm. But if quantum mechanics applies to the physicist, then she should be in an uncertain state that combines both outcomes until Wigner opens the box.

Frauchiger and Renner have a yet more sophisticated version (see "New Cats in Town" graphic). They have two Wigners, each doing an experiment on a physicist friend whom they keep in a box. One of the two friends (call her Alice) can toss a coin and—using her knowledge of quantum physics—prepare a quantum message to send to the other friend (call him Bob). Using his knowledge of quantum theory, Bob can detect Alice's message and guess the result of her coin toss. When the two Wigners open their boxes, in some situations they can conclude with certainty which side the coin landed on, Renner says—but occasionally their conclusions are inconsistent. "One says, 'I'm sure it's tails,' and the other one says, 'I'm sure it's heads,'" Renner says.

The experiment cannot be put into practice, because it would require the Wigners to measure all quantum properties of their friends, which includes reading their minds, points out theorist Lídia Del Rio, a colleague of Renner's at ETH Zurich.

Yet it might be feasible to make two quantum computers play the parts of Alice and Bob: the logic of the argument requires only that they know the rules of physics and make decisions based on them, and in principle one can detect the complete quantum state of a quantum computer. (Quantum computers sophisticated enough to do this do not yet exist, Renner points out.)

DUELING INTERPRETATIONS

Physicists are still coming to terms with the implications of the result. It has triggered heated responses from experts in the foundations of quantum theory, many of whom tend to be protective of their pet interpretation. "Some get emotional," Renner says. And different researchers tend to draw different conclusions. "Most people claim that the experiment shows that their interpretation is the only one that is correct."

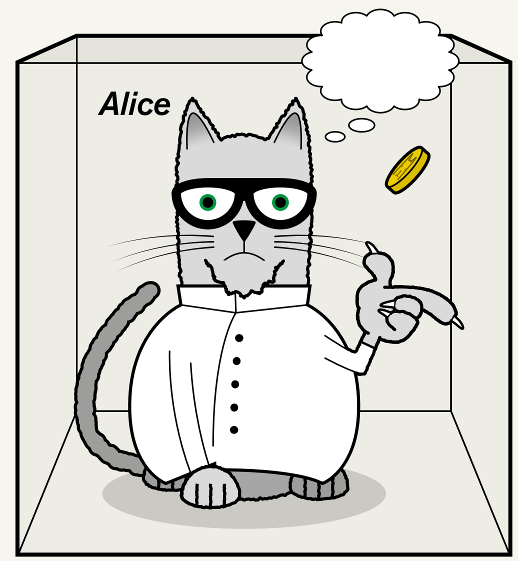
For Leifer, producing inconsistent results should not necessarily be a deal breaker. Some interpretations of quantum mechanics already allow for views of reality that depend on perspective. That could be less unsavory than having to admit that quantum theory does not apply to complex things such as people, he says.

Robert Spekkens, a theoretical physicist at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, says that the way out of the paradox could hide in some subtle assumptions in the argument, in particular in the communication between Alice and Bob.

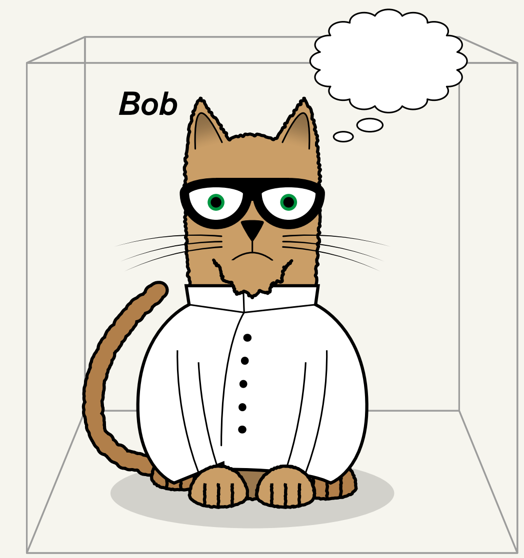
"To my mind, there's a lot of situations where taking somebody's

NEW CATS IN TOWN

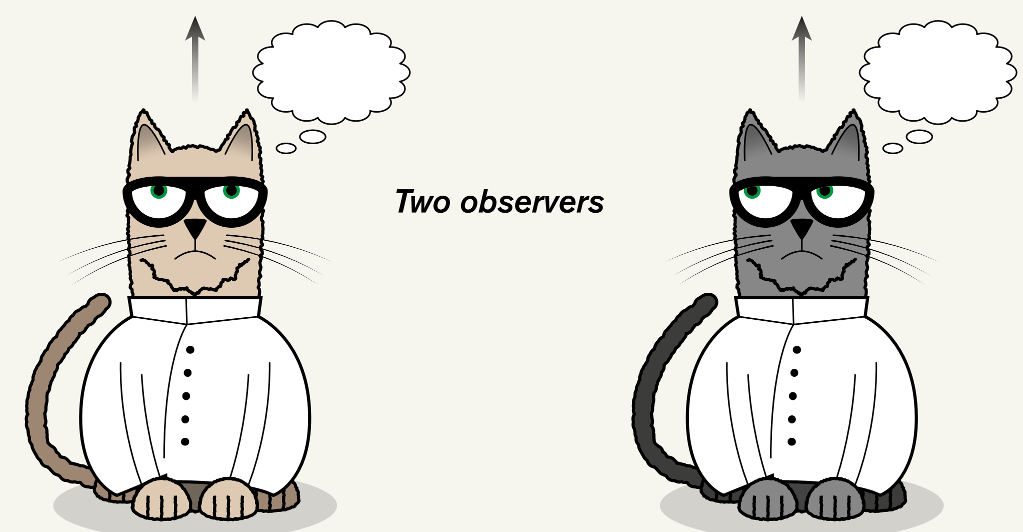
Physicists have devised a variation of the iconic Schrödinger's cat thought experiment that involves several players who understand quantum theory. But surprisingly, using the standard interpretation of quantum mechanics, the observers sometimes seem to come to different conclusions about a particular event — suggesting that the interpretation contradicts itself for complex systems.



Alice tosses a coin and, using her knowledge of quantum physics, sends a quantum message to Bob.



Using his knowledge of quantum theory, Bob can detect Alice's message and guess the result of her coin toss.



When the two observers open their boxes, in some situations they can conclude with certainty how the coin landed — but their conclusions are different. This means that the standard interpretation of quantum theory gives an inconsistent description of reality.

CREDIT: *NATURE*, SEPTEMBER 18, 2018; DOI: 10.1038/D41586-018-06749-8

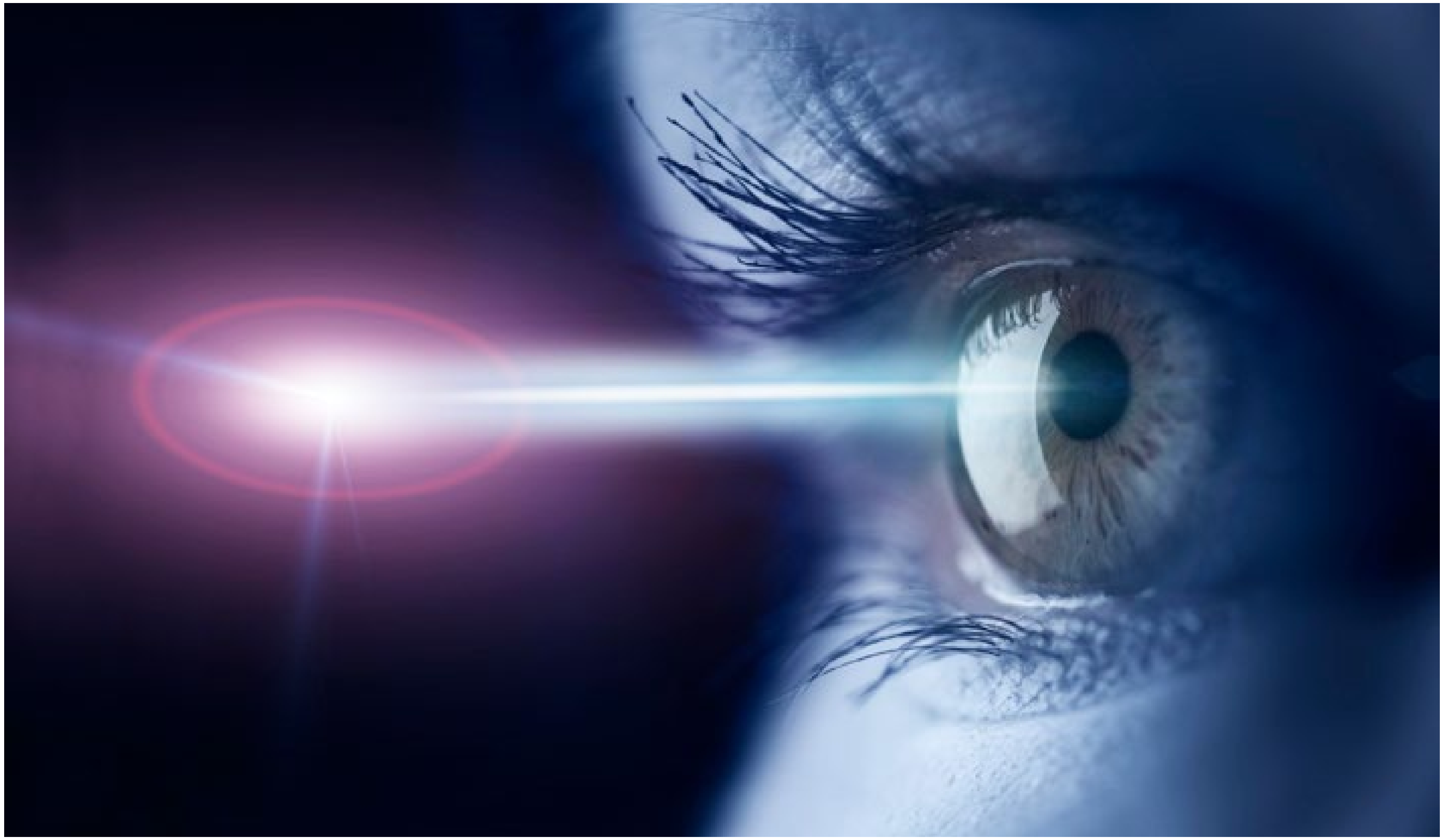
knowledge on board involves some translation of their knowledge." Perhaps the inconsistency arises from Bob not interpreting Alice's message properly, he says. But he admits that he has not found a solution yet.

For now, physicists are likely to continue debating. "I don't think we've made sense of this," Leifer says.

—Davide Castelvecchi

"Optical Tweezers" and Tools Used for Laser Eye Surgery Snag Physics Nobel

The award's recipients include the first female physics laureate in 55 years



GETTY IMAGES

OPTICAL PHYSICISTS ARTHUR Ashkin, Gérard Mourou and Donna Strickland have won this year's Nobel Prize in Physics for "groundbreaking inventions in the field of laser physics."

Half of this year's nine-million-kronor (about $1-million) prize goes to American physicist Arthur Ashkin for his invention of "optical tweezers," lasers that can probe the machinery of life without causing damage. The other half will be split jointly between French physicist Gérard Mourou and Canadian physicist Donna Strickland for their development of "chirped pulse amplification" (CPA)—a method for making ultra-short, high-intensity laser pulses now routinely used in corrective eye surgery and precision machining. Strickland is the first female physics laureate in 55 years, and only the third in the prize's long, venerable history. The new laureates will receive their prizes in December at a ceremony in Stockholm.

At 96, Ashkin is the oldest person to win a Nobel. His development of optical tweezers traces back to the 1960s, and culminated in 1986 during his tenure at Bell Laboratories in New Jersey. The technique uses the gentle pressure of light itself to trap and push a microscopic, transparent sphere into the center of a laser beam. The laser-controlled sphere can make and measure exceedingly minute forces when tethered to a biological sample, allowing researchers to delicately manipulate microbes, viruses and even a cell's individual components. In a video played during a press conference at the Royal Swedish Academy of Sciences in Stockholm, Anders Irbäck, a physicist at Sweden's Lund University and member of the Nobel Committee for Physics, provided a simple demonstration of the principle behind Ashkin's tweezers, using exhaust from a hair dryer to hold and manipulate a ping-pong ball in midair without touching it.

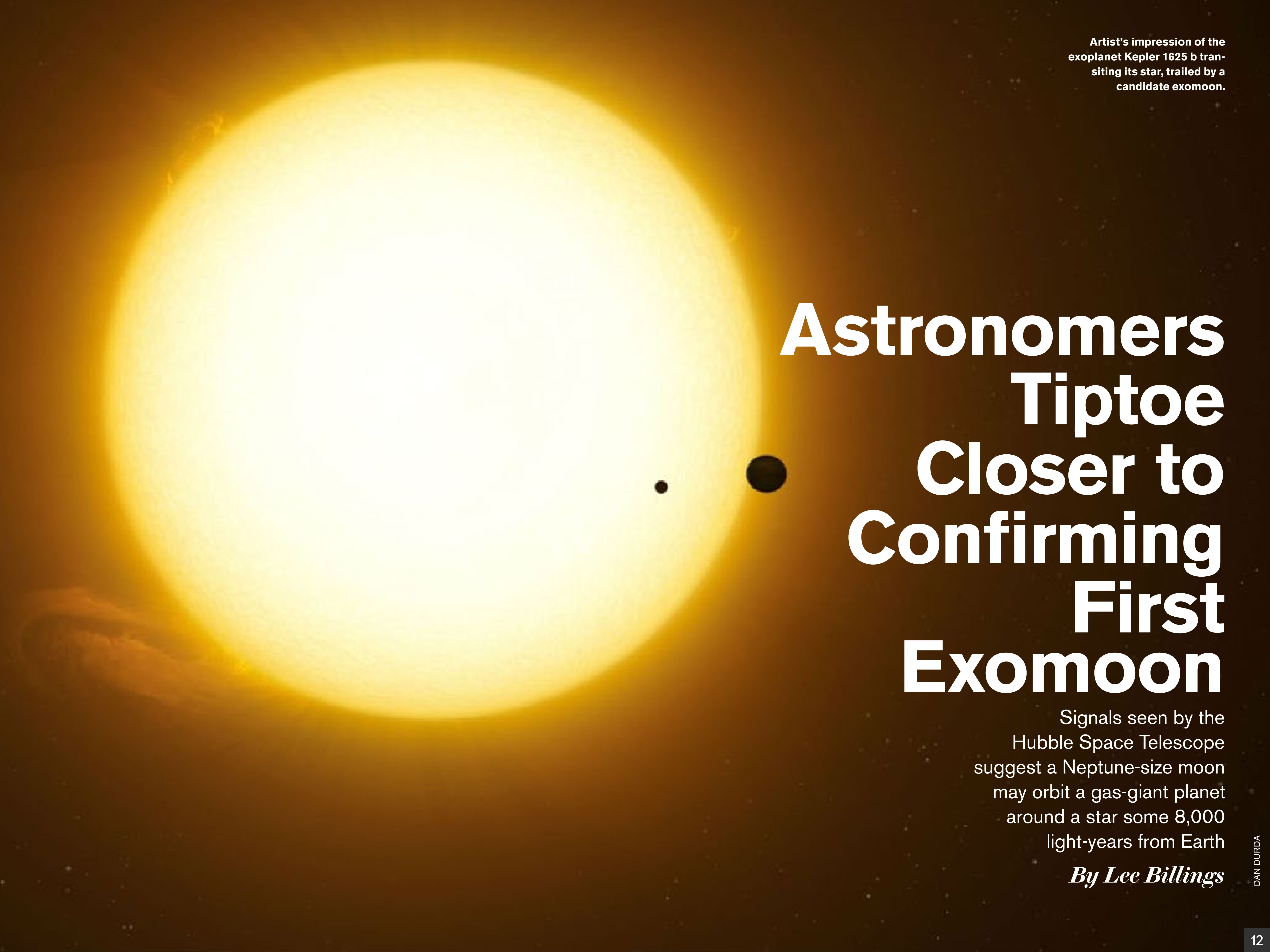
Mourou, 74, now a professor at the École Polytechnique in France, was Strickland's academic advisor at the University of Rochester in New York State in the 1980s, where together they created CPA. Strickland, 59, is now an associate professor at the University of Waterloo in Ontario. Before their breakthrough, optical physicists had hit a wall in developing lasers of ever-increasing intensity. "The technology wasn't scalable," said Mats Larsson, a physicist at Sweden's Stockholm University and member of the Nobel physics committee, speaking during the press conference. "It wasn't possible to go to higher intensity because of amplifier damage."

With CPA, Mourou and Strickland shattered this wall, sparking a trend that allowed lasers to, on average, double in intensity twice per decade. The technique relies on first stretching out short, energetic laser pulses in time, reducing their peak power and allowing them to be safely fed through an amplifier, after which they are finally compressed back to their original size—dramatically boosting their intensity. The resulting ultrabrief, ultrasharp beams can be used to make extremely precise cuts and holes in a variety of materials, and have been used in surgery to correct nearsightedness in millions of people.

"This year's prize is about tools made from light," said Göran Hansson, secretary general of the Royal Swedish Academy, summarizing awards during his remarks at the press conference. It was, to some degree, also about recognizing the achievements of women in the physical sciences.

Taking reporters' questions via phone from her home in Waterloo, Strickland reacted with surprise when told only two women had preceded her in winning the prize: "Is that all, really?" she asked. "I thought there might have been more…. We need to celebrate women physicists because we're out there, and hopefully in time it'll start to move forward at a faster rate. I'm honored to be one of those women."

—Lee Billings



Artist's impression of the exoplanet Kepler 1625 b transiting its star, trailed by a candidate exomoon.

DAN DURDA

Astronomers Tiptoe Closer to Confirming First Exomoon

Signals seen by the Hubble Space Telescope suggest a Neptune-size moon may orbit a gas-giant planet around a star some 8,000 light-years from Earth

By Lee Billings

Lee Billings is an associate editor for *Scientific American*. He covers space and physics.

HAVE ASTRONOMERS JUST FOUND THE FIRST-EVER exomoon, a lunar companion of a planet orbiting another star? Definitely maybe.

Using data from NASA's Kepler and Hubble space telescopes, Columbia University astronomers Alex Teachey and David Kipping report the potential signal of a Neptune-size moon around a planet three times heavier than Jupiter, all orbiting a nearly 10-billion-year-old sun-like star called Kepler 1625 b about 8,000 light-years from Earth. Such a large moon defies easy explanation based on prevailing theories. The findings appear in a study published October 3 in Science Advances, and follow from the duo's earlier work reported last year that first offered more tentative evidence of the moon.

If confirmed, this discovery would challenge scientists' current understanding of planet and moon formation while bearing potentially profound implications for the prevalence of life throughout the cosmos, revealing once again that when it comes to alien worlds, the universe is often stranger than anyone can suppose.

AN EXTRAORDINARY EXOMOON

IF OUR SOLAR SYSTEM IS any guide at all, moons should vastly outnumber planets in the universe, and could make up most of the habitable real estate in any given galaxy. Pinning down how—and how often—they form would thus give astrobiologists a leg up on finding life elsewhere in our galaxy. Already, Kipping and Teachey's statistics derived from Kepler data suggest moons are conspicuously absent around planets in temperate orbits around their stars—hinting that most large lunar companions must lurk farther out in colder climes, and that habitable moons akin to *Star Wars*' Endor or *Avatar*'s Pandora may be exceedingly rare.

Moons, it is thought, can form in three ways: coalescing from rings of gas and dust leftover from a planet's formation; from debris knocked into orbit around a planet from a giant impact; or by being gravitationally captured by a planet via rare close encounters with pairs of co-orbiting asteroids or comets. But this newly proposed exomoon fails to fit neatly in any of those origin stories. It appears to be too big to easily coalesce alongside its planet, which itself is too massive and gassy to readily eject debris from any conceivable impact. Capture via close encounter, although possible, would require an implausibly perfect concatenation of unlikely circumstances. "If valid, this would probably open up a new formation scenario for moons," says René Heller, a theorist at the Max Planck Institute for Solar System Research in Germany who was not part of the study. "Actually, the very existence of the proposed moon would call for a need to rethink our concepts of what a 'moon' actually is in the first place."

For perspective, consider that our solar system's largest moon, Jupiter's Ganymede, is less than half as massive as our sun's smallest planet, Mercury. Kepler 1625 b's moon, by contrast, would be about 10 times as massive as all the terrestrial planets and the hundreds of moons in our solar system combined. This suggests, Heller says, "that this moon would have formed in a completely different way than any moon in our solar system."

Even the study's authors agree their potentially historic claim should give pause—no one has ever conclusively discovered an exomoon before, let alone one so utterly bizarre. "This moon would have fairly surprising properties, which is a good reason for skepticism," says Kipping, an assistant professor at Columbia who has spent the last decade pioneering the hunt for exomoons. "If this was the 10th known object of its type, we would be calling it a 'discovery,' no question. But because it's the first of its kind, it demands a higher level of scrutiny.... I can't yet convince myself 100 percent this is definitely real."

"We are urging caution here—the first exomoon is obviously an extraordinary claim, and it requires extraordinary evidence," says Teachey, the study's lead author and a Ph.D. candidate under Kipping's wing at Columbia. "We are not cracking open champagne bottles just yet on this one."

Scarcely anything else is known about this potential satellite, save that its estimated size and three-million-kilometer separation from its planetary host would make it appear in that world's skies twice as large as Earth's own moon. Based on the planet-moon pair's 287-day orbit around its star, Teachey and Kipping have crudely calculated average temperatures there might approach that of boiling water—uncomfortably warm, to be sure, but easy enough for Earth's hardiest microbes to thrive in. Biology's bigger challenge would be the lack of surfaces on both the planet and its moon—expect no aliens there.

CAUGHT IN TRANSIT

CLAIMS OF EXOMOONS HAVE come and gone over the years, but a couple stand out as particularly plausible. In 2013 scientists reported the potential detection of what could have been either a Mars- to Neptune-mass exomoon circling a Jupiter-mass exoplanet floating freely through space—or a Jupiter-like gas giant orbiting a small, faint star. Whatever its nature, the system was only detected in the first place due to a phenomenon called gravitational microlensing that occurs just once and entirely by chance in any given instance, and thus could not be observed again. Then, in 2015, a separate analysis of a gargantuan ring system found around the "super-Saturn" exoplanet J1407 b revealed multiple gaps potentially cleared by what might be several Mars- to Earth-mass exomoons otherwise hidden in the rings. Yet beyond these circumstantial findings no credible candidates existed.

The first hints of a breakthrough discovery emerged last year, as part of a five-year hunt Kipping and Teachey conducted for exomoons around nearly 300 planets from Kepler's massive data set, which contains thousands of known worlds. Almost all of Kepler's planets transit, meaning they cross the faces of their suns as seen from Earth, casting a shadow toward us that astronomers measure as a star's brief dimming. If some of those planets harbor conspicuously large moons in wide orbits, the moons might detectably transit, too, imprinting their own much smaller diminution in a star's light either shortly before or after a planet's passage. Kipping and Teachey spied what looked to be just such a signal in three transits of Kepler 1625 b. This was enough to net them 40 hours of time using Hubble's Wide Field Camera 3 (WFC3) instrument for a follow-up observation of a single additional transit of the planet and its potential moon, predicted to take place on October 28 and 29, 2017. In addition to looking for a moon's transit, their Hubble program would also attempt to pin down the precise timing of Kepler 1625 b's transit, which could be altered by the gravitational tugging of a moon or a nearby nontransiting planet.

Reaching four times greater precision than Kepler's data, Hubble's observations revealed that, indeed, this transit of Kepler 1625 b was shifted in time, arriving about 75 minutes ahead of schedule—just as would be expected if the planet's motions were being perturbed by a massive accompanying moon. Additionally, 3.5 hours after the planet's transit concluded, Hubble picked up a second, far smaller dip as the star's brightness appeared to fade by just five hundredths of 1 percent. Stars dim more than that all the time due to starspots and convective patterns on their surfaces, but basic observational tests suggest such stellar activity was not the culprit here, Kipping says. Instead, he says, the minuscule signal was consistent with a Neptune-size moon "trailing the planet like a dog following its owner on a leash."

> **"A moon is the simplest, most elegant and self-consistent hypothesis—that's why we favor it."**
> ***—David Kipping***

Alas, Kipping and Teachey's allotted Hubble time expired before they could capture the conclusion of the smaller transit's conclusion, rendering their data set incomplete and leaving wide open the possibility that the apparent shadow of the moon had been something else entirely.

A TIME TO KILL

"I don't see any reason why it wouldn't be an exomoon," says Peter McCullough, an astronomer and expert on Hubble's instrumentation at Johns Hopkins University who was not involved in the research. "Alternatively, I don't see any reason why it would be. Either statement is justifiable."

Against the exomoon hypothesis, McCullough and other researchers familiar with the results note Hubble's WFC3 instrument is notorious for routinely exhibiting minor, hard-to-pin-down variations in its performance that could mimic the subtle signal of a moon. Furthermore, they point to the latest data release from the Kepler mission, in which new, state-of-the-art analytical methods caused the already borderline signs of the exomoon to fade to insignificance in the Kepler data. "I think this shows how fluid the interpretation can be, with so few observed transits [of Kepler 1625 b]," McCullough says. "The researchers are fully aware of that—they are the world's experts in this field. It's just the nature of the problem—it's hard."

Teachey and Kipping maintain that after spending almost a year being their own harshest critics and trying as best they can to explain away the evidence, their most extraordinary claim remains the most compelling. "As far as we can tell, there is no way to kill this signal—there really is a second dip in the star's light," Kipping says. And yes, the time shift in Kepler 1625 b's transit could alternatively be due to the influence of a very massive unseen planet—but no such planet has been found despite Kepler's and Hubble's combined scrutiny. "A moon is the simplest, most elegant and self-consistent hypothesis—that's why we favor it." Kipping says. "The time has come to let the community interrogate our findings."

There is only one way to truly settle the issue: more data. NASA's upcoming James Webb Space Telescope should be more than capable of definitively ruling for or against this hoped-for first exomoon, but it is not slated to launch until 2021 at the earliest. In the meantime Kipping and Teachey are awaiting approval of another Hubble observing proposal, which would use twice as much telescope time to catch complete transits of Kepler 1625 b and of its putative moon during the celestial pair's next predicted crossing in May 2019.

This time, they predict the moon will be on the opposite side of its orbit, with a transit preceding that of the planet itself. "We should see a separate, clean moonlike event," Kipping says. "If we see that, then I think we're done.... I think we'd have a very closed case on this system." Except, of course, on how it formed in the first place.

An illustration of the space debris surrounding Earth, with each piece greatly enlarged for emphasis.

MACIEJ FROLOW GETTY IMAGES

The Quest to Conquer Earth's Space Junk Problem

Zombie satellites, rocket shards and collision debris are creating major traffic risks in orbits around the planet. Researchers are working to reduce the threats posed by more than 20,000 objects in space

By Alexandra Witze

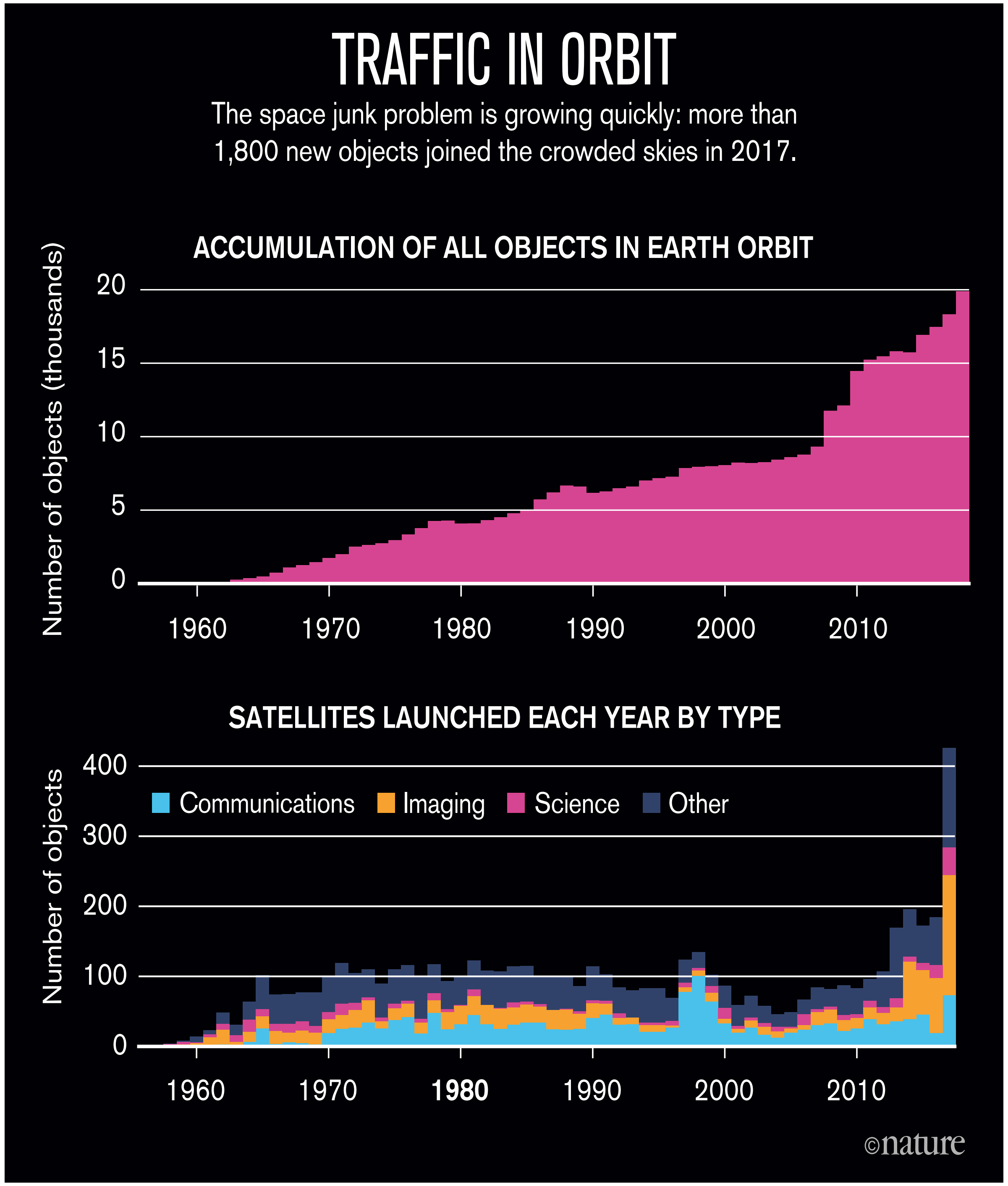
Alexandra Witze works for *Nature* magazine.

ON MONDAY JULY 2, THE CRYOSAT-2 spacecraft was orbiting as usual, just over 700 kilometers above Earth's surface. But that day, mission controllers at the European Space Agency (ESA) realized they had a problem: a piece of space debris was hurtling uncontrollably toward the €140-million (U.S. $162-million) satellite, which monitors ice on the planet.

As engineers tracked the paths of both objects, the chances of a collision slowly increased—forcing mission controllers to take action. On 9 July, ESA fired the thrusters on CryoSat-2 to boost it into a higher orbit. Just 50 minutes later, the debris rocketed past at 4.1 kilometers a second.

This kind of maneuver is becoming much more common each year, as space around Earth grows increasingly congested. In 2017, commercial companies, military and civil departments and amateurs lofted more than 400 satellites into orbit, over four times the yearly average for 2000–2010. Numbers could rise even more sharply if companies such as Boeing, OneWeb and SpaceX follow through on plans to deploy hundreds to thousands of communications satellites into space in the next few years. If all these proposed mega-constellations go up, they will roughly equal the number of satellites that humanity has launched in the history of spaceflight.

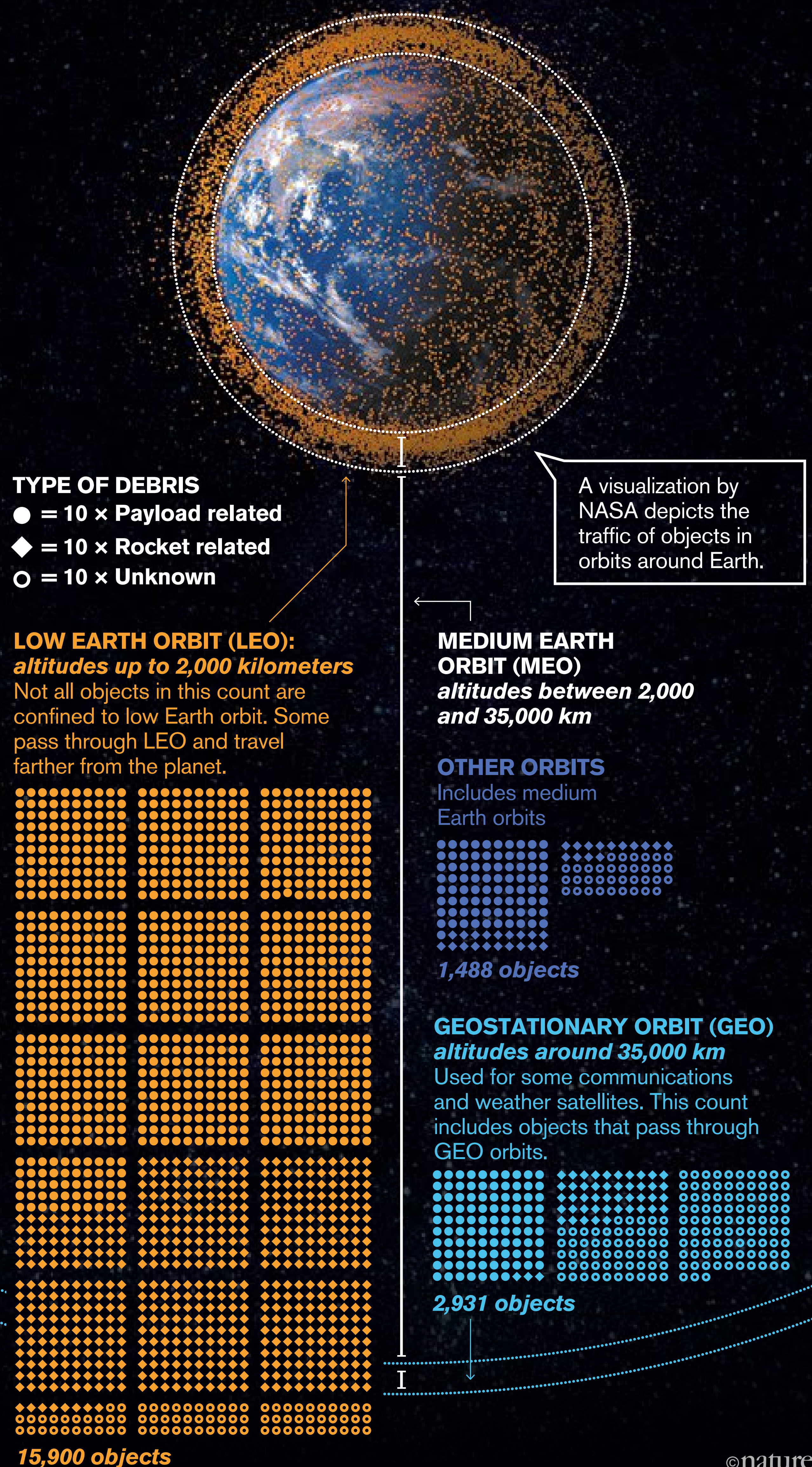
All that traffic can lead to disaster. In 2009, a U.S. commercial Iridium satellite smashed



NATURE, SEPTEMBER 5 2018, DOI: 10.1038/D41586-018-06170-1; SOURCE: ESA ANNUAL SPACE ENVIRONMENT REPORT

BUSY SKIES

There are currently more than 20,000 objects in orbit around Earth, according to catalogues that track operational satellites, dead ones and other human-made debris, such as pieces from rockets.

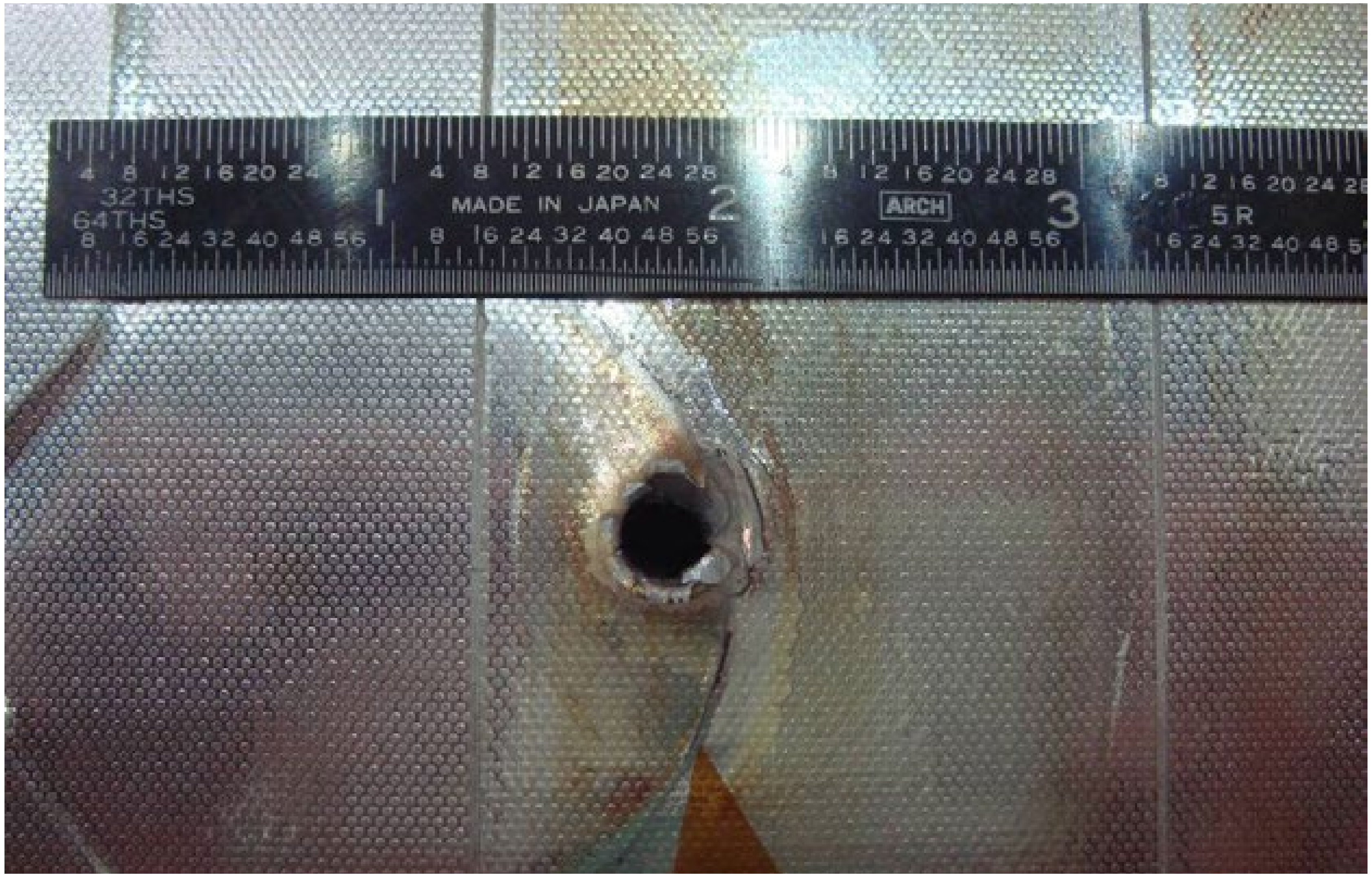


NATURE, SEPTEMBER 5 2018, DOI: 10.1038/D41586-018-06170-1; SOURCE: ESA ANNUAL SPACE ENVIRONMENT REPORT. EARTH DEBRIS IMAGE: NASA GODDARD SPACE FLIGHT CENTER AND JSC

into an inactive Russian communications satellite called Cosmos-2251, creating thousands of new pieces of space shrapnel that now threaten other satellites in low Earth orbit—the zone stretching up to 2,000 kilometers in altitude. Altogether, there are roughly 20,000 human-made objects in orbit, from working satellites to small shards of solar panels and rocket pieces. And satellite operators can't steer away from all potential collisions, because each move consumes time and fuel that could otherwise be used for the spacecraft's main job.

Concern about space junk goes back to the beginning of the satellite era, but the number of objects in orbit is rising so rapidly that researchers are investigating new ways of attacking the problem. Several teams are trying to improve methods for assessing what is in orbit, so that satellite operators can work more efficiently in ever-more-crowded space. Some researchers are now starting to compile a massive data set that includes the best possible information on where everything is in orbit. Others are developing taxonomies of space junk—working out how to measure properties such as the shape and size of an object, so that satellite operators know how much to worry about what's coming their way. And several investigators are identifying special orbits that satellites could be moved into after they finish their missions so they burn up in the atmosphere quickly, helping to clean up space.

The alternative, many say, is unthinkable. Just a few uncontrolled space crashes could generate enough debris to set off a runaway cascade of fragments, rendering near-Earth space unusable. "If we go on like this, we will reach a point of no return," says Carolin Frueh, an astrodynamical researcher at Purdue University in West Lafayette, Ind.



Damage to the Space Shuttle Endeavour from a collision with piece of space debris or a micrometeorite.

NASA

DIRTYING ORBITS

Astronomers and others have worried about space junk since the 1960s, when they argued against a U.S. military project that would send millions of small copper needles into orbit. The needles were meant to enable radio communications if high-altitude nuclear testing were to wipe out the ionosphere, the atmospheric layer that reflects radio waves over long distances. The Air Force sent the needles into orbit in 1963, where they successfully formed a reflective belt. Most of the needles fell naturally out of orbit over the next three years, but concern over dirtying space nevertheless helped to end the project.

It was one of the first examples of the public viewing space as a landscape that should be kept clean, says Lisa Rand, a historian of science in Philadelphia and a fellow with the American Historical Association and NASA.

Since the Soviet Union launched the first satellite, Sputnik, in 1957, the number of objects in space has surged, reaching roughly 2,000 in 1970, about 7,500 in 2000 and about 20,000 known items today. The two biggest spikes in orbital debris came in 2007, when the Chinese government blew up one of its satellites in a missile test, and in the 2009 Iridium-Cosmos collision. Both events generated thousands of fresh fragments, and they account for about half of the 20-plus satellite maneuvers that ESA conducts each year, says Holger Krag, head of ESA's space-debris office in Darmstadt, Germany.

Each day, the U.S. military issues an average of 21 warnings of potential space collisions. Those numbers are likely to rise dramatically next year, when the Air Force switches on a powerful new radar facility on Kwajalein in the Pacific Ocean. That facility will allow the U.S. military to detect objects smaller than today's 10-centimeters limit for low Earth orbit, and this could increase the number of tracked objects by a factor of five.

Even as our ability to monitor space objects increases, so too does the total number of items in orbit. That means companies, governments and other players in space are having to collaborate in new ways to avoid a shared threat. Since the 2000s, international groups such as the Inter-Agency Space Debris Coordination Committee have developed guidelines for achieving space sustainability. Those include inactivating satellites at the end of their useful lifetimes by venting leftover fuel or other pressurized materials that could lead to explosions. The intergovernmental groups also recommend lowering satellites deep enough into the atmosphere that they will burn up or disintegrate within 25 years.

But so far, only about half of all missions have abided by this 25-year guideline, says Krag. Operators of the planned megaconstellations say they will be responsible stewards of space, but Krag worries that the problem could increase, despite their best intentions. "What happens to those that fail or go bankrupt?" he asks. "They are probably not going to spend money to remove their satellites from space."

Tiny CubeSats are released from the International Space Station in 2012.

NASA

TRAFFIC COPS FOR SPACE

In theory, satellite operators should have plenty of room for all these missions to fly safely without ever nearing another object. So some scientists are tackling the problem of space junk by trying to understand where all the debris is to a high degree of precision. That would alleviate the need for many unnecessary maneuvers that today are used to avoid potential collisions. "If you knew exactly where everything was, you would almost never have a problem," says Marlon Sorge, a space-debris specialist at the Aerospace Corporation in El Segundo, Calif.

The field is called space-traffic management, because it's analogous to managing traffic on the roads or in the air. Think about a busy day at an airport, says Moriba Jah, an astrodynamicist at the University of Texas at Austin: planes line up in the sky like a string of pearls, landing and taking off close to one another in a carefully choreographed routine. Air-traffic controllers know the location of the planes down to one meter in accuracy.

The same can't be said for space debris. Not all objects in orbit are known, and even those included in databases are tracked to varying levels of precision. On top of that, there is no authoritative catalogue that accurately lists the orbits of all known space debris.

Jah illustrates this with a Web-based database that he developed, called ASTRIAGraph. It draws on several sources, such as catalogues maintained by the U.S. and Russian governments, to visualize the locations of objects in space. When he types in an identifier for a particular space object, ASTRIAGraph draws a purple line to designate its orbit.

Only this doesn't quite work for a number of objects, such as a Russian rocket body launched in 2007 and designated in the database as object number 32280. When Jah enters that number, ASTRIAGraph draws two purple lines: the U.S. and Russian sources contain two completely different orbits for the same object. Jah says that it is almost impossible to tell which is correct, unless a third source of information could help to cross-correlate the correct location.

ASTRIAGraph currently contains some, but not all, of the major sources of information about tracking space objects. The U.S. military catalogue—the largest such database publicly available—almost certainly omits information on classified satellites. The Russian government similarly holds many of its data close. Several commercial space-tracking databases have sprung up in the past few years, and most of those do not share openly.

Jah describes himself as a space environmentalist: "I want to make space a place that is safe to operate, that is free and useful for future generations." Until that happens, he argues, the space community will continue devolving into a tragedy of the commons, in which all spaceflight operators are polluting a common resource.

He and other space environmentalists are starting to make headway, at least when it comes to U.S. space policy. Jah testified on space-traffic management in front of Congress last year, at the invitation of Ted Cruz, a Republican senator from Texas who co-introduced a space-regulations bill this July. In June, President Donald Trump also signed a directive on space policy that, among other things, would shift responsibility for the U.S. public space-debris catalogue from the military to a civilian agency—probably the Department of Commerce, which regulates business.

The space-policy directive is a rare opportunity to dis-

A piece of space debris that is thought to be from a space shuttle mission in 1998.

NASA

cuss space junk at the highest levels of the U.S. government. "This is the first time we're really having this conversation in a serious fashion," says Mike Gold, vice president for regulatory, policy and government contracts at Maxar Technologies in Westminster, Colo., which owns and operates a number of satellites.

THE ORBITING DEAD

The space around Earth is filled with zombies: some 95 percent of all objects in orbit are dead satellites or pieces of inactive ones. When someone operating an active satellite gets an alert about an object on a collision course, it would be helpful to know how dangerous that incoming debris is. "With more and more objects, and the uncertainties we currently have, you just get collision warnings no end," says Frueh. (Micrometeorites represent a separate threat and can't be tracked at all.)

To assess the risk of an impending collision, satellite operators need to know what the object is, but tracking catalogues have little information about many items. In those cases, the military and other space trackers use telescopes to gather clues in the short period before a potential collision.

Working with the Air Force, Frueh and her colleagues are developing methods to rapidly decipher details of orbiting objects even when very little is known about them. By studying how an object reflects sunlight as it passes overhead, for instance, she can deduce whether it is tumbling or stable—a clue to whether or not it is operational. Her team is also experimenting with a machine-learning algorithm that could speed up the process of characterizing items.

Once researchers know what an orbiting object is made of, they have a number of potential ways to reduce its threat. Some sci-fi–tinged proposals involve using magnets to sweep up space junk, or lasers to obliterate or deflect debris in orbit. In the coming weeks, researchers at the University of Surrey in Guildford, U.K., will experiment with a net to ensnare a test satellite. The project, called RemoveDEBRIS, will then redirect the satellite into an orbit that will re-enter the atmosphere.

But such active approaches to cleaning up space junk aren't likely to be practical over the long term, given the huge number of objects in orbit. So some other experts consider the best way of mitigating space junk to be a passive approach. This takes advantage of the gravitational pulls of the sun and the moon, known as resonances, that can put the satellites on a path to destruction. At the University of Arizona in Tucson, astrodynamicist Aaron Rosengren is developing ways to do so.

Rosengren first came across the idea when studying the fates of satellites in medium Earth orbit (MEO). These travel at altitudes anywhere between about 2,000 kilometers up, where low Earth orbit ends, and 35,000 kilometers up, where geostationary orbits begin.

Satellites in low Earth orbit can be disposed of by forcing them to re-enter the atmosphere, and most satellites in the less heavily trafficked geostationary region can be safely placed in "graveyard" orbits that never interact with other objects. But in MEO, satellite trajectories can be unstable over the long term because of gravitational resonances.

An early hint that spacecraft operators could harness this phenomenon came from ESA's INTEGRAL γ-ray space telescope, which launched in 2002. INTEGRAL travels in a stretched-out orbit that spans all the way from low Earth orbit, through MEO, and into geostationary orbit. It would normally have remained in space for more than a century, but in 2015, ESA decided to tweak its orbit. With a few small thruster burns, mission controllers placed it on a path to interact with gravitational resonances. It will now re-enter the atmosphere in 2029, rather than decades later.

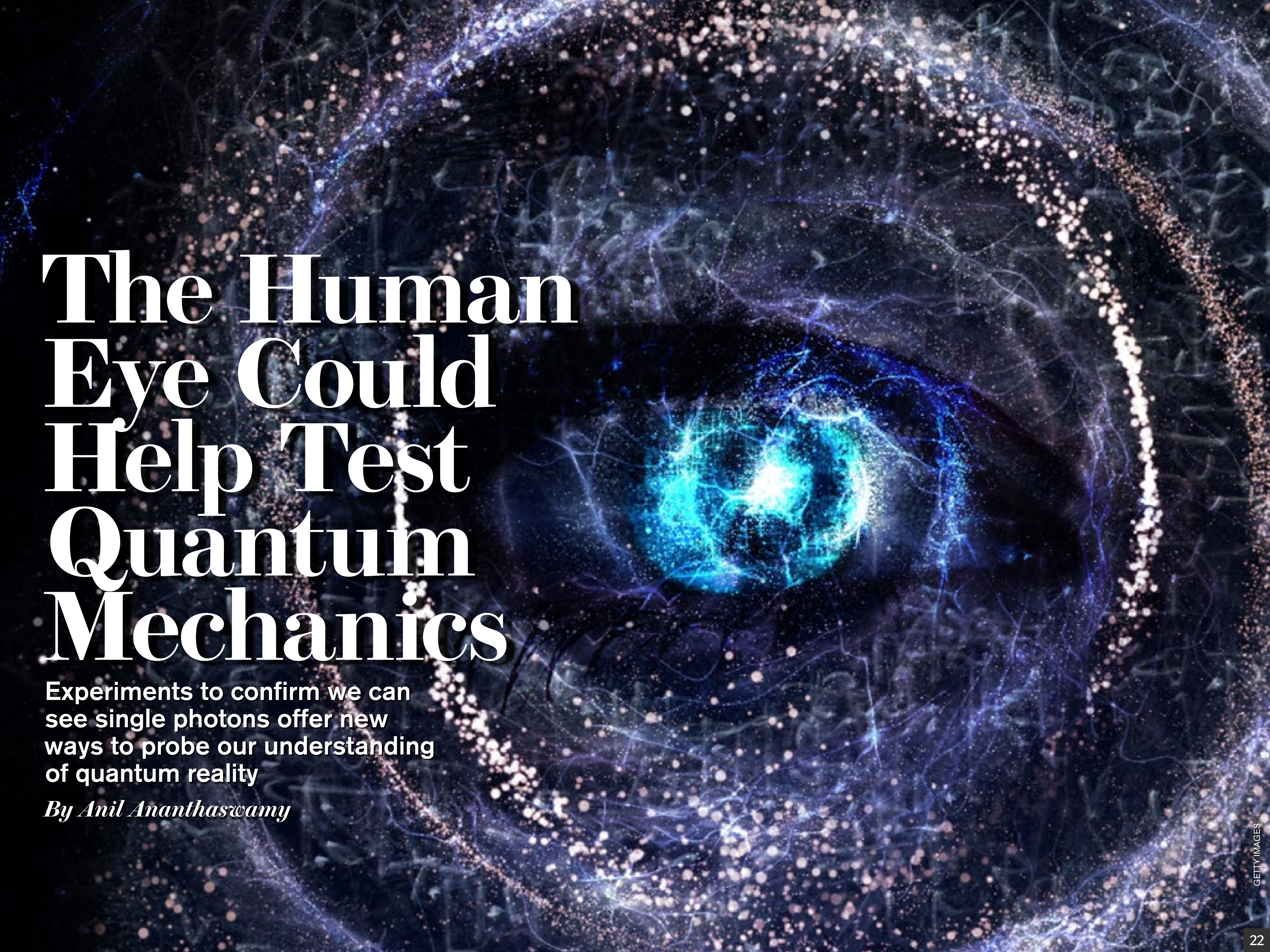
In 2016, Rosengren and his colleagues in France and Italy showed that there is a dense web of orbital resonances that dictates how objects behave in MEO (J. Daquin *et al. Celest. Mech. Dyn. Astr.* 124, 335–366; 2016). Rosengren thinks this might offer a potential solution. There are paths in this web of resonances that lead not to MEO, but directly into the atmosphere, and operators could take advantage of them to send satellites straight to their doom. "We call it passive disposal through resonances and instabilities," says Rosengren. "Yeah, we need a new name."

Other researchers have explored the concept before, but Rosengren is trying to push it into the mainstream. "It's one of the newer things in space debris," he says.

These disposal highways in the sky could be easy to access. At a space conference in July in Pasadena, Calif., Rosengren and his colleagues reported on their analysis of U.S. Orbiting Geophysical Observatory satellites from the 1960s. The scientists found that changing the launch date or time by as little as 15 minutes could lead to huge differences in how long a satellite remains in orbit. Such information could be used to help calculate the best times to depart the launch pad.

Being proactive now could head off a lot of trouble down the road, as operators of satellites such as CryoSat-2 have found. When ESA decided to take evasive action in early July, its engineers had to scramble and work through the weekend to get ready for the maneuver. Once the space junk had safely flown by, CryoSat-2 took a few days to get back into its normal orbit, says Vitali Braun, a space-debris engineer with ESA.

But the alerts didn't stop coming. In the weeks that followed, mission controllers had to shift various satellites at least six times to dodge debris. And in August, they nudged the Sentinel-3B satellite out of the way of space junk for the first time. It had been in orbit for only four months.



The Human Eye Could Help Test Quantum Mechanics

Experiments to confirm we can see single photons offer new ways to probe our understanding of quantum reality

By Anil Ananthaswamy

GETTY IMAGES

Anil Ananthaswamy is the author of *The Edge of Physics, The Man Who Wasn't There* and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality.*

PAUL KWIAT ASKS HIS VOLUNTEERS TO SIT INSIDE A SMALL, dark room. As their eyes adjust to the lack of light, each volunteer props his or her head on a chin rest—as you would at an optometrist's—and gazes with one eye at a dim red cross. On either side of the cross is an optical fiber, positioned to pipe a single photon of light at either the left or the right side of a volunteer's eye. Even as he verifies the human eye's ability to detect single photons, Kwiat, an experimental quantum physicist at the University of Illinois at Urbana-Champaign, and his colleagues are setting their sights higher: to use human vision to probe the very foundations of quantum mechanics, according to a paper they submitted to the preprint server arXiv on June 21.

Rather than simply sending single photons toward a volunteer's eye through either the left or the right fiber, the idea is to send photons in a quantum superposition of effectively traversing both fibers at once. Will humans see any difference? According to standard quantum mechanics, they will not—but such a test has never been done. If Kwiat's team produces conclusive results showing otherwise, it would question our current understanding of the quantum world, opening the door to alternative theories that argue for a dramatically different view of nature in which reality exists regardless of observations or observers, cutting against the grain of how quantum mechanics is interpreted today. "It could possibly be evidence that something's going on beyond standard quantum mechanics," says Rebecca Holmes, Kwiat's former student who designed equipment, and who is now a researcher at Los Alamos National Laboratory.

The effort to determine whether humans can directly detect single photons has a storied history. In 1941 researchers from Columbia University reported in *Science* the human eye can see a flash from as few as five photons landing on the retina. More than three decades later Barbara Sakitt, a biophysicist then at the University of California, Berkeley, performed experiments suggesting that the eye could see a single photon. But these experiments were far from conclusive. "The problem with all these experiments is that they were just trying to use 'classical' light sources" that do not reliably emit single photons, Holmes says. That is, there was no guarantee each of these early trials involved just one photon.

Then, in 2012, came firm evidence that individual photoreceptors, or rod cells, can detect single photons—at least in the eyes of a frog. Leonid Krivitsky of the Agency for Science, Technology and Research in Singapore and his colleagues extracted rod cells from adult frogs' eyes and performed laboratory tests showing the cells reacted to single photons. Now, "there's absolutely no doubt that individual photoreceptors respond to single photons," Kwiat says. That is not the same as saying those rod cells do the same in a living frog—or, for that matter, a human being. So Kwiat, along with Illinois colleague physicist Anthony Leggett and others, began envisioning tests of human vision using single-photon sources. Soon Kwiat's group, which now included Holmes, was actually experimenting. But "we got beat on that," Holmes says.

In 2016 a team led by biophysicist Alipasha Vaziri, then at the University of Vienna, reported using single-photon sources to show "humans can detect a single-photon incident on their eye with a probability significantly above chance."

Kwiat's team, somewhat skeptical of the result, wants to improve the statistics by doing a much larger number of trials with many more subjects. Their key concern is the low efficiency of the eye as a photon detector. Any incident photon has to get past the cornea, the clear outer layer of the eye, which reflects some of the light. The photon then enters a lens that, together with the cornea, focuses the light on the retina at the back of the eye. But between the lens and the retina is a clear, gel-like substance that gives the eye its shape—and this too can absorb or scatter the photon. Effectively, less than 10 percent of the photons that hit the cornea make it to the rod cells in the retina, which result in nerve signals that travel into the brain, causing perception. So getting statistically significant results that rise above chance is a daunting challenge. "We are hoping in the next six months to have a definitive answer," Kwiat says.

That has not stopped them from dreaming up new experiments. In the standard setup a half-silvered mirror steers a photon to either the left or the right fiber. The photon then lands on one side or the other of a volunteer's retina, and the subject has to indicate which by using a keyboard. But it is trivial (using quantum optics) to put the photon in a superposition of going through both fibers, and onto both sides of the eye, at once. What occurs next depends on what one believes happens to the photon.

Physicists describe a photon's quantum state using a mathematical abstraction called the wave function. Before the superposed photon hits the eye its wave function is spread out, and the photon has an equal probability of being seen on the left or the right. The photon's interaction with the visual system acts as a measurement that is thought to "collapse" the wave function, and the photon randomly ends up on one side or the other, like a tossed coin coming up "tails" or "heads." Would humans see a difference in the photon counts on the left versus the right when perceiving superposed photons as compared with photons in classical states? "If you trust quantum mechanics, then there should be no difference," Kwiat says. But if their experiment finds an irrefutable, statistically significant difference, it would signal something amiss with quantum physics. "That would be big. That would be a quite earth-shattering result," he adds.

"Is there any perceptual difference on the part of the person when they directly observe a quantum event?"
—Paul Kwiat

Such a result would point toward a possible resolution of the central concern of quantum mechanics: the so-called measurement problem. There's nothing in the theory that specifies how measurements can collapse the wave function, if indeed wave functions do collapse. How big should the measuring apparatus be? In the case of the eye, would an individual rod cell do? Or does one need the entire retina? What about the cornea? Might a conscious observer need to be in the mix?

Some alternative theories solve this potential problem by invoking collapse independently of observers and measurement devices. Consider, for instance, the "GRW" collapse model (named after theorists Giancarlo Ghirardi, Alberto Rimini and Tullio Weber). The GRW model and its many variants posit wave functions collapse spontaneously; the more massive the object in superposition, the faster its collapse. One consequence of this would be that individual particles could remain in superposition for interminably long times, whereas macroscopic objects could not. So, the infamous Schrödinger's cat, in GRW, can never be in a superposition of being dead and alive. Rather it is always either dead or alive, and we only discover its state when we look. Such theories are said to be "observer-independent" models of reality.

If a collapse theory such as GRW is the correct description of nature, it would upend almost a century of thought that has tried to argue observation and measurement are central to the making of reality. Crucially, when the superposed photon lands on an eye, GRW would predict ever-so-slightly different photon counts for the left and the right sides of the eye than does standard quantum mechanics. This is because differently sized systems in the various stages of the photon's processing—such as two light-sensitive proteins in two rod cells versus two assemblies of rod cells and associated nerves in the retina—would exhibit different spontaneous collapse rates after interacting with a photon. Although both Kwiat and Holmes stress it is highly unlikely they will see a difference in their experiments, they acknowledge that any observed deviation would hint at GRW-like theories.

Michael Hall, a theoretical quantum physicist at the Australian National University who was not part of the study, agrees GRW would predict a very small deviation in the photon counts but says such deviations would be too tiny to be detected by the proposed experiment. Nevertheless, he thinks any aberration in the photon counts would deserve attention. “It would be quite serious. I find that unlikely but possible,” he says. “That would be amazingly interesting.”

Kwiat also wonders about the subjective perception of quantum states versus classical states. “Is there any perceptual difference on the part of the person when they directly observe a quantum event?” he asks. “The answer is ‘probably not,’ but we really don’t know. You can’t know the answer to that unless either you have a complete physical model down to the quantum mechanical level of what’s going on in the human visual system—which we don’t have—or you do the experiment.”

Robert Prevedel, a member of Vaziri’s 2016 team who is now at the European Molecular Biology Laboratory in Germany, is more interested in teasing out exactly where collapse actually occurs in the chain of events. Does it happen at the beginning, when a photon strikes a rod cell? Or in the middle, with generation and transmission of neural signals? Or does it happen at the end, when the signals register in conscious perception? He suggests firing superposed photons at extracted retinas and recording from different levels of visual processing (say, from rod cells or from the different types of photo cells that make up the retina) to see how long the superposition lasts.

“Consciousness… arises in our brain as the combined effect of millions, if not billions, of cells and neurons.”

—Robert Prevedel

Prevedel thinks first absorption by a rod should destroy the photon’s superposition. But “if we can see quantum [superposition] in any of the subsequent levels inside the different cell layers in the retina, or any downstream neuronal circuits even, that would be really a breakthrough,” he says. “This would be an amazing finding.”

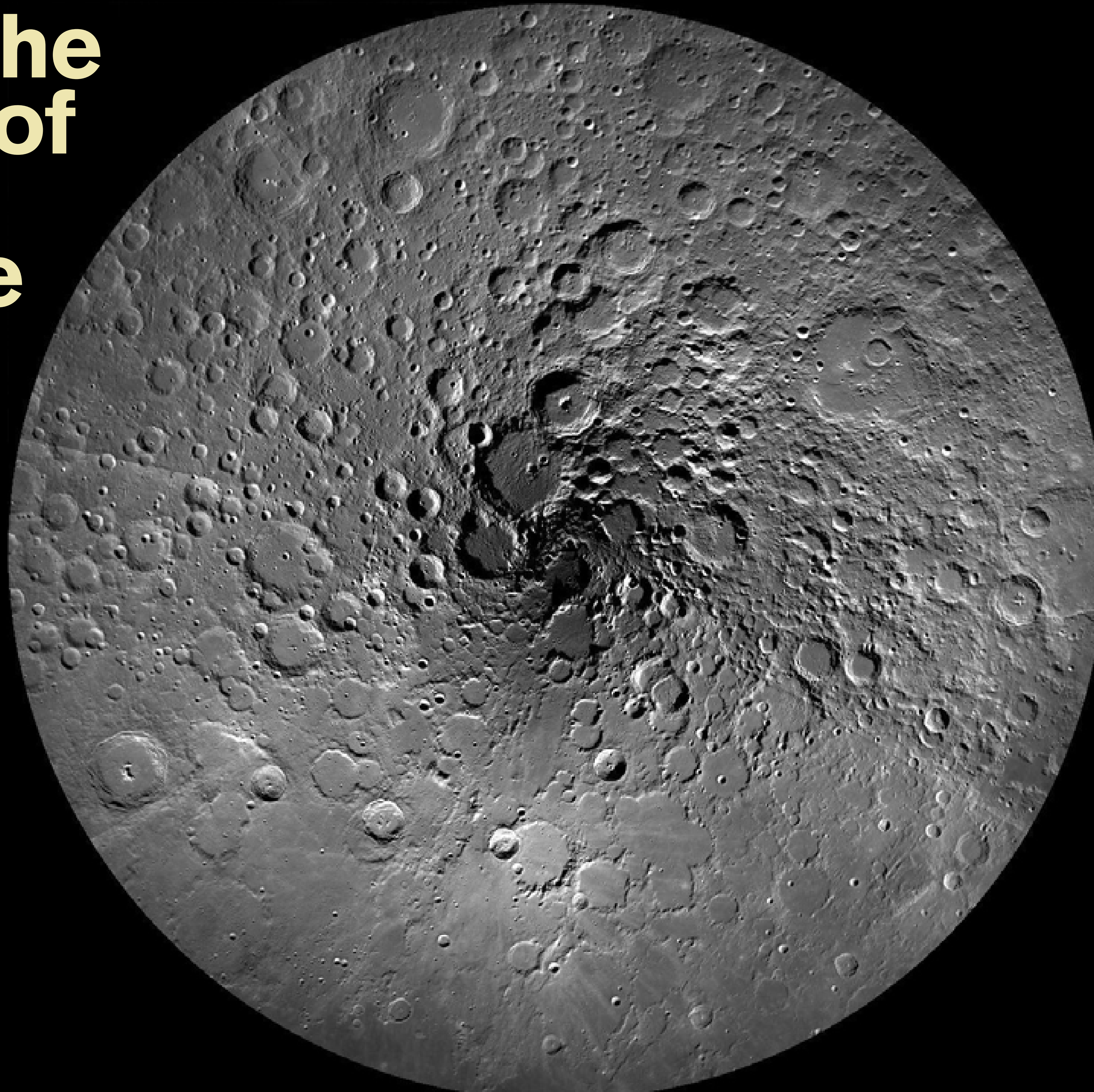
There is, of course, an elephant in the room: human consciousness. Could conscious perception ultimately cause the collapse of the quantum state, making the photon show up on one or the other side? Prevedel doubts consciousness has anything whatsoever to do with measurement and collapse.

“Consciousness … arises in our brain as the combined effect of millions, if not billions, of cells and neurons. If there is a role of consciousness in the detection of quantum superposition, it’d involve a really macroscopic object on the level of the entire brain, i.e. a huge ensemble of atoms and electrons that make up the biological cells,” Prevedel says. “From all that we know, this kind of macroscopic object would not be able to sustain quantum [superposition].”

Beyond the Shadow of a Doubt, Water Ice Exists on the Moon

Deposited in perpetually dark craters around the poles, the ice could be a boon for future crewed lunar outposts

By Leonard David



NASA, GSFC AND ARIZONA STATE UNIVERSITY

Mosaic of 983 images of the moon's north polar region. Taken over the course of a month by the Lunar Reconnaissance Orbiter Camera.

Leonard David is author of *Mars: Our Future on the Red Planet*, published by *National Geographic*. The book is a companion to the National Geographic Channel series, "Mars." A longtime writer for *SPACE.com*, David has been reporting on the space industry for more than five decades.

THE VIEW THAT EARTH'S MOON IS A DRIED-OUT, DESOLATE WORLD MAY BE ALL WET.

A new analysis of data from the Indian Space Research Organization's Chandrayaan 1 orbiter, which operated at the moon from 2008 to 2009, has revealed what researchers say is definitive proof of water ice exposed on the lunar surface. Gathered by NASA's Moon Mineralogy Mapper (M3) spectrometer onboard the Indian probe, the data all but confirm extensive but tentative evidence from earlier missions hinting at water ice deposits lurking in permanently shadowed craters at the moon's poles. Such deposits could someday support crewed lunar outposts while also revealing previously hidden chapters of the moon's history. The results appeared in a study published August 20 in *Proceedings of the National Academy of Sciences USA*.

Based on M3's measurements of water ice's near-infrared absorption features at and around the lunar poles, the study's authors concluded the ice is only exposed in around 3.5 percent of the craters' shadowed area, and is intermixed with large volumes of lunar dust. Such sparse coverage and heterogeneity suggests this lunar ice has a substantially different history than similar deposits found on other airless rocky worlds, such as Mercury and the dwarf planet Ceres, where water ice in permanently shadowed craters is more abundant and of greater purity.

A DISCOVERY DECADES IN THE MAKING

"Before our work there is no direct evidence to show there is surface-exposed water ice on the moon," says lead author Shuai Li, a planetary scientist at the University of Hawaii in Mānoa. For decades radar sweeps from Earth of the lunar polar regions and by moon-orbiting craft have delivered ambiguous results. Similarly, instruments carried onboard NASA's still-circling Lunar Reconnaissance Orbiter cannot directly, definitively detect the presence of water ice, he says. In fact, he notes, many past claims of "water" on the moon were really just detections of hydrogen-enriched, bone-dry minerals on the lunar surface.

Likewise, Shuai adds, although NASA's Lunar CRater Observation and Sensing Satellite (LCROSS) mission did uncover signs of lunar water in 2009, when it sent probes crashing into the permanently shadowed region of Cabeus Crater near the moon's south pole, that water was not necessarily from exposed ice at the surface. "LCROSS is a great mission.... However, the conclusion of surface-exposed ice from this mission is based on modeling; it is indirect. And also, there is only one data point in the south polar region," Shuai says. In contrast, he notes, the "very unique" spectral features of water in the M3 data incontrovertibly show the presence of exposed ice on the floors of craters across the moon's polar regions.

"The results seem very convincing to me," says Ian Crawford, a planetary scientist at Birkbeck, University of London, who was not a part of the study.

Now that these deposits have been found exposed on the lunar surface, Shuai and other researchers say, they could be more easily used to fuel future exploration and sustain human outposts. The ice could be melted and distilled to provide potable water, and could also be broken apart into its constituent hydrogen and oxygen to produce breathable air as well as rocket propellant.

A FROSTY VENEER—OR THE TIP OF AN ICEBERG?

Before any of that water is exploited for exploratory gain, however, most scientists would prefer to know just how much of it there is, and how it got there in the first place.

According to Anthony Colaprete, who served as principal LCROSS investigator at NASA's Ames Research Center, the ice's patchy distribution is key for determining its history. "Assuming [it] isn't a measurement effect, this says to me that these patches of water ice are not in equilibrium with a current, ongoing source of water," Colaprete says. A more uniform distribution—like that seen for ice in craters at Mercury's poles—could indicate the ice was being supplied by periodic impacts from water-rich comets or asteroids.

But if the moon's polar ice is not the product of regular, geologically recent impact events, where did it come from? "One possibility is it is from an ancient reservoir," Colaprete says, referring to the early stages of more than 4.5 billion years of lunar history, when outgassing from volcanoes and colossal impacts may have briefly imbued the moon with a warm, wet atmosphere. Any deposits of water ice leftover from that bygone era could later be excavated, mixed and diffused to and around the surface via subsequent impacts and solar irradiation.

In the paper Shuai and his co-authors note the ice's patchiness may be due to a hypothesized phenomenon called "true polar wander," in which the orientation of the moon's axis of spin shifts over long periods of time. In this scenario the distribution of exposed surface ice would hew close to how the moon's polar wandering altered its craters' exposure to sunlight across geologic time.

Because of such uncertainties about its origins as well as the limited nature of the M3 observations, Colaprete says it is currently impossible to say how much bulk water lurks in the moon's polar caters. "At [M3's] wavelengths we are only sampling the top 10 microns or so; thus the water could be a frost or veneer only 100 microns thick—or it could be the tip of the 'iceberg.'"

What is needed, says Crawford, is more high-resolution mapping from low-orbiting satellites, which could use neutron spectrometry to peer beneath the surface—or better yet, on-location robotic landers to obtain samples.

A COMMUNITY CONVINCED

"When Shuai Li first described what he wanted to investigate using M3 data, I thought he was crazy," says Carle Pieters, a planetary scientist at Brown University and principal investigator for the M3 instrument who was not a part of Shuai's study. Whereas the concept behind Shuai's work is sound, she says, many researchers had given up on searching for water ice within the M3 data, due to its relatively poor quality for most of the moon's shadowy poles. Shuai and his team tackled the problem by developing multiple independent statistical tests to demonstrate the data's indications of water ice were genuine and not coincidental flukes.

"Through the years, I've learned not to tell a bright, energetic young scientist that something really hard is impossible. Often it is, but sometimes—like now—I'm delighted to be surprised," Pieters says. "They have indeed convinced me of the existence of water ice in the polar shadows."

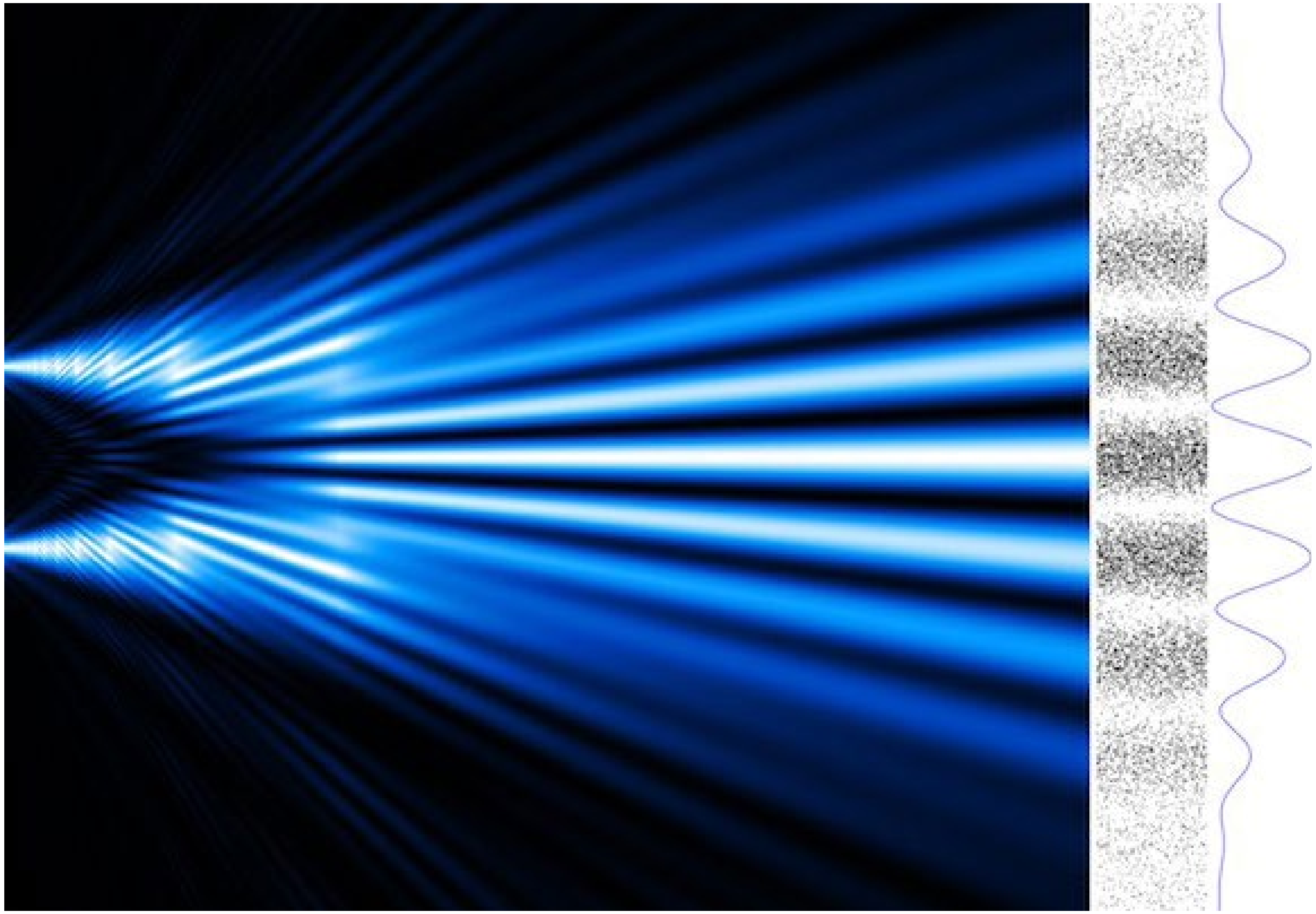
Additional reporting by Lee Billings.

Anil Ananthaswamy is the author of *The Edge of Physics, The Man Who Wasn't There* and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality.*

PHYSICS

What Does Quantum Theory Actually Tell Us about Reality?

Nearly a century after its founding, physicists and philosophers still don't know—but they're working on it



ALEXANDRE GONDRAN WIKIMEDIA (CC BY-SA 4.0)

For a demonstration that overturned the great Isaac Newton's ideas about the nature of light, it was staggeringly simple. It "may be repeated with great ease, wherever the sun shines," the English physicist Thomas Young told the members of the Royal Society in London in November 1803, describing what is now known as a double-slit experiment, and Young wasn't being overly melodramatic. He had come up with an elegant and decidedly homespun experiment to show light's wavelike nature, and in doing so refuted Newton's theory that light is made of corpuscles, or particles.

But the birth of quantum physics in the early 1900s made it clear that light is made of tiny, indivisible units, or quanta, of energy, which we call photons. Young's experiment, when done with single photons or even single particles of matter, such as electrons and neutrons, is a conundrum to behold, raising fundamental questions about the very nature of reality. Some have even used it to argue that the quantum world is influenced by human consciousness, giving our minds an agency and a place in the ontology of the universe. But does the simple experiment really make such a case?

In the modern quantum form, Young's experiment involves beaming individual particles of light or matter at two slits or openings cut into an otherwise opaque barrier. On the other side of the barrier is a screen that records the arrival of the particles (say, a photographic plate in the case of photons). Common sense leads us to expect that photons should go through one slit or the other and pile up behind each slit.

They don't. Rather, they go to certain parts of the screen and avoid others, creating alternating bands of light and dark. These so-called interference fringes, the kind you get when two sets of waves overlap. When the crests of one wave line up with the crests of another, you get constructive interference (bright bands), and when the crests align with troughs you get destructive interference (darkness).

But there's only one photon going through the apparatus at any one time. It's *as if* each photon is going through both slits at once and interfering with itself. This doesn't make classical sense.

Mathematically speaking, however, what goes through both slits is not a physical particle or a physical wave but something called a wave function—an abstract mathematical function that represents the photon's state (in this case its position). The wave function behaves like a wave. It hits the two slits, and new waves emanate from each slit on the other side, spread and eventually interfere with each other. The combined wave function can be used to work out the probabilities of where one might find the photon.

The photon has a high probability of being found where the two wave functions constructively interfere and is unlikely to be found in regions of destructive interference. The measurement—in this case the interaction of the wave function with the photographic plate—is said to "collapse" the wave function. It goes from being spread out before measurement to peaking at one of those places where the photon materializes upon measurement.

This apparent measurement-induced collapse of the wave function is the source of many conceptual difficulties in quantum mechanics. Before the collapse, there's no way to tell with certainty where the photon will land; it can appear at any one of the places of non-zero probability. There's no way to chart the photon's trajectory from the source to the detector. The photon is not real in the sense that a plane flying from San Francisco to New York is real.

Werner Heisenberg, among others, interpreted the mathematics to mean that reality doesn't exist until observed. "The idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them ... is impossible," he wrote. John Wheeler, too, used a variant of the double-slit experiment to argue that "no elementary quantum phenomenon is a phenomenon until it is a registered ('observed,' 'indelibly recorded') phenomenon."

But quantum theory is entirely unclear about what constitutes a "measurement." It simply postulates that the measuring device must be classical, without defining where such a boundary between the classical and quantum lies, thus leaving the door open for those who think that human consciousness needs to be invoked for collapse. Last May, Henry Stapp and colleagues argued, in this forum, that the double-slit experiment and its modern variants provide evidence that "a conscious observer may be indispensable" to make sense of the quantum realm and that a transpersonal mind underlies the material world.

But these experiments don't constitute empirical evidence for such claims. In the double-slit experiment done with single photons, all one can do is verify the probabilistic predictions of the mathematics. If the probabilities are borne out over the course of sending tens of thousands of identical photons through the double slit, the theory claims that each photon's wave function collapsed—thanks to an ill-defined process called measurement. That's all.

Also, there are other ways of interpreting the double-slit experiment. Take the de Broglie-Bohm theory, which says that reality is both wave and particle. A photon heads towards the double slit with a definite position at all times and goes through one slit or the other; so each photon has a trajectory. It's riding a pilot wave, which goes through both slits, interferes and then guides the photon to a location of constructive interference.

In 1979, Chris Dewdney and colleagues at Birkbeck, University of London, simulated the theory's prediction for the trajectories of particles going through the double slit. In the past decade, experimentalists have verified that such trajectories exist, albeit by using a controversial technique called weak measurements. The controversy notwithstanding, the experiments show that the de Broglie-Bohm theory remains in the running as an explanation for the behavior of the quantum world.

Crucially, the theory does not need observers or measurements or a non-material consciousness.

Neither do so-called collapse theories, which argue that wave functions collapse randomly: the more the number of particles in the quantum system, the more likely the collapse. Observers merely discover the outcome. Markus Arndt's team at the University of Vienna in Austria has been testing these theories by sending larger and larger molecules through the double slit. Collapse theories predict that when particles of matter become more massive than some threshold, they cannot remain in a quantum superposition of going through both slits at once, and this will destroy the interference pattern. Arndt's team has sent a molecule with more than 800 atoms through the double slit, and they still see interference. The search for the threshold continues.

Roger Penrose has his own version of a collapse theory, in which the more massive the mass of the object in superposition, the faster it'll collapse to one state or the other, because of gravitational instabilities. Again, it's an observer-independent theory. No consciousness needed. Dirk Bouwmeester at the University of California, Santa Barbara, is testing Penrose's idea with a version of the double-slit experiment.

Conceptually, the idea is to not just put a photon into a superposition of going through two slits at once, but to also put one of the slits in a superposition of being in two locations at once. According to Penrose, the displaced slit will either stay in superposition or collapse while the photon is in flight, leading to different types of interference patterns. The collapse will depend on the mass of the slits. Bouwmeester has been at work on this experiment for a decade and may soon be able to verify or refute Penrose's claims.

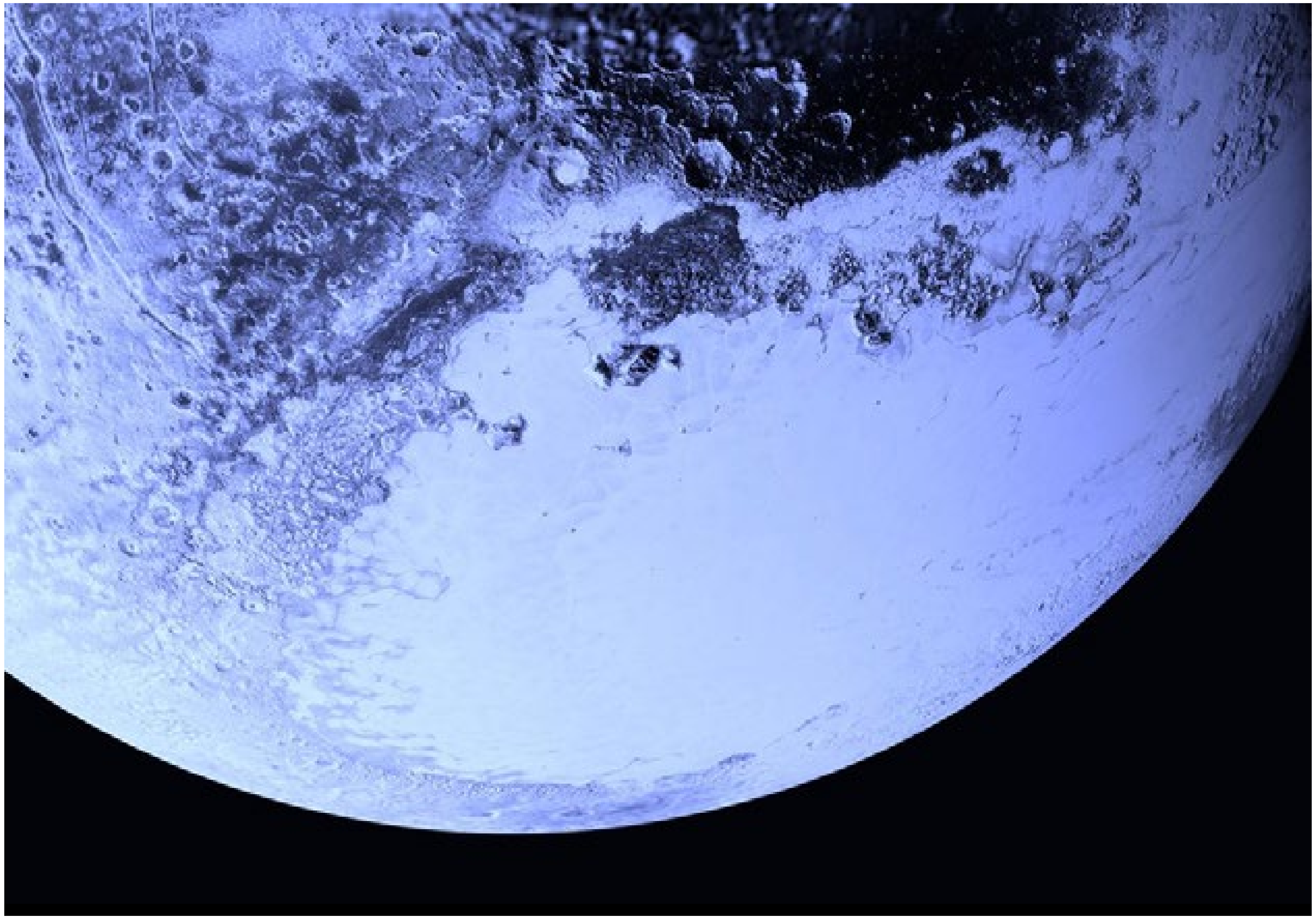
If nothing else, these experiments are showing that we cannot yet make any claims about the nature of reality, even if the claims are well-motivated mathematically or philosophically. And given that neuroscientists and philosophers of mind don't agree on the nature of consciousness, claims that it collapses wave functions are premature at best and misleading and wrong at worst.

Caleb A. Scharf is director of astrobiology at Columbia University. His work has been featured in *New Scientist, Scientific American, Science News, Cosmos Magazine, Physics Today* and *National Geographic*. His textbook for undergraduate and graduate students, *Extrasolar Planets and Astrobiology*, won the 2012 Chambliss Prize from the American Astronomical Society.

SPACE

Will Pluto Be the Last Habitable World?

The sun's future is going to change the status quo



NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND SOUTHWEST RESEARCH INSTITUTE

Astronomers often talk about our sun's future and how it will likely bring about the end of the Earth. Specifically: like all hydrogen-fusing stars, the sun gets gradually brighter with time as it converts more and more hydrogen in its core into helium (changing its own composition and therefore central temperature). But it will also eventually get to a point where the central hydrogen runs out, the core contracts, and the rest of the star responds. In what's termed the Red-Giant-Branch (RGB) stage, the outer envelope of the sun will begin to inflate—growing more than100 times in radius over less than100 million years if it doesn't lose too much material.

At this point it's bye-bye to Mercury and Venus (even if their orbits expand due to stellar mass loss, as I talk about below). But eventually the sun will shrink again. This happens when its core of helium starts fusing, once more altering the balance and flow of energy in the star. Later, just as the core hydrogen ran out, the helium in the core will also run out—resulting in a new inflation of the outer envelope. This time the Sun gets even bigger. As an Asymptotic-Giant-Branch (AGB) object, its radius might crank up to nearly 1,000 times the present solar dimensions. Now it's a distinct possibility that Earth and Mars get engulfed.

Except some other stuff is also happening throughout these phases. Energy is still being generated by fusion in shell regions around the core and the sun is in fact going to lose quite a lot of its mass—literally blowing material away in a strengthened solar wind. This may mute the physical diameter it reaches as an RGB and then AGB star, but not by a great deal. It could be enough to save Earth and Mars, though. Because as the sun loses mass, the orbits of the planets will actually expand in order to conserve angular momentum.

Another critical factor for our planetary system is that the larger the surface area of a star the larger its luminosity—the total power it can push out as electromagnetic radiation. By the time the sun gets into its RGB and AGB phases, its luminosity can grow to 1,000 or even several thousand times its present value.

We can work out what this might do to the nominal temperature of other bodies in the system. The bottom line is that their temperature should increase roughly like the fourth root of solar luminosity. That means that they'll get hotter by anywhere from a factor of 2 to perhaps a factor of 7 or 8 depending on the stellar output. The first round of this heating will come during the RGB stellar phase. It'll then get cold again until the AGB phase kicks in, after which it'll reach its second and utterly final peak.

For fun we can take a look at the implications for icy, chemically rich objects like Europa, Titan, and good old Pluto. The question to ask is—who's last? Which is the final potentially habitable body within the most familiar orbital terrain of our solar system?

Today the icy moon Europa has an equatorial surface temperature of around 110 Kelvin (-163 Celsius). That means that it could get as hot as over 770 Kelvin (497 Celsius) by the time the sun has reached the end of its AGB phase, and perhaps even during the earlier RGB phase. Naturally there will be intermediate periods where things might be more temperate, but as the stellar clock ticks Europa will get seriously hot.

Further away is Titan, a place with lots of frozen water and a hydrocarbon-rich surface environment—if there was ever a place that might get really interesting with a heat spell it would be Titan. If Titan's surface is about 94 Kelvin (-179 Celsius) today, it might certainly warm up to a temperate state. But like Europa, as the Sun gets to its maximum luminosity we'd expect Titan to hit as high as about 680 Kelvin (407 Celsius). That's not so comfy.

Pluto is a slightly different story. In the present-day solar system Pluto is coated in frozen everything: Solid water, solid carbon monoxide, solid nitrogen, solid methane, all at a chilly 43 Kelvin (-230 Celsius). But by the time the sun reaches peak luminosity (during its RGB and then AGB stages), Pluto may warm up to an acceptably habitable 300 Kelvin (27 Celsius). On the way to that peak it might spend millions of years between the freezing and boiling point of water (assuming a thick atmosphere).

Of course, as a frozen object gets heated it will lose a lot of sublimated material to the vacuum of space. Water, carbon monoxide and so on will just stream away. However, even a low gravitational surface acceleration like Pluto's (about 1/12th of Earth's) will cause some buildup of atmosphere. And atmosphere is good at encouraging more atmosphere, by making it harder for molecules to make it from the surface to space. In other words, Pluto could develop a thicker envelope, and conceivably much more clement conditions.

All of this new found status would be fleeting, though. Pluto would have at best a few hundred thousand, or possibly a million or two years to bask in the glory of being the last habitable world of the solar system. After that it too would return to the eternal cold of the cosmos.

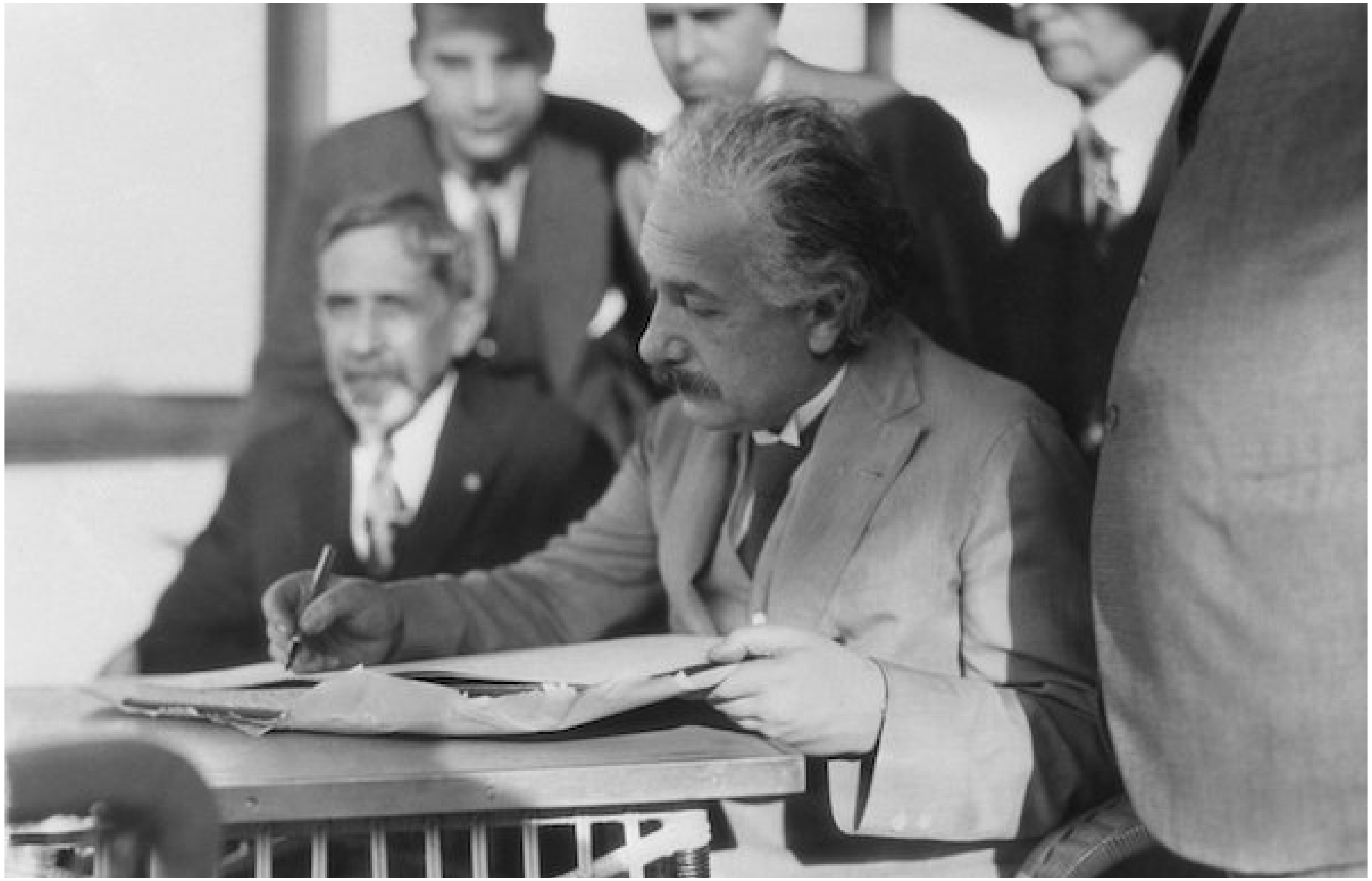
Of course, as a frozen object gets heated it will lose a lot of sublimated material to the vacuum of space. Water, carbon monoxide and so on will just stream away.

Mario Livio is an astrophysicist and author of *Brilliant Blunders: From Darwin to Einstein—Colossal Mistakes by Great Scientists That Changed Our Understanding of Life and the Universe.*

PHYSICS

Einstein's Famous "God Letter" Is Up for Auction

A note the physicist wrote in 1954 reveals his thinking on religion and science



Albert Einstein used to mention God more frequently than you might expect for a scientist, often in relation to the design of the universe.

Take, for instance, his opinion on the successful theory of the subatomic world—quantum mechanics. In a letter to physicist Max Born on December 4, 1926, he wrote, "Quantum mechanics is certainly imposing. But an inner voice tells me that this is not yet the real thing. The theory yields much, but it hardly brings us closer to the Old One's secrets. I, in any case, am convinced that He does not play dice." Even with the accumulation of a large body of experimental evidence for the validity of quantum mechanics, Einstein continued to repeat this view for the rest of his life.

Or, take his oft-cited pronouncement in 1921 that "The Lord God is subtle, but malicious he is not" (meaning nature may be difficult to decipher, but not bent on trickery). Einstein even wondered whether there was any choice in the cosmic blueprint: "What really interests me is whether God could have created the world any differently; in other words, whether the requirement of logical simplicity admits a margin of freedom."

But what did Einstein really mean when referring to "God"? And what was his attitude toward religion in general? Recently, the auction house Christie's announced it was putting one of Einstein's letters on sale. The fact that in this particular letter Einstein expresses his views on a few of these intriguing questions has helped put the subject of "Einstein's God" at center stage. And by examining these writings, we can learn quite a lot about the great man's thinking—not just about religion but science as well.

Einstein wrote the letter up for auction about a year before his death in 1955, and it was addressed to the German Jewish philosopher Eric Gutkind in response to Gutkind's book *Choose Life: The Biblical Call to Revolt*, a religious, optimistic, humanistic manifesto based on biblical teachings. The letter is expected to sell for more than $1 million when it goes on sale December 4.

Einstein did not mince words: "The word 'God' is for me nothing but the expression and product of human weaknesses; the *Bible* a collection of venerable but still rather primitive legends," he wrote. How can we reconcile these rather harsh statements with the citations about God above? The crucial point to recognize is Einstein does not refer here to God as a cosmic designer. Rather, he expresses his lifelong disbelief in a personal god—one that controls the lives of individuals. In 1929 Rabbi Herbert Goldstein sent him a telegram asking "Do you believe in God?" In response Einstein made an even clearer distinction between the awe humans feel when faced with the vastness, complexity and harmony of nature, and the belief in a god that monitors ethical behavior and punishes the wicked. He admired the Dutch Jewish philosopher Baruch Spinoza, and wrote: "I believe in Spinoza's god, who reveals Himself in the lawful harmony of the world, not in a god who concerns himself with the fate and the doings of mankind."

"Quantum mechanics is certainly imposing. But an inner voice tells me that this is not yet the real thing. The theory yields much, but it hardly brings us closer to the Old One's secrets. I, in any case, am convinced that He does not play dice."
—Albert Einstein

In his letter to Gutkind, Einstein again referred to Spinoza to express his objection to any type of claimed superiority for the Jewish belief in monotheism: "It pains me that you claim a privileged position and try to defend it by two walls of pride—an external one as a human being and an internal one as a Jew. As a human being you claim to a certain extent a dispensation from the causality which you otherwise accept, as a Jew a privileged status for monotheism. *But a limited causality is no longer a causality at all* [emphasis added], as indeed our wonderful Spinoza originally recognized with absolute clarity." Einstein emphasized that although he felt "profoundly anchored" in the mentality of the Jewish people, that did not offer him any "different kind of dignity" from all other peoples.

From a historical perspective, it is also interesting to note Einstein differed from some other great scientists in the frequency of his references to God. The great 18th-century French physicist Pierre-Simon Laplace, for instance, never mentioned God in his writings because, in his words, he "did not need to make that hypothesis." In relation to religious beliefs, on the other hand, even a "heretic" such as Galileo still thought biblical scripture represented truth, if properly reinterpreted when an apparent conflict with scientific evidence arose. On this issue, Einstein's opinion was entirely different and categorical: "No interpretation [of the Bible], no matter how subtle, can [for me] change anything" about the fact that the text represented to him "an incarnation of primitive superstition."

To conclude, perhaps the most meaningful sentiment expressed in Einstein's letter to Gutkind was his agreement with the philosopher on the notion human endeavors should be directed at "an ideal that goes beyond self-interest, with the striving for release from ego-oriented desires, the striving for the improvement and refinement of existence, with an emphasis on the purely human element." Amen.

Those of us without a million dollars who wish to ponder the letter further can see it on public view in New York City November 30 to December 3.

Celestial Movement

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

BRAD GOLDPAINT GETTY IMAGES

Astronomical Events
December 2018–January 2019

December	Event
2	Venus: maximum brightness (–4.9 mag)
3	Morning sky: moon near Venus
5	Mercury: morning visibility begins
	Before sunrise: old moon (waning crescent) visible low in the east-southeast
7	Moon: new moon
	Minor planet (433) Eros (9.7 mag) in opposition
9	Moon reaches southernmost declination (–21.54°)
	Evening Sky: moon near Saturn
12	Moon at apogee (405,177 km), apparent diameter 29´ 32´´
14	Maximum of Geminid meteor shower
15	Moon: first quarter
	Mercury in greatest elongation west (21.3°)
20	Evening Sky: moon near Aldebaran in constellation Taurus
21	Winter solstice
22	Moon: full moon
	Maximum of Ursid Meteor shower
23	Moon reaches northernmost declination (+21.55°)
24	Moon at perigee (361,061 km), apparent diameter 32´ 35´´
28	Mercury: morning visibility ends
29	Moon: last quarter

December 2018 — January 2019: Visibility of the planets

The end of the year and start of 2019 offer several special opportunities for planetary viewing. If you have never seen Mercury before, you can observe this elusive planet during December above the eastern horizon in the morning. In the coming weeks, spot Venus and the giant planet Jupiter. An exciting highlight in the New Year: a total lunar eclipse on January 21, 2019.

Mercury can be seen in December low above the southeastern horizon for nearly three weeks. After reaching its maximum separation from the sun in mid-December the distance begins to shrink rapidly. On December 22 Mercury passes Jupiter—an interesting binocular sight. By the end of the month, the innermost planet vanishes in the glare of the sun. In January 2019, Mercury is unobservable.

Venus becomes a dazzling sight high above the southeastern horizon. The planet reaches its greatest angular separation from the sun (greatest elongation) on January 6. Don't miss the encounter of the “morning star” with the giant planet Jupiter on January 22 as well as the gathering of Venus, Jupiter and the crescent moon on January 30.

BRAD GOLDPAINT GETTY IMAGES

Astronomical Events
December 2018—January 2019

January •	Event
1	Morning sky: moon near Venus in constellation Libra
2	Saturn in conjunction with sun
3	Earth at perihelion (147,100,000 km)
	Morning sky: moon near Jupiter in constellation Ophiuchus
	Maximum of Quadrantid meteor shower
5	New moon (partial solar eclipse visible in northeast Asia and the northern Pacific)
	Moon reaches southernmost declination (–21.6°)
6	Venus: greatest elongation west (46.9°)
8	Moon at apogee, 406,116 km, 29.4’
14	Moon: first quarter
17	Moon near Aldebaran in constellation Taurus
19	Moon reaches northernmost declination (+21,54°)
21	Full moon
	Moon at perigee, 357,345 km, 33.4’
	Total lunar eclipse visible in North and South America, Europe, the central Pacific, and Africa
22	Morning sky: Venus near Jupiter in constellation Ophiuchus
	Morning Sky: moon near Regulus in constellation Leo
27	Moon: last quarter
30	Mercury in superior conjunction
	Morning sky: moon near Jupiter and Venus in constellation Ophiuchus

December 2018 — January 2019: Visibility of the planets

The end of the year and start of 2019 offer several special opportunities for planetary viewing. If you have never seen Mercury before, you can observe this elusive planet during December above the eastern horizon in the morning. In the coming weeks, spot Venus and the giant planet Jupiter. An exciting highlight in the New Year: a total lunar eclipse on January 21, 2019.

Mars can still be seen in the evening sky after sunset. During December and January the red planet moves from the constellation of Aquarius to Pisces while its apparent brightness decreases from 0.0 mag to +0.9 mag.

Jupiter, the largest and most massive planet of the solar system, becomes more conspicuous in the morning sky. After December 15, you can easily spot the giant low above the eastern horizon. On December 22, Jupiter will have a visitor: Mercury approaches, and the movement of both planets can be observed during the days before and after closest encounter.

Saturn is about halfway between Jupiter and Mars in the evening sky in the constellation Sagittarius, close to the Milky Way’s center. If you want to observe Saturn’s famous rings in a telescope, now is the time—for the remainder of the year Saturn will move too close to the sun for observation.

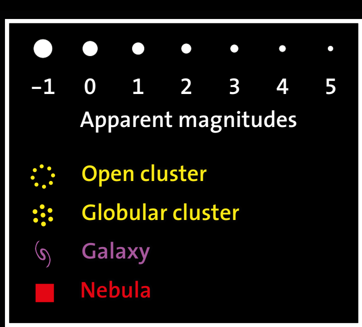
BRAD GOLDPAINT GETTY IMAGES

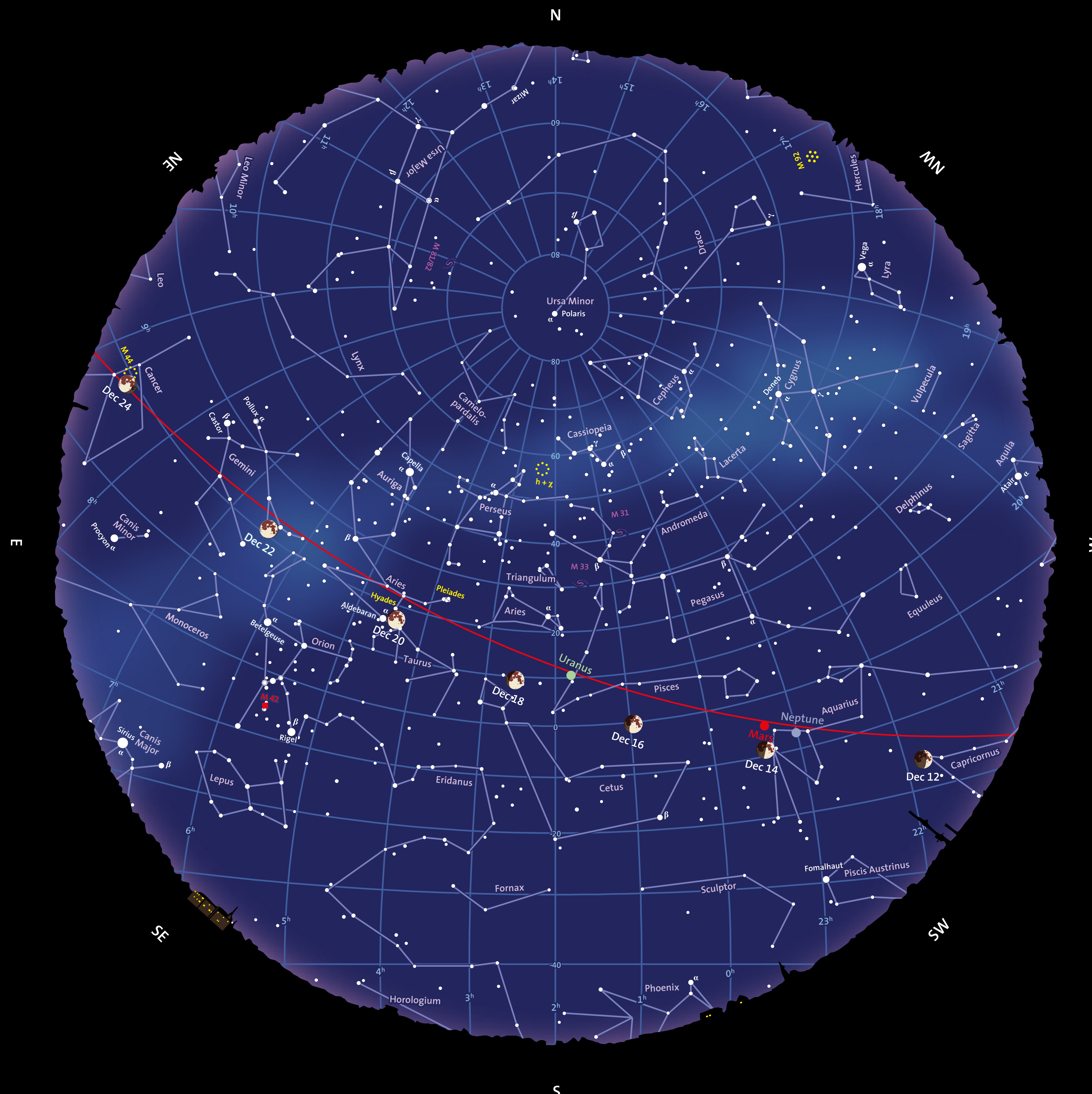
SKY REPORT

December

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.

The reference point is 100° W and 40° N and the exact time is 10 p.m. EST or 9 p.m. CST.





ERNST VON VOIGT

SKY REPORT

January

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.

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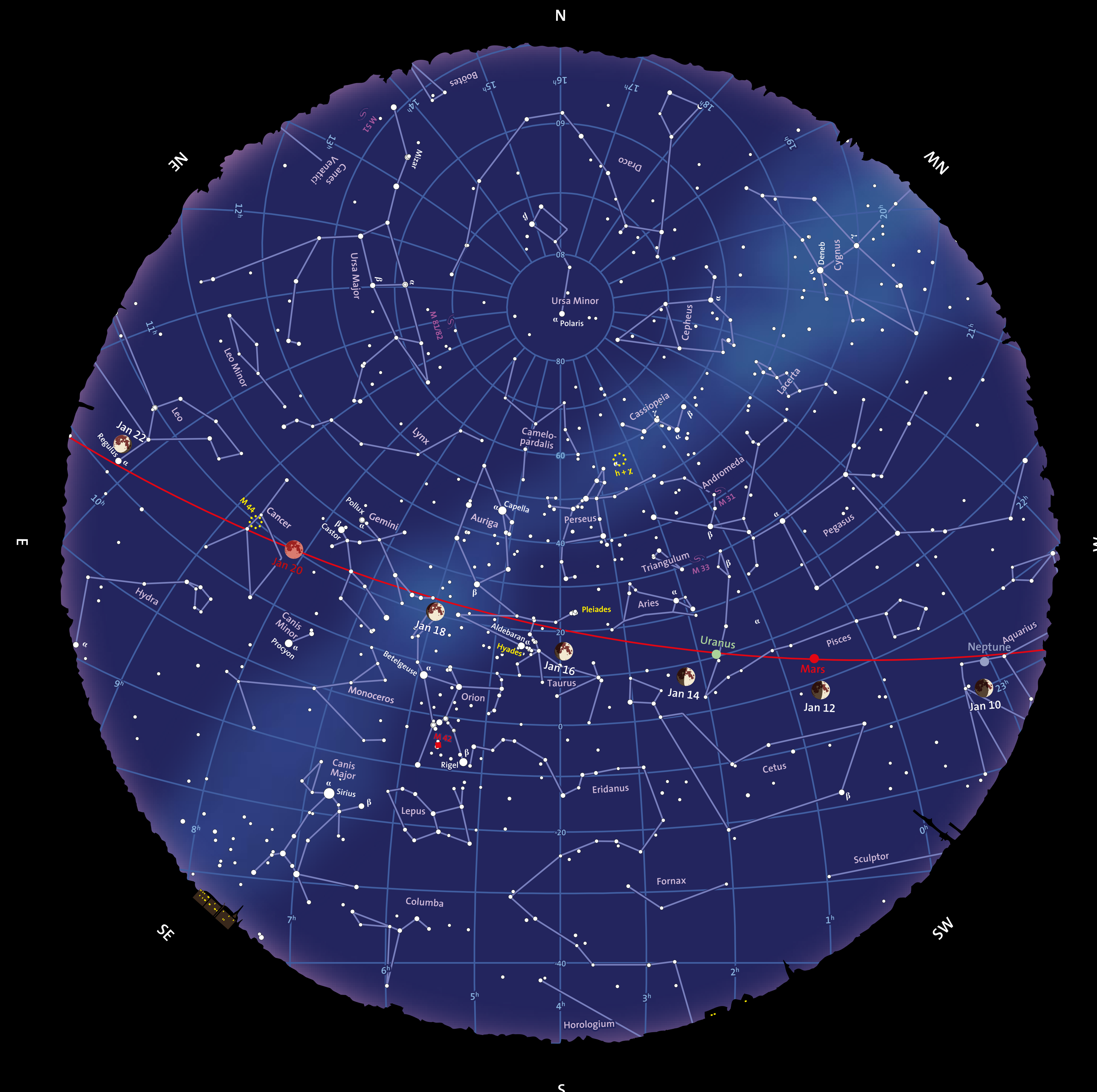
−1 0 1 2 3 4 5
Apparent magnitudes

Open cluster
Globular cluster
Galaxy
Nebula



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LETTERS TO THE EDITOR:
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