FEBRUARY/MARCH 2020 | SCIENTIFICAMERICAN.COM

SCIENTIFIC AMERICAN Space & Physics

Plus:

PROBING BLACK HOLES AT THE HEART OF COLOSSAL GALAXIES

SHOULD WE BELIEVE IN THE MULTIVERSE?

QUANTUM HEAT TRANSFER IN A VACUUM

Interstellar Interlopers

OBJECTS ENTERING OUR SOLAR SYSTEM ARE UPENDING SOME LONG-HELD ASTRONOMICAL ASSUMPTIONS

WITH COVERAGE FROM **nature**

FROM THE EDITOR


LIZ TORMES

The Majesty of Cosmic Chaos

I must have been in about eighth grade when I first learned about one of the most recognizable cosmic formations that humans have ever observed. The Horsehead Nebula, a sculpted pillar of dust and gas that forms the far edge of the Orion B molecular cloud, is part of a massive stellar nursery where gravity, magnetic forces and radiation winds force matter together to birth new stars. That such a volatile, powerful place in the universe could also resemble the majestic beauty of a horse's head had me hooked. Now some astronomers hypothesize that colossal black holes, too, may arise from so-called nurseries. As Charlie Wood details in this issue, a handful of candidates for this type of black hole formation have been discovered using LIGO observations, but much more data is needed (see "Black Hole Factories May Hide at Cores of Giant Galaxies").

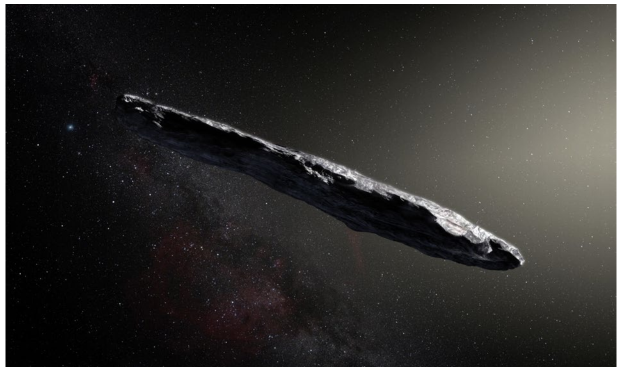
Elsewhere in these pages, Alexandra Witze details the ways that the appearance of two recent alien objects in our solar system are overturning long-held astronomical assumptions (see "Two Interstellar Intruders Are Upending Astronomy"). And XiaoZhi Lim reports on new "supercool materials" that can absorb heat and reradiate it directly through Earth's atmosphere and into space (see "The Supercool Materials That Send Heat to Space"). As always, enjoy this issue!

Andrea Gawrylewski
Senior Editor, Collections
editors@sciam.com

SPACE & PHYSICS

Your Opinion Matters!

Help shape the future of this digital magazine. Let us know what you think of the stories within these pages by emailing us: editors@sciam.com.


ESO/M. KORNMESSER

On the Cover

Objects entering our solar system are upending some long-held astronomical assumptions

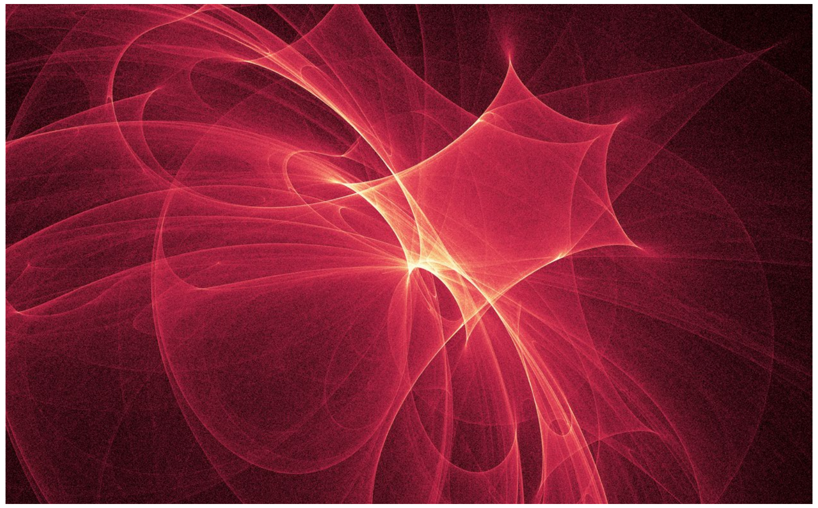
WHAT'S INSIDE

February-March 2020
Volume 3 • No. 1

NEWS

NASA AND SOFIA; NASA, JPL-CALTECH AND ROMA TRE UNIVERSITY

ESO/M. KORNMESSER



GETTY IMGAES

FEATURES

OPINION

NEWS

ANDREW AGS *GETTY IMAGES*

Space Heater: Scientists Find New Way to Transfer Energy through a Vacuum

Nanoscale experiments reveal that quantum effects can transmit heat between objects separated by empty space

Early in life, most children learn that touching a hot stove or even being near a roaring fire can burn them. Whether conveyed via direct contact or rays of light zipping through space, the often painful lessons of heat transfer are as intuitive as they are unforgettable. Now, however, scientists have revealed a strange new way that warmth can wend its way from point A to B. Through the bizarre quantum-mechanical properties of empty space, heat can travel from one place to another without the aid of any light at all.

Generally speaking, heat is the energy that arises from the motions of particles—the faster they move, the hotter they are. On cosmic scales, most heat transfer occurs through a vacuum via photons, or particles of light, emitted by stars—this is how the sun warms our planet despite being some 150 million kilometers away. Here on Earth, heat flow is often more intimate, taking place via direct contact between materials and helped along by the wavelike collective vibrations of atoms known as phonons.

Phonons, it was long thought, could not transfer heat energy through empty space; they require two objects to touch or, at least, to be in mutual contact with a suitable medium such as air. This principle is how thermoses keep their content hot or cold: they use a wall enclosing a vacuum to insulate an inner chamber. Yet scientists have speculated for years about the possibility that phonons might impart heat across a vacuum, enamored by the mind-boggling fact that quantum mechanics dictates space can never be truly empty.

Quantum mechanics suggests the universe is inherently fuzzy—for

An artist's impression of a virtual particle popping in and out of existence in a vacuum. Such quantum fluctuations are at the heart of a newfound way for heat to move between objects.

example, try as one might, one can never pin down a subatomic particle's momentum and position at the same time. A consequence of this uncertainty is that a vacuum is never completely empty but instead buzzes with quantum fluctuations—so-called virtual particles that constantly pop in and out of existence. "Vacuum is never totally vacuum," says Xiang Zhang, a physicist at the University of California, Berkeley, and senior author of the new study on phonon heat transfer, which appeared in *Nature* on December 11, 2019.

Decades ago scientists found that virtual particles were not just theoretical possibilities but could generate detectable forces. For instance, the Casimir effect is an attractive force seen between certain objects in proximity, such as two mirrors placed close together in a vacuum. These reflective surfaces move because of the force generated by virtual photons blinking in and out of existence.

If these ephemeral quantum fluctuations could give rise to real forces, theorists mused, perhaps they could also do other things—such as transfer heat sans thermal radiation. To envision how phonon heating via quantum fluctuations might work, picture two objects with different temperatures separated from one another by a vacuum. The phonons in the warmer object could impart thermal energy onto virtual photons in the vacuum, which could then go on to transfer such energy to the cooler object. If both objects are essentially collections of jiggling atoms, the virtual particles could act like springs to help carry vibrations from one to the other.

The question of whether quantum fluctuations could really help phonons transfer heat across a vacuum "had been argued about by theorists for a decade or so, sometimes with wildly different estimates for the strength of the effect—the calculations are quite tricky," says physicist John Pendry of Imperial College London, who did not participate in this study. In general, this prior work predicted that researchers could only see the effect between objects separated by a few nanometers (billionths of a meter) or less, he explains. At such tiny distances, electrical interactions or other nanoscale phenomena between objects might easily obscure this phonon effect, Pendry says—making it very hard to test.

To meet that challenge, Zhang and his colleagues spent four years of painstaking trial and error in crafting and perfecting experiments to see if they could achieve phonon heat transfer across greater distances in a vacuum, on the scale of hundreds of nanometers. For example, the experiments involved two silicon nitride membranes, each roughly 100 nanometers thick. The extraordinarily thin and light nature of these sheets makes it easier to see when energy from one has an effect on the motions of the other. Vibrating atoms in the sheets make each membrane flex back and forth at frequencies that depend on their temperature.

If the sheets were both the same size but disparate temperatures, Zhang's team realized, they would quiver at different frequencies. With all these details in mind, the scientists tailored the sizes of the membranes so that even though they started at different temperatures (13.85 and 39.35 degrees Celsius, respectively), they both vibrated about 191,600 times per second. Two objects resonating at the same frequency tend to exchange energy efficiently—one well-known example of resonance can be seen when an opera singer hits the right note to cause a champagne glass to resonate and shatter.

In addition, the researchers made sure the membranes were within about a few nanometers of being perfectly parallel to each other, all to help precisely measure the forces one might exert on the other. They also took care that the membranes were extremely smooth, with surface variations no greater than 1.5 nanometers in size. Clamped to a surface in a vacuum chamber, one membrane would be mated to a heater, whereas the other would be connected to a cooler. Both would be coated with a gossamer-thin layer of gold for reflectivity and bathed in faint laser beams to detect their oscillations—and thus their temperature. In trial after trial, the scientists checked to ensure the membranes did not exchange heat through the surface they were clamped onto or through any emission of visible light or other electromagnetic radiation across the vacuum.

"This experiment required very sensitive control of temperature, distance and alignment," Zhang says. "We once had trouble running the experiment in the summertime because of the hot weather warming up the lab. Also, the measurement itself takes a very long time in order to eliminate noise—each data point took four hours to obtain."

Eventually, Zhang and his colleagues found that when the membranes were brought less than 600 nanometers apart, they began exhibiting otherwise inexplicable changes in temperature. Below 400 nanometers, the rate of heat exchange was enough for the membranes to have a nearly identical temperature, demonstrating the effect's efficiency (or lack thereof). With successful results in hand, the researchers were able to calculate the maximum rate of energy they saw transferred by phonons across the vacuum: some 6.5×10^{-21} joules per second. At that rate, it would take about 50 seconds to transfer the amount of energy in one photon of visible light. That figure may seem paltry, but Zhang notes it still constitutes "a new mechanism of how heat is transferred between objects."

"It is good to see some experimental data confirming that phonons can leap the gap," Pendry says. "This is a great experiment—a first, I believe."

In principle, stars may even heat their planets through this newfound mechanism. Given the distances involved, however, the magnitude of this effect would be "exceedingly small," essentially to the point of utter insignificance, Zhang says.

Closer to home, as the electronics in everything from smartphones to laptops get ever smaller, these findings might allow engineers to better manage heat in nanoscale technologies. "For example, in hard drives, the magnetic read/write head moves above the disk surface with a separation as little as three nanometers," Zhang says. "At such a short distance, the new heat-transfer effect is expected to play a significant role and so should be considered in the design of magnetic recording devices."

Zhang notes that quantum fluctuations do not just include virtual photons. There are many other kinds of virtual particles, including virtual gravitons, or packets of gravitational energy. "Whether quantum fluctuations of gravitational fields could give rise to a heat-transfer mechanism that plays a role on cosmological scales is an interesting open question," Zhang says.

—Charles Q. Choi

Swirling Magnetic Fields Hint at Origins of Spiral Galaxy Shapes

The formation of spiral galaxies remains an open question in astronomy, but a new study offers a fresh look into how these structures emerge

Galaxies in the universe come in all shapes and sizes. Some are giant spheres of stars many times larger than the Milky Way. Others are flattened disks, with pancakelike stellar swirls orbiting a central bulge. But others still, including our own, are arrangements of stars that dance in spirals around their center. Astronomers have long puzzled over how these spirals form, and a number of theories have been proposed. Now new observations are revealing the galactic-scale magnetic fields associated with these spirals, providing what may be vital clues to their formation.

In a paper posted on the preprint server arXiv.org and accepted for publication in the *Astrophysical Journal*, a team of astronomers performed observations from NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA), a telescope that flies on a modified Boeing jet, to observe a galaxy called M77 with a new instrument called the High-Resolution Airborne Wideband Camera–Plus (HAWC+). Although M77 is some 47 million light-years from Earth, the team was able to use SOFIA's far-infrared capabilities to observe its magnetic field, finding it closely correlated with the galaxy's star-filled spiral arms.

"The region between stars in our galaxy and in other galaxies is full of dust," says Terry Jones of the University of Minnesota, one of the co-authors of the paper. "That dust absorbs the light from the stars, and it warms up and radiates in the far infrared. If you line all those up in the same direction, it acts like a weak polarizer, like a pair of [polarized] sunglasses. How do you line up all the [dust]? Well, that's what the magnetic field does. The polarization of the light from this dust tells us the direction of the magnetic field."

SOFIA was able to produce its stunning visualization of M77 thanks to its unique ability to fly high in the atmosphere, above layers of water vapor that would otherwise absorb the faint far-infrared signature emitted from dust in distant galaxies. "That was really not very possible before," Jones says. "This is a new way to map or make pictures of other galaxies in polarized light in the far infrared. You can't do it from the ground, because the atmosphere absorbs everything, and previous instruments weren't sensitive enough."

This study, the researchers say, is the first time astronomers have mapped another galaxy's magnetic field in far-infrared light. That achievement is significant, notes Bruce Draine of Princeton University, who was not involved in the work, because that light is "almost entirely radiated by dust grains." Although the dust particles themselves are too small to see, their large-scale alignment causes them to radiate more brightly, revealing their distribution across the entirety of M77.

How M77 and other galaxies get their spirals remains an open question in astronomy, although it is believed gravity has a major part to play. In one predominant model known as the density wave theory, denser regions of a galaxy rotate more slowly than their surroundings, meaning that the stars within them essentially bunch up into the spiral arms that we can observe from afar. And this effect may shape the magnetic field in a galaxy, rather than vice versa. "The magnetic field looks like it's along for the ride," Jones says. "In other words, the magnetic field itself is not telling us where the spiral arms should be; the spiral arms are telling us where the magnetic field points."

Ronald Drimmel of the Astrophysical Observatory of Turin in Italy, who was also not involved in the new study, says the existence of galaxy-spanning magnetic fields is "not a surprise." But SOFIA's revelation of very distinct large-scale patterns is novel and important. "It's showing that the magnetic field in these galaxies isn't just turbulent or random," he says. "It's not obvious that the magnetic field should be ordered in this regular way over large scales. So that is interesting"—and potentially relevant for solving the mystery of why some galaxies have a spiral shape while others do not.

Many galaxies are thought to get

Magnetic field lines swirl across the spawn of the spiral galaxy M77 in this composite image from multiple observatories.

NASA AND SOFIA; NASA, JPL-CALTECH AND ROMA TRE UNIVERSITY their shape through collisions with other galaxies. But the relative rarity of such cosmic collisions, in comparison with the prevalence of spiral galaxies, may demand a broader theory to explain the cosmic swirls. "Our theories of spiral structure are incomplete," Draine says. "In some galaxies, it develops in a much more pronounced way than others. And exactly what determines whether the galaxy is going to have this very pronounced structure or less [discernible] spiral structure is not always clear."

To get to the bottom of this question, studies that follow this latest SOFIA research will need to be conducted in higher resolution, says George Helou of the California Institute of Technology, who was not involved in that recent paper. Such high-resolution observations could show how a galaxy's gas is compressed and shaped throughout the galaxy's life. "We have a good working theory, spiral density wave theory, that was proposed six decades ago that seems to pass all the tests," Helou says. "But it has many parameters that play into it. If I gave you all the parameters that we know about the disk of a galaxy, there isn't a simple way for you to derive what the spirals should look like. We still have many aspects that we need to understand better."

We have seen before, thanks to SOFIA, that wind emitted from a galaxy is aligned with its magnetic field. But this recent study gives us a whole new look into what role magnetic fields play inside galaxies—or at least, what shape they are formed into by the galaxies themselves. And, Jones says, there are tantalizing potential observations that can be made with SOFIA in the future that can give us a better handle on galactic shapes than ever before. "We can find them crashing into one another, and we haven't observed that yet with this technique," he says. "We haven't measured the magnetic field geometry of [galaxies without spiral arms] yet either. So this is just the tip of the iceberg."

—Jonathan O'Callaghan

Japan Will Build the World's Largest Neutrino Detector

Cabinet greenlights $600-million Hyper-Kamiokande experiment, which scientists hope will bring revolutionary discoveries

Japan is set to build the largest neutrino detector in history, after a cabinet committee approved billions of yen for its construction on December 13, 2019, according to scientists involved in the project. Hyper-Kamiokande will hold 260,000 tons of ultrapure water—more than five times the amount contained by its already enormous sibling, the Super-Kamiokande. The new detector will be built inside a gigantic cavern to be dug next to Hida City's Kamioka mine and will, physicists hope, bring groundbreaking discoveries about these ubiquitous particles.

The enormous size of the Hyper-Kamiokande (Hyper-K) will enable it to detect unprecedented numbers of neutrinos produced by various sources—including cosmic rays, the sun, supernovae and beams artificially produced by an existing particle accelerator. In addition to catching neutrinos, it will monitor the water for the possible spontaneous decay of protons in atomic nuclei, which, if observed, would be a revolutionary discovery.

Although the government has not yet made an official statement about the approval, several scientists have told *Nature* that the country's cabinet approved the first ¥3.5-billion (U.S.$32-million) tranche toward construction as part of a supplementary budget for the current financial year—which ends in March—during a meeting last December.

A HUGE UNDERTAKING

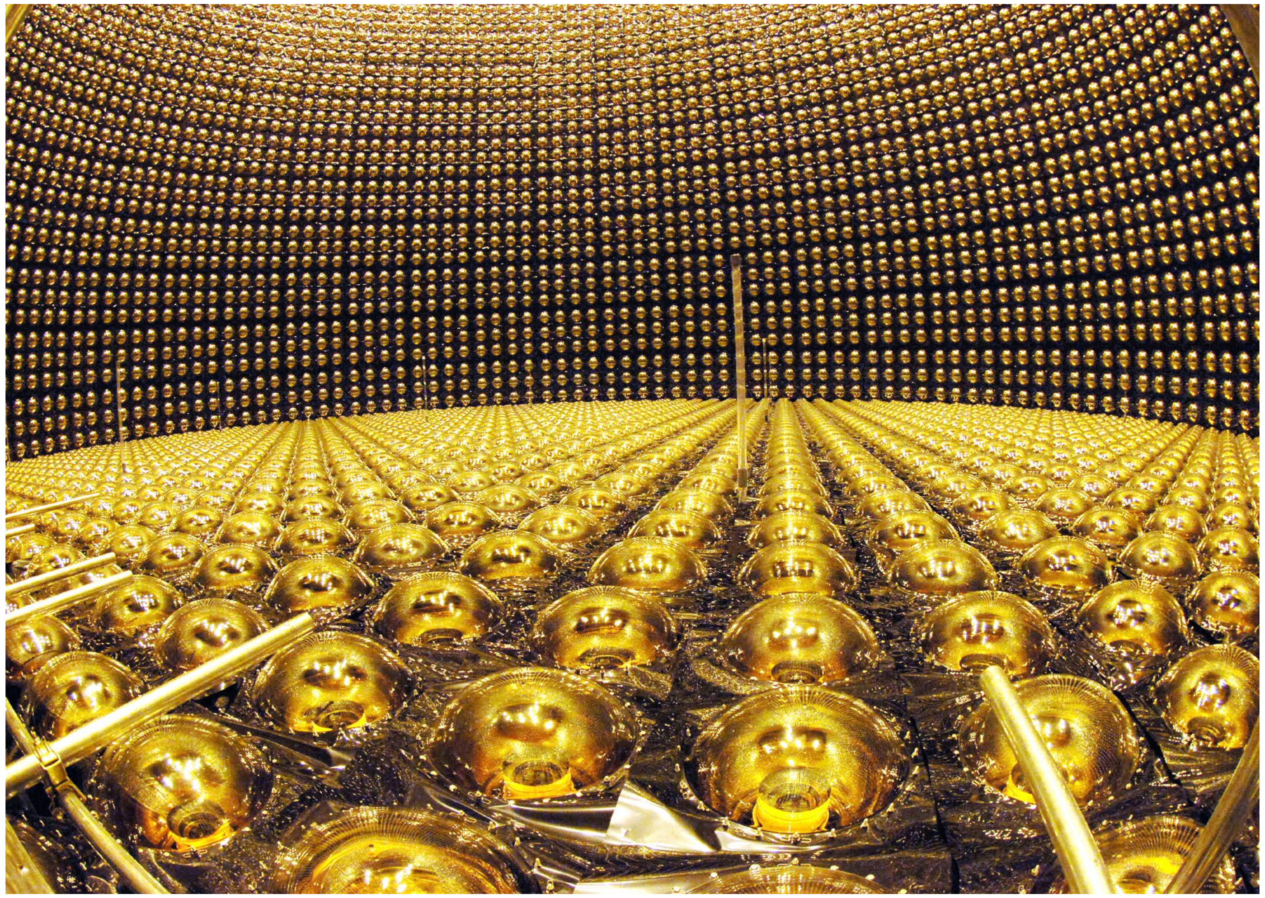
Building the detector is expected to cost ¥64.9 billion, about U.S.$600 million, says Masato Shiozawa, a neutrino physicist at the University of Tokyo and the project's co-leader. An extra ¥7.3 billion will be required for upgrades at the J-PARC accelerator—which is about 300 kilometers away in Tokai—where the neutrino beam will be produced.

Japan will provide about 75 percent of the project's total funds, with the rest to be covered by international partners. Several other countries, including the U.K. and Canada, will be involved in the project, although the size of their financial contributions has yet to be finalized, says Francesca Di Lodovico, a physicist at King's College London, who is also co-leader of Hyper-K.

Hyper-K will consist of a drum-shaped tank 71 meters deep and 68 meters wide. A hall to house the tank will be dug with explosive charges at a site eight kilometers from the existing Kamioka facilities, to avoid vibrations disturbing the KAGRA gravitational-wave detector, which is about to start operating. The Kamioka site was chosen decades ago because of the existing mining facilities and the high quality of the rock, as well as the abundant supply of freshwater.

As in Super-K, the water tank inside Hyper-K will be lined with sensitive light detectors called photomultipliers. These will capture faint flashes emitted when a neutrino collides with an atom in the water, causing a charged particle to shoot out at high speed.

Hyper-K will be one of three major next-generation neutrino experiments to start in the 2020s; the others are the Deep Underground Neutrino Experiment (DUNE), due to start in the U.S. in 2025, and the Jiangmen Underground Neutrino Observatory (JUNO) in China, which is expected to begin collecting data in 2021.



Light sensors in Japan's Super-Kamiokande neutrino detector capture faint flashes that occur when neutrinos collide with water atoms.

PRECISION MEASUREMENTS

Neutrino physicists are excited about Hyper-K because it will be able to study differences in the behaviors of neutrinos and their antimatter counterparts, antineutrinos, said Takaaki Kajita, a physicist at the University of Tokyo, at a conference in London on December 16, 2019. Such asymmetry could help to explain why the universe seems to contain mostly matter and little antimatter, said Kajita, who shared the 2015 Nobel Prize in Physics for his co-discovery of neutrino oscillations, made using the Super-K in the 1990s.

Super-K has already seen hints of this discrepancy, but both Hyper-K and DUNE should be able to measure it with high precision using two different techniques—DUNE will use liquid argon rather than water—providing an important cross-check. "They have similar sensitivity, but to me, complementarity is an important aspect," Kajita said.

But the biggest discovery that Hyper-K can hope to make is of proton decay, says Masayuki Nakahata, a physicist at the University of Tokyo and the spokesperson of Super-K, which is an international collaboration led by Japan and the U.S. Proton decay has never been observed and must, therefore, be exceedingly rare—if it happens at all—meaning that the proton has a very long average lifetime, of more than 1,034 years.

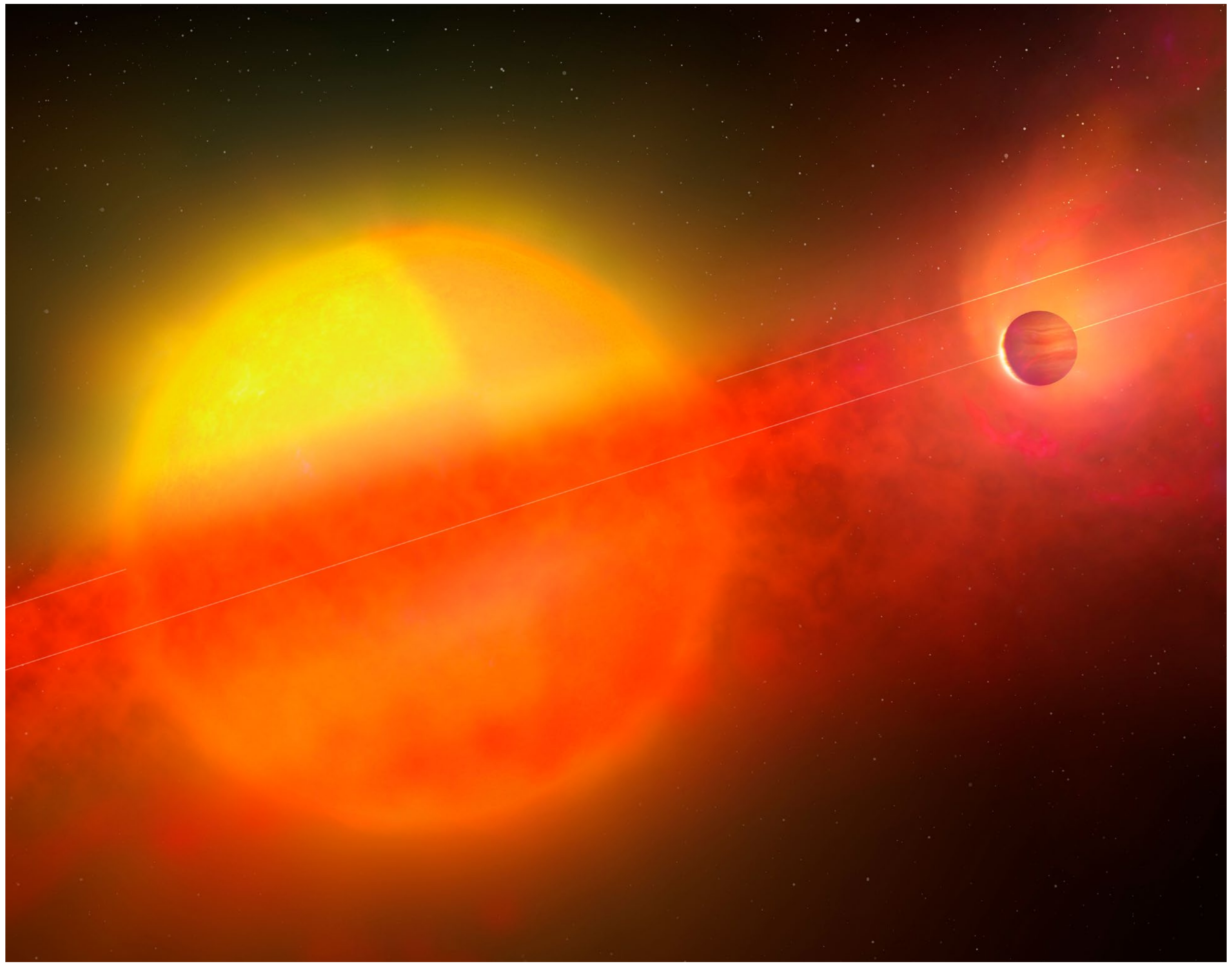
The current Standard Model of particle physics does not allow for proton decay, but many of the theories proposed to supersede it and unify the fundamental forces of nature do predict the phenomenon. Because Hyper-K will monitor a much larger volume of water than Super-K does, it will have a better chance of seeing protons decay. If it doesn't detect the phenomenon, the limit on the average lifetime of the proton will increase 10-fold.

—Davide Castelvecchi

GETTY IMAGES

Newfound "Ablating" Exoplanets Could Reveal Alien Geology

By probing close-in worlds, the discovery will help astronomers better understand how planets form and evolve



An artist's visualization of the evaporating giant planet DMPP-2b, which resides in a five-day orbit around the pulsating star DMPP-2. The star is enshrouded by a cloud of gas lost from the broiling planet.

MARK A. GARLICK

Move over, Icarus. Six newly discovered exoplanets have been discovered flying so close to their host stars that they are literally evaporating—creating a ring of debris. The discovery of the planets, published last December in three separate papers in *Nature Astronomy*, were identified using a new technique that first looked for that ring of debris. It is thus an efficient method to find small planets orbiting extremely close to their star, which have long eluded detection. In addition, follow-up studies should allow astronomers to probe the geology of these "ablating" worlds and better understand how such planets form and evolve—perhaps even shedding light on the oddities within our own solar system.

In 2009 Carole Haswell, an astronomer at the Open University in England, observed the exoplanet Wasp-12b—a Jupiter-like world that orbits its host star so tightly a year there lasts just 26 hours—when she noticed something odd about its parent star. The hot, outer layers of its atmosphere known as the chromosphere appeared to be missing. And she had an inkling that the star's close-in planet just might be the culprit. At the time, astronomers knew that this world was so hot that the outer reaches of its atmosphere were effectively boiling off into space. "They're just too close to the fire," says David Grinspoon, a scientist at the Planetary Science Institute, who was not involved in the study. "It's like you're roasting your marshmallow, and you put it too close to the fire—and poof!" Haswell hypothesized that the resulting trail of gas from the planet absorbed the same wavelengths of light that the star's chromosphere emits, making it appear dark.

The idea was tantalizing. It suggested that astronomers could search for stars with the same signature—a "missing" chromosphere—to target close-in exoplanets. Moreover, if astronomers used this new technique to scrutinize the already well-surveyed nearby stars, they would likely find only small worlds given that large ones had already been discovered through other methods. That would be particularly valuable because, to date, small exoplanets have proved notoriously difficult to find. So Haswell set out on a mission. She and her colleagues scoured data from 2,700 nearby sunlike stars and found that 39 appeared to be missing their chromospheres. Then, the team used a planet-finding instrument on the European Southern Observatory's 3.6-meter telescope at the La Silla Observatory in Chile to take a closer look.

"What we found was a success beyond my wildest dreams," Haswell says. Her team discovered planets around the first three stars that they were able to observe in detail. And these systems are pretty wild. The star DMPP-1 hosts multiple planets with three inner planets—3.5 to 10 times the mass of Earth—and one outer planet heavier than Neptune. The star DMPP-2 hosts a planet with a mass roughly half that of Jupiter in a five-day orbit; the world had been overlooked because of DMPP-2's stellar pulsations. And the star DMPP-3 hosts a small planet roughly twice the mass of Earth and also a second star that orbits at a greater distance. All the newfound planets orbit their stars substantially closer than Mercury does the sun, and many of them are quite small—on par with rocky worlds like Earth. "We think we're identifying a hidden population of planets," says co-author John Barnes, also at the Open University.

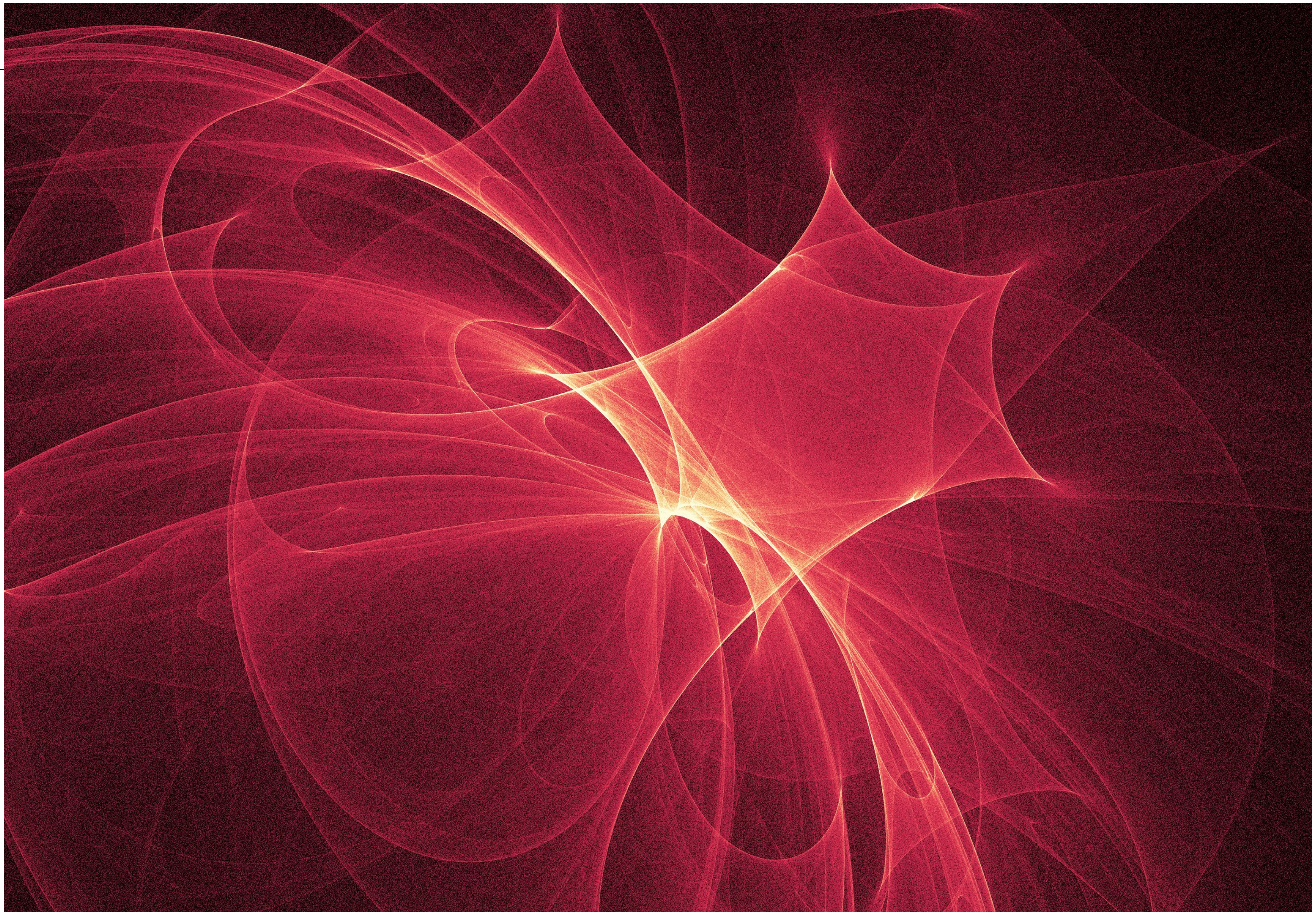
Grinspoon called the study "ingenious." He has long thought that we would know little about exoplanets. "But then you have these incredibly clever techniques that people keep devising," he says. "I read about them and think, 'I'll be damned, they figured out a way to do this.' And to me, this is another step in that progression."

"We think we're identifying a hidden population of planets."
—John Barnes

Not only do the results show a new technique that will allow astronomers to uncover these planets efficiently, they also point toward a number of follow-up studies that could allow astronomers to understand these worlds in amazing detail. To confirm the planets' existence, the team used the "radial velocity" method, which looks for the wobbles in a star's movement induced by the gravitational tugs of accompanying worlds. The team suspects, however, that many of these planets will also be detectable via the "transit" technique, which spots tiny dips in starlight caused when a planet crosses in front of its host star as seen from Earth. Radial velocity measurements allow astronomers to estimate planets' masses, whereas transits allow them to measure the sizes of worlds. When combined, the two techniques can reveal a density for each planet—a crucial step in better understanding a world's composition. Moreover, astronomers can gain an even better handle on the geology of ablating planets by studying the disks of cast-off debris that encircles their host stars, looking for the presence of various chemical elements by their absorption of specific wavelengths of starlight.

Grinspoon is excited to use this technique to better understand how planets evolve—particularly in their early stages, when their young host stars may pelt them with violent outbursts of intense radiation. "This may be a window into that particular phase," he says. Take Venus as an example. Some models suggest that the planet might have held oceans for billions of years—meaning that the now torrid and toxic world was once eminently Earth-like and habitable. But the veracity of such ideas hinges on the activity of our young sun. A newborn Venus is thought to have been a "magma world," which would have become a "steam world" as it cooled, rapidly venting its water—as steam—off into space, much like the small planets that Haswell's team has uncovered. Alternatively, Venus could have experienced an intermediate phase, in which its steam condensed and rained down on the surface, creating an ocean. When and how the sun bombarded young Venus is the most likely arbiter between these two vastly different planetary fates. And so, by better understanding this process in other systems, we might further understand what occurred early in our own solar system.

But before Haswell and her colleagues plan to conduct follow-up studies, they will keep poring over the other systems that likely host close-in planets. With only three fully observed, they have 36 left on their to-do list. Luckily, they received telescope time for 10 nights in 2020. As Barnes says, "It's a good Christmas present." *—Shannon Hall*



Evidence of New X17 Particle Reported, but Scientists Are Wary

Could the mysterious particle be our window into studying dark matter?

The hunt for dark matter—and the associated particles and forces that we expect to accompany it—has turned up numerous false dawns over the years. Try as we might, any evidence of what makes up this invisible form of matter—thought to be the vast majority of matter in the known universe—has remained elusive. But a team of Hungarian researchers suggested in 2015 that they had found a particle, dubbed X17, that possibly interacted with dark matter in some way. Recently, in a second experiment, the team says it has fresh evidence for the X17 particle, which would change physics as we know it. But not everyone is convinced, and new experimental plans are afoot to root out the truth.

In a paper posted on the preprint server arXiv.org, which has not yet been peer-reviewed, Attila Krasznahorkay of the Institute for Nuclear Research (also known as Atomki) at the Hungarian Academy of Sciences and his colleagues report the new findings. Back in 2015 the team observed the decay of beryllium 8 nuclei and found that pairs of electrons and positrons (electrons' antimatter counterparts) ejected in the process were consistent with the additional decay of a mysterious extra particle, the X17 particle, with a mass of about 17 million electron volts (MeV). Now the researchers say they have seen evidence for this particle again but this time in the decay of helium 4 nuclei. "We studied the decay of high-energy nuclear states, first of all in beryllium 8 and then, more recently, in helium 4," Krasznahorkay says. "We got a short difference between the prediction and the experimental data, an anomaly. In order to understand this anomaly, we assumed a

GETTY IMAGES

new particle, which is created in the atomic nucleus and ejected, then decays to electron-positron pairs."

The experimental setup at Atomki involves bombarding a target with protons to examine its nuclear decay. This technique is somewhat different than the usual methods of particle detection such as at the Large Hadron Collider (LHC) at CERN near Geneva, which smashes particles together at high energies and observes the resultant particles emitted in the collision. The Atomki process, however, provides a unique method to look for unexpected particles. The scale of 17 MeV is "difficult to probe using the Large Hadron Collider, which tends to be operating at a much higher energy," says Jesse Thaler of the Massachusetts Institute of Technology Center for Theoretical Physics, who was not involved in the experiment.

Since the Hungarian team published its first paper back in 2015, other scientists have tried and failed to find evidence for the X17 particle. An outside analysis in 2016, however, suggested that if this particle truly exists, it could be evidence for a supposed "fifth force" of nature, specifically related to dark matter.

"This fifth force really means there is a new particle that intermediates new interactions, or new forces," says Daniele Alves, a particle physicist at Los Alamos National Laboratory, who was not involved in the Hungarian team's work. "It's possible that this particle is part of a larger 'dark sector,' meaning it could also interact with dark matter particles. It could be a portal to this sector."

Matt Strassler, a theoretical physicist at Harvard University, who also wasn't involved in the Hungarian team's studies, notes this particle would be "a window into some aspect of the universe that we are completely unaware of," with huge implications. "Not only would it be obviously Nobel Prize–winning because it would be a new [fundamental] particle, but this particular particle doesn't fit into the existing table of particles," he says. "The Standard Model, all of the existing elementary particles, forms sort of a closed book. [But] X17 interacts with matter much more weakly. And that's an indication that it's not part of the structure of the Standard Model. Its interactions with matter are through some other story we don't know yet."

The existence of this particle is anything but a certainty, however. The fact that only the Hungarian team has been able to spot it so far has raised alarm bells for some scientists, suggesting the data could be explained by a fault in its experimental setup. And Strassler notes that the supposed properties of the particle require it to have some odd characteristics. "To set up mathematical equations where you have a particle that interacts with neutrons and electrons more than with protons and neutrinos turns out to be not so simple to do," he says. "This just makes the story somewhat implausible."

That assessment does not mean other scientists are not trying to look for X17, however. The NA64 collaboration at CERN has previously tried and failed to find signs of the particle. But when upgrades to the LHC are complete, scientists plan to use the Large Hadron Collider beauty (LHCb) experiment, which studies another particle known as the beauty quark, to see if the mysterious X17 turns up. "The LHCb experiment, based on our study, should have been able to collect enough data [by 2023] in order to make a definitive statement about the X17 [particle]," Thaler says.

Alves and her colleagues are exploring the possibility of using Los Alamos to search for the particle, too. "We are investigating whether some of the studies that Los Alamos does for other purposes could also be repurposed to look for signs of this new particle," says Alves, who notes that their method of searching would be somewhat different from the Hungarian team's. "The Hungarians looked at two nuclear transitions, one in beryllium 8 and one in helium 4," she says. "We will be looking at the production of particles in neutron-capture reactions, when a neutron is captured by another nucleus, and in the process, it might emit things. The most common thing it might emit is a photon, but it could also possibly emit this new X17 particle."

Although skepticism remains high, there is still considerable excitement at the possibility of the X17 particle. It may take years until we know for sure if it really exists, but if it does, it would herald an entirely new branch of physics and a chance to peer into the unknown. "Of course, I'm confident [that it exists]," Krasznahorkay says. "But I've got strong critics."

—Jonathan O'Callaghan

Two Interstellar Intruders Are Upending Astronomy

Researchers grapple with the meaning of the first objects entering our solar system from beyond

By Alexandra Witze

Comet 2I/Borisov appears as a fuzzy blue dot in an image from the Hubble Space Telescope.

TERNATIONAL GEMINI OBSERVATORY/NSF'S NATIONAL OPTICAL-INFRARED ASTRONOMY RESEARCH LABORATORY/AURA

Alexandra Witze works for *Nature* magazine.

FROM THE TALLEST PEAK IN HAWAII TO A HIGH PLATEAU IN THE ANDES, SOME of the biggest telescopes on Earth pointed toward a faint smudge of light last December. The same patch of sky drew the attention of Gennady Borisov, an amateur astronomer in Crimea, and many other hobbyists who sacrificed proper sleep and dozed through their day jobs rather than miss this golden opportunity.

What they were looking for was a rare visitor making its closest approach to the sun. Now they have just months to grab as much information as they can from the object before it disappears forever into the blackness of space.

This chunk of rock and ice started its journey many light-years from Earth, millions of years ago. The object got kicked out of its own neighborhood by a violent gravitational push—maybe from a nearby planet, maybe from a passing star. Since then, it has been adrift in the space between the stars, eventually heading in our direction.

On August 30, Borisov first spotted the object in the predawn sky—it was glowing dimly, with a broad stubby tail. Later named Comet 2I/Borisov after its discoverer, it captured global attention because it's only the second object—aside from exotic dust particles—ever known to have entered our solar system from interstellar space. "This is my eighth comet, and so amazing," says Borisov, who adds it was "great luck that I got such a unique object."

It is remarkably different from the first interstellar interloper, which was a small, dark, rocky-looking object named 1I/'Oumuamua that whizzed past the sun in 2017. Together these two interstellar objects are rewriting what researchers know about the icy bodies—estimated to number as many as 1,026—that float unmoored throughout the Milky Way.

Among other things, 1I/'Oumuamua and 2I/Borisov have provided the first direct glimpse of the physics and chemistry of the squashed debris clouds that surround young stars and serve as the birthing grounds for planets. These samples from other planetary systems are allowing scientists to explore whether the solar system is unique or whether it shares building blocks with other planetary systems in the Milky Way.

Because astronomers spotted 2I/Borisov on its way into the solar system, they have many months to study it—unlike their fleeting glimpse of 'Oumuamua, which was discovered on its way out. As a result, they expect to learn much more from 2I/Borisov, such as what chemical compounds make up its icy heart. It is their best look yet at an object known to have formed around another star.

As telescopes keep probing the sky for faint, fast-moving objects, researchers expect that they will spot many more interstellar interlopers in coming years. "It's been so much fun to see this suddenly crack open and watch a new field develop," says Michele Bannister, a planetary astronomer at Queen's University Belfast in Northern Ireland.

DUSTY ORIGINS

Interstellar objects probably began their lives when icy grains clumped together in a disk of gas and dust around a young star. These are the same regions where planets grow from small nuclei and then ping-pong into different orbits around the star because of collisions and gravitational shoves.

The planets push through the icy rubble like a snowplow shouldering its way through a pile of hailstones. And modeling results suggest that the planets fling more than 90 percent of those "hailstones" out of their star's sphere of influence and into interstellar space. There they drift, as lonely scattered objects, until they happen to pass close enough to another star to be attracted by its gravity for a quick visit.

Astronomers had expected that the first interstellar object they saw would look like a typical comet. Most comets in the solar system hail from the distant realm known as the Oort cloud, a sort of cosmic deep freeze that lies roughly 1,000 times farther away from the sun than Pluto. Occasionally something perturbs one of these comets and sends it careering toward the sun; as it gets closer and warms up, its nucleus sprays out dust and gas that form a classic cometary tail.

But when the first interstellar visitor showed up, it didn't look like a conventional comet. Unlike them, 'Oumuamua was tiny—just 200 meters or so across—and rocky. Also, it was shaped like a cigar and tumbling end over end. That's about all scientists could work out before 'Oumuamua headed out of the solar system.

In contrast, 2I/Borisov looks like an ordinary comet—

and researchers are taking advantage of their time to study it. “We are keenly interested in seeing what the chemistry of this comet is, to see if it is different from those in the solar system,” says Karen Meech, an astrobiologist at the University of Hawaii, Honolulu.

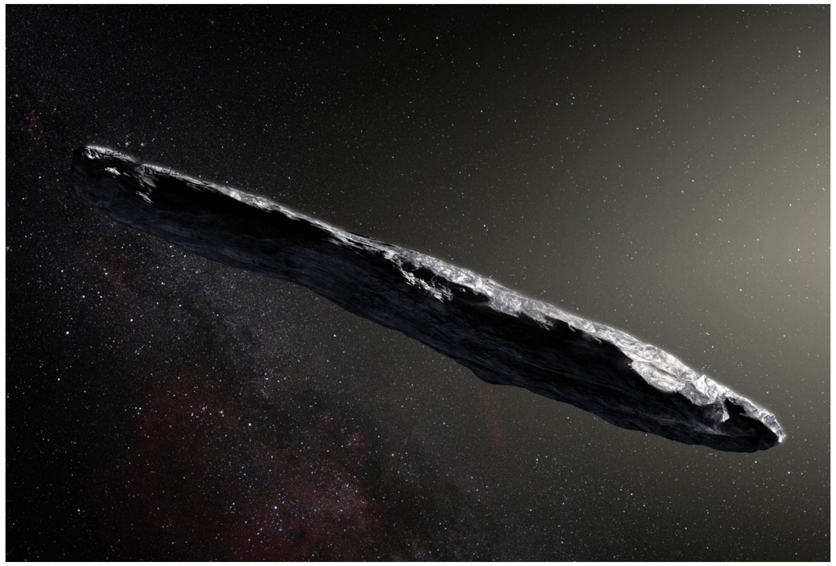
2I/Borisov is reddish in color and is steadily spraying out dust particles. Its nucleus is relatively small, perhaps just one kilometer across, but that’s not unheard of for solar system comets.

“After ’Oumuamua, we had to completely revise what we thought interstellar objects might be like,” says Matthew Knight, a comet specialist at the University of Maryland, College Park. “But now the second one coming through looks more or less, so far, like what we thought we might see from a comet ejected from another star. Now I feel a lot better.” That suggests that the star systems where other worlds form might be much like our own.

The discoveries are coming fast. Just three weeks after 2I/Borisov was first seen, astronomers trained the 4.2-meter William Herschel Telescope in Spain’s Canary Islands on it and spotted molecules of cyanide gas streaming off the comet. It was the first-ever detection of gas from an alien visitor to the solar system.

On October 11, 2019, another research team used a 3.5-meter telescope in New Mexico to detect oxygen coming off the comet. The oxygen probably came from water breaking apart in the comet’s nucleus, making this the first time that researchers have spotted water from another star system entering our own. Together the amounts of cyanide and water spraying from the comet aren’t surprising compared with what astronomers have seen from many other bodies.

Astronomers are watching keenly to see what other molecules, such as carbon monoxide, they can spot coming off 2I/Borisov as it gets closer to the sun and warms up, which will further reveal how similar—or how different—it is to comets in the solar system, says Maria Womack, an astronomer at the Florida Space Institute at the University of Central Florida.



An artist’s impression of ’Oumuamua.

Early observations also suggest that 2I/Borisov might contain relatively low amounts of carbon-chain molecules such as C2 and C3. About 30 percent of the comets in the solar system are similarly carbon-depleted. They typically come from relatively close to the sun, rather than from the far reaches of the Oort cloud.

As months pass and astronomers gather more observations of 2I/Borisov, they hope to be able to understand much more about the planet-forming disk where it originated. “It’s going to be really exciting to figure out what the building blocks of other systems are going to look like relative to ours,” says Malena Rice, a graduate student in astronomy at Yale University.

Researchers also hope to start unraveling how interstellar objects might have voyaged through deep space before showing up in the solar system. Estimates suggest the objects experience many forces as they orbit the center of the galaxy, including occasional encounters with other stars or nudges from galactic tides. Some scientists have tried to calculate which stars 1I/’Oumuamua and 2I/Borisov could have formed around, but tracing their orbits back is difficult—like trying to reconstruct which bar London pub crawlers started at from the final one they visited.

Other questions include when we can expect the next interstellar visitor and how different it might be from 1I/’Oumuamua and 2I/Borisov. Scientists didn’t expect two in such rapid succession after decades of fruitless searching. “I remain confused and astounded that the second object came along so fast,” says Robert Jedicke, an asteroid specialist at the University of Hawaii, who has worked to calculate the frequency of interstellar visitors. “They’re like buses,” says Alan Fitzsimmons, an astronomer at Queen’s University Belfast. “You wait decades for one to come along, and then two come along almost at once.”

Some astronomers are now poring through archival data to see whether objects spotted years ago were actually interstellar visitors that researchers did not recognize at the time. And the future rate of discovery is expected to rise—perhaps to one interstellar object a year—when the Large Synoptic Survey Telescope goes online in Chile in 2022, from where it will survey the entire visible sky every three nights. The European Space Agency has been working on a spacecraft concept, known as Comet Interceptor, that could visit future interstellar objects as they wing their way past the sun.

Once astronomers have 10 or 20 interstellar objects under their belts, they should have a much better picture of what these deep-space wanderers are really like. “Eventually we’ll be talking about the galaxy as something in which we are exchanging the products of planetary systems,” Bannister says. “It will be an entirely different way of doing astronomy.”

This article is reproduced with permission and was first published in Nature *on November 20, 2019*.

ESO/M. KORNMESSER

The Supercool Materials That Send Heat to Space

Paints, plastics and even wood can be engineered to stay cool in direct sunlight—but their roles in displacing power-hungry air conditioners remain unclear

By XiaoZhi Lim

A thermal image of a panel with a "supercool" coating outside Columbia University.

JYOTIRMOY MANDAL

XiaoZhi Lim is a freelance science reporter based in Singapore.

WHEN BUSINESSMAN HOWARD BISLA WAS tasked with saving a local shop from financial ruin, one of his first concerns was energy efficiency. In June 2018 he approached his local electricity provider in Sacramento, Calif., about upgrading the lights. The provider had another idea. It offered to install an experimental cooling system: panels that could stay colder than their surroundings, even under the blazing hot sun, without consuming energy.

Supercool panels on the roof of a shop in Sacramento, Calif.

AASWATH PATTABHI RAMAN

The aluminum-backed panels now sit on the shop's roof, their mirrored surfaces coated with a thin cooling film and angled to the sky. They cool liquid in pipes underneath that run into the shop and, together with new lights, have reduced electricity bills by around 15 percent. "Even on a hot day, they're not hot," Bisla says.

The panels emerged from a discovery at Stanford University. In 2014 researchers there announced that they had created a material that stayed colder than its surroundings in direct sunlight. Two members of the team, Shanhui Fan and Aaswath Raman, with their colleague Eli Goldstein, founded a start-up firm, SkyCool Systems, and supplied Bisla's panels. Since then, they and other researchers have made a host of materials, including films, spray paints and treated wood, that stay cool in the heat.

These materials all rely on enhancing a natural heat-shedding effect known as passive radiative cooling. Every person, building and object on Earth radiates heat, but the planet's blanketlike atmosphere absorbs most of it and radiates it back. Infrared rays between eight and 13 microns in wavelength, however, are not captured by the atmosphere and leave Earth, escaping into cold outer space. As far back as the 1960s, scientists sought to harness this phenomenon for practical use. But passive radiative cooling is noticeable only at night: in the daytime, sunlight bathes us in much more heat energy than we can send into space.

The new materials reflect a broad spectrum of light, in much the same way as mirrors or white paint do. In the crucial 8- to 13-µm part of the infrared spectrum, however, they strongly absorb and then emit radiation. When the materials point at the sky, the infrared rays can pass straight through the atmosphere and into space. That effectively links the materials to an inexhaustible heat sink, into which they can keep dumping heat without it coming back. As a result, they can radiate away enough heat to consistently stay a few degrees cooler than surrounding air; research suggests that temperature differences could exceed 10 degrees Celsius in hot, dry places. David Sailor, who leads the Urban Climate Research Center at Arizona State University, has termed them supercool materials.

These materials might not only save on electricity bills, enthusiasts say, but also reduce a surge in demand for power-hungry refrigeration and air-conditioning as the world warms. “My belief is that in four to five years, daytime radiative cooling systems will be the number-one technology for buildings,” says Mattheos Santamouris of the University of New South Wales in Sydney, Australia, who himself is working to improve such materials. “It is the air conditioner of the future.”

A few researchers have even suggested that the materials might be considered as part of a geoengineering strategy, to help Earth shed heat to counteract global rising temperatures. “Rather than trying to block the incoming heat from the sun, can we just make Earth emit more?” asks Jeremy Munday, a physicist at the University of California, Davis.

But many scientists are cautious about these ideas. So far theoretical estimates of how much electrical power can be saved have been based on data from small samples tested over short times. There are also doubts about the materials’ ability to work in a wide variety of climates and places. The cooling effect works best in dry climates and with clear skies; when it’s cloudy or humid, water vapor traps the infrared radiation. And the supercool materials might not last in all weathers or fit easily to all buildings.

Another unknown is whether consumers will embrace the idea. Even the simple measure of replacing worn-out roofs with reflective white ones to cool houses has not been widely adopted by homeowners, Sailor says. His modeling work, however, suggests that use of a supercool paint might double the energy savings compared with a white roof. “It’s a bit of a game changer—potentially,” he says.

OVERCOMING THE SUN

In 2012 Raman—who was completing his Ph.D. with Fan on materials for harvesting solar energy—stumbled on old studies about passive radiative cooling, an effect he’d not heard of. Realizing that no one had worked out how to use it under direct sunlight, he examined the optical properties a material would need to overcome the sun’s heat. It must reflect the solar spectrum in wavelengths from 200 nanometers to 2.5 µm even more effectively than white paint, which is already up to 94 percent reflective. And it must absorb and emit as close as possible to 100 percent of the wavelengths in the crucial 8- to 13-µm range.

All this could be done by engineering materials at the nanoscale, Raman and Fan thought. Creating structures smaller than the wavelengths of light that will pass through them should enhance the absorption and emission of some wavelengths and suppress that of others.

The group came up with the idea to etch patterns into surfaces and published it in 2013. Then the team submitted a proposal to the U.S. Advanced Research Projects Agency—Energy (ARPA-E) for funding to make it.

“I immediately thought, ‘Wow, I’d really like to see somebody actually do this,’ ” recalls Howard Branz, then a program director at ARPA-E in Washington, D.C., and now a technology consultant in Boulder, Colo. “There’d been a lot of nighttime radiative-cooling work, but to do it under broad, full sunlight is quite startling.”

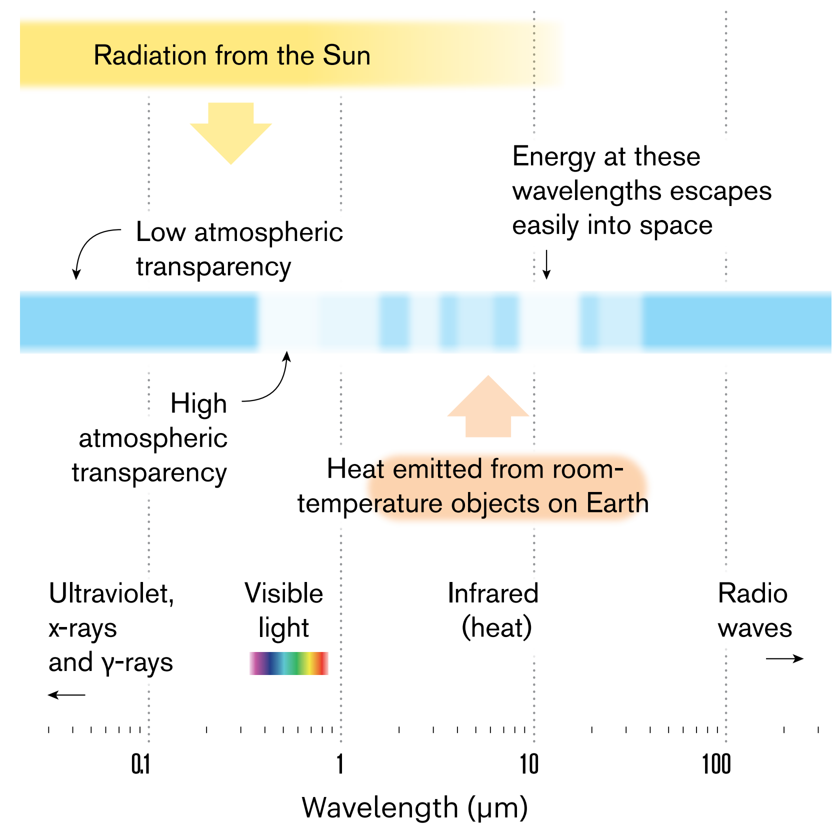
Branz gave the researchers U.S.$400,000 and a year. With so little time, the Stanford team decided to simplify the design and try layering materials in more familiar ways. To create something highly reflective, the researchers alternated four thin layers of materials that refract light strongly (hafnium dioxide) and weakly (silicon dioxide, or glass), a commonly used motif in optical engineering that works because of how light waves interfere as they pass through different layers. They used the same principle to amplify infrared emissions, depositing three thicker layers of the same materials on top.

When they tested their material outdoors, it stayed almost 5 degrees C cooler than the ambient temperature,

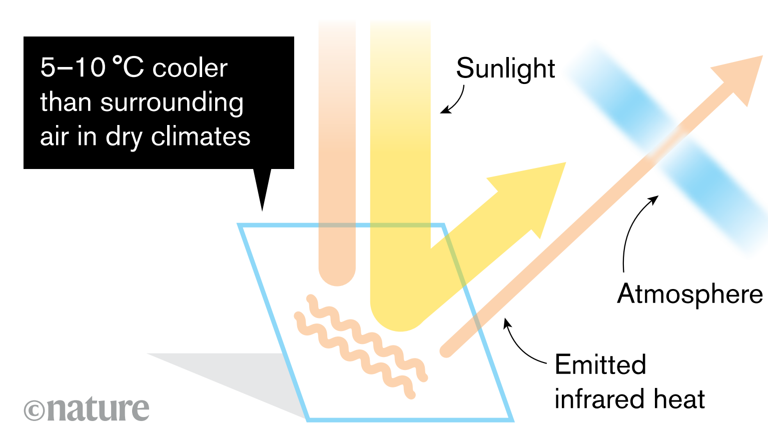
KEEPING THEIR COOL

‘Supercool’ materials stay colder than their surroundings even in direct sunlight, by emitting heat that can pass through the atmosphere and into space.

Transparent atmosphere
Earth’s blanket-like atmosphere absorbs most infrared wavelengths but is transparent to those between 8 and 13 microns.



Reflect and emit
Supercool materials are extremely reflective (even more so than white paint), so they are relatively unaffected by sunlight. They also absorb wavelengths between 8 and 13 µm, then emit them into space.



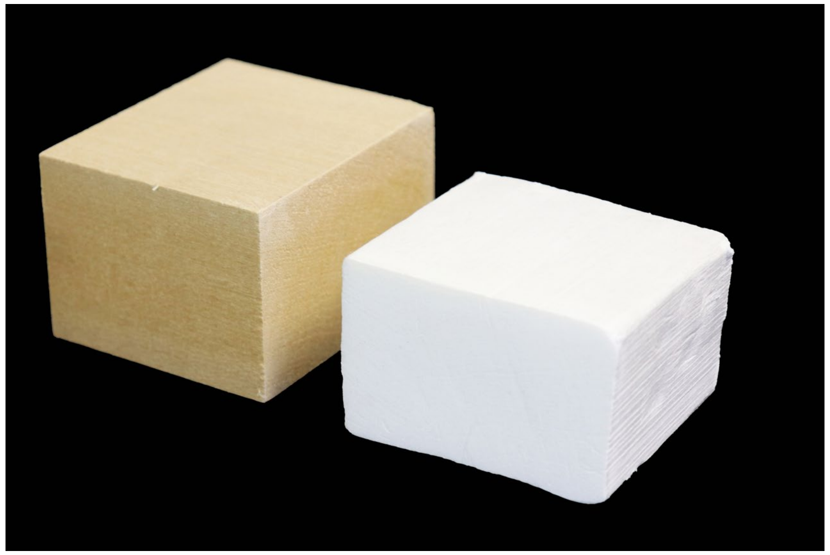
NATURE

even under direct sunlight of around 850 watts per square meter. (On a bright, clear day at sea level, the intensity of sunlight directly overhead reaches around 1,000 Wm^{-2}.)

After that success, ARPA-E funded other proposals for supercool materials. Among these was an idea from Xiaobo Yin and Ronggui Yang of the University of Colorado Boulder, who wanted to make materials at large scale. They chose to work with cheap plastic and glass. Glass spheres of the right size—a few microns across—emit strongly in the 8- to 13-µm range. Embedding these in a 50-µm-thick film of transparent polymethylpentene—a plastic used in some lab equipment and cookware—and backing this with reflective silver was sufficient to create a supercool material. More important, the researchers could make the film with roll-to-roll technology that churns out five meters per minute.

It turned out that many materials exhibit supercooling if structured in the right way—not just exotic or speciality ones. In 2018 researchers at Columbia University and Argonne National Laboratory in Batavia, Ill., reported a supercool paint, based on a sprayable polymer coating. Many polymers naturally emit in the infrared 8- to 13-µm range because their chemical bonds, such as those between carbon atoms or between carbon and fluorine, eject packets of infrared light when they stretch and relax, explains team member Yuan Yang. The key was to strengthen the polymers' ability to reflect sunlight.

Yang's student Jyotirmoy Mandal—who is now a postdoctoral researcher in Raman's lab at the University of California, Los Angeles—dissolved fluorinated polymer precursors in acetone with a small amount of water. This mixture can be sprayed onto a surface to create an even polymer coating with tiny water droplets dispersed through it. The volatile acetone dries first, followed by the water droplets, leaving behind pores that fill with air. The overall result is a white coating with pores inside that reflect the sunlight, Yang says.



Natural wood (*left*) next to treated wood that sheds heat.

Last May the Colorado team reported another material: a cooling wood, created with Liangbing Hu and Tian Li of the University of Maryland, College Park. Just like polymers, wood contains chemical bonds that emit the right kind of infrared radiation, Li says. A net cooling effect can be achieved by chemically removing a rigid component called lignin to make the wood reflective and compressing the product to align its cellulose fibers and amplify infrared emissions.

Scientists have also made supercool thin films from polydimethylsiloxane (PDMS), a silicone material found in products such as lubricants, hair conditioners and Silly Putty, by spraying it onto a reflective backing. As recently as last August, Zongfu Yu of the University of Wisconsin–Madison and Qiaoqiang Gan of the State University of New York at Buffalo found that an aluminum film spray-coated with a 100-µm layer of PDMS stayed 11 degrees C cooler than ambient air when placed in a campus parking lot in the middle of the day.

STAYING COOL

Almost all the research teams have patented their inventions and are now trying to market them. Gan is working with industry partners, which he declined to name, to commercialize the PDMS–aluminum film. Columbia University has licensed its supercool paint to New York start-up MetaRE, founded by Mandal and Yang's Columbia collaborator Nanfang Yu, for development. MetaRE is also working with industry to develop the paint for roofing, refrigerated transportation, storage and textile applications, says chief executive April Tian. The product is "highly competitive" with conventional paints, she says.

Other start-ups have highlighted how much electricity their products could save. Fan and Raman have developed a proprietary system for SkyCool Systems' panels. In 2017 they predicted that the system could reduce the amount of electricity a building uses for cooling by 21 percent during the summer in hot, dry Las Vegas. Raman says the panels will pay for themselves in three to five years. Yin and Ronggui Yang have started a company in Boulder called Radi-Cool, to commercialize the glass-embedded plastic. In January 2019 they reported that the material could reduce electricity consumption for cooling in the summer by 32 to 45 percent if it were integrated with water chillers in commercial buildings in Phoenix, Miami and Houston. Hu, meanwhile, has licensed the supercool wood material to a Maryland-based firm he co-founded called InventWood. He predicts that it could save 20 to 35 percent of cooling energy across 16 U.S. cities.

But these estimates are based on experiments and models that are too limited to be extrapolated to entire buildings in cities, cautions Diana Ürge-Vorsatz, an environmental scientist at the Central European University in Budapest, who specializes in climate change mitigation. Actual energy savings and how quickly a supercool material will pay for itself will depend on a building's structure, location and weather conditions, Yin adds.

Location is the biggest obstacle. "There are certain geo-

LIANGBING HU, INVENTWOOD

graphical regions where it just won't work, because the atmosphere isn't dry enough," says James Klausner, a mechanical engineer at Michigan State University, who served as an ARPA-E program director after Branz and has funded some proposals in the field. But that's not too off-putting, he says, because the regions where the effect works well are arid areas such as the southwestern U.S. or the Middle East, which have high demands for air-conditioning.

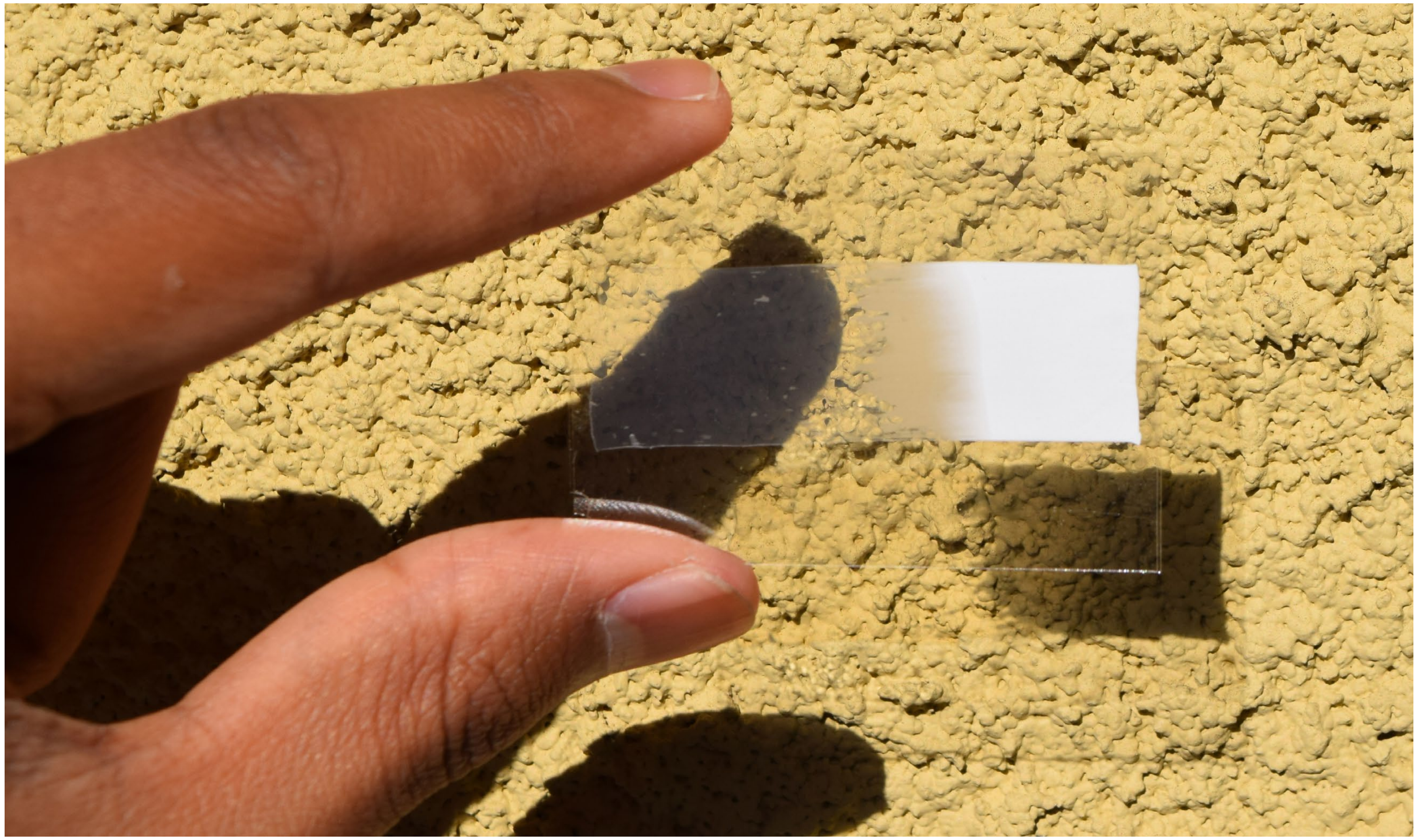
Another challenge is that radiative-cooling systems might increase heating costs in winter. To address this problem, Santamouris is trying to introduce a liquid layer on top of the supercool materials that would freeze when the temperature drops low enough. Once the liquid solidifies, radiation can no longer escape to space, so the cooling effect is cut off. And last October, Mandal and Yang reported another way to stop overcooling. If they fill the pores of their polymer coating with isopropanol, the coating starts to trap heat rather than shedding it. This can be reversed by blowing air through the pores to dry them out.

There's another issue: the materials achieve supercooling only if they can send their radiation directly to the cold heat sink of outer space. In an urban setting, buildings, people and other objects can get in the way, absorbing the heat and reemitting it. The best-performing materials currently remove heat at a rate of around 100 Wm^{-2}. Gan and Yu hope to double that by positioning their films perpendicular to the roof so that emissions can escape from both surfaces. But this will require adding materials around the films that can reflect the emissions up into the sky.

Researchers are looking at other ways to increase the materials' cooling ability. Last October, Evelyn Wang of the Massachusetts Institute of Technology and her colleagues reported that covering a radiative-cooling film with a light, insulating aerogel kept the structure 13 degrees C cooler than its surroundings at noon in the dry Atacama Desert in Chile, compared with just 1.7 degrees C without the aerogel. The aerogel concept could be used with other supercool materials, she says.

Dreams of using the supercool materials for geoengineering to mitigate global warming seem further off and unlikely from a practical perspective. Last September, Munday used "back-of-the-envelope calculations" to suggest that current rising temperatures could be balanced by covering 1 to 2 percent of Earth's surface with existing materials that generate around 100 Wm^{-2} of cooling power in the daytime. But because solar panels still don't reach that level of cover after decades of development, it seems impossible that this nascent technology could do so in time to be useful, says Mark Lawrence, a climate scientist at the Institute for Advanced Sustainability Studies in Potsdam, Germany. As with any geoengineering proposal, Munday acknowledges the possible unintended consequences of disturbing precipitation patterns and local climates—which Ürge-Vorsatz agrees are likely to be a problem.

Still, passive radiative cooling might have many benefits, Raman says. It could, for instance, help to stop solar panels losing efficiency as the temperature rises. And all electricity generation and conversion processes produce waste heat, Yin says, even if they use renewable energy rather than fossil fuels. "This is the only technology that



A porous white paint can be used to cool buildings in summer; when wetted with alcohol, it turns transparent and traps heat (*left side*), which might warm buildings in winter.

JYOTIRMOY MANDAL

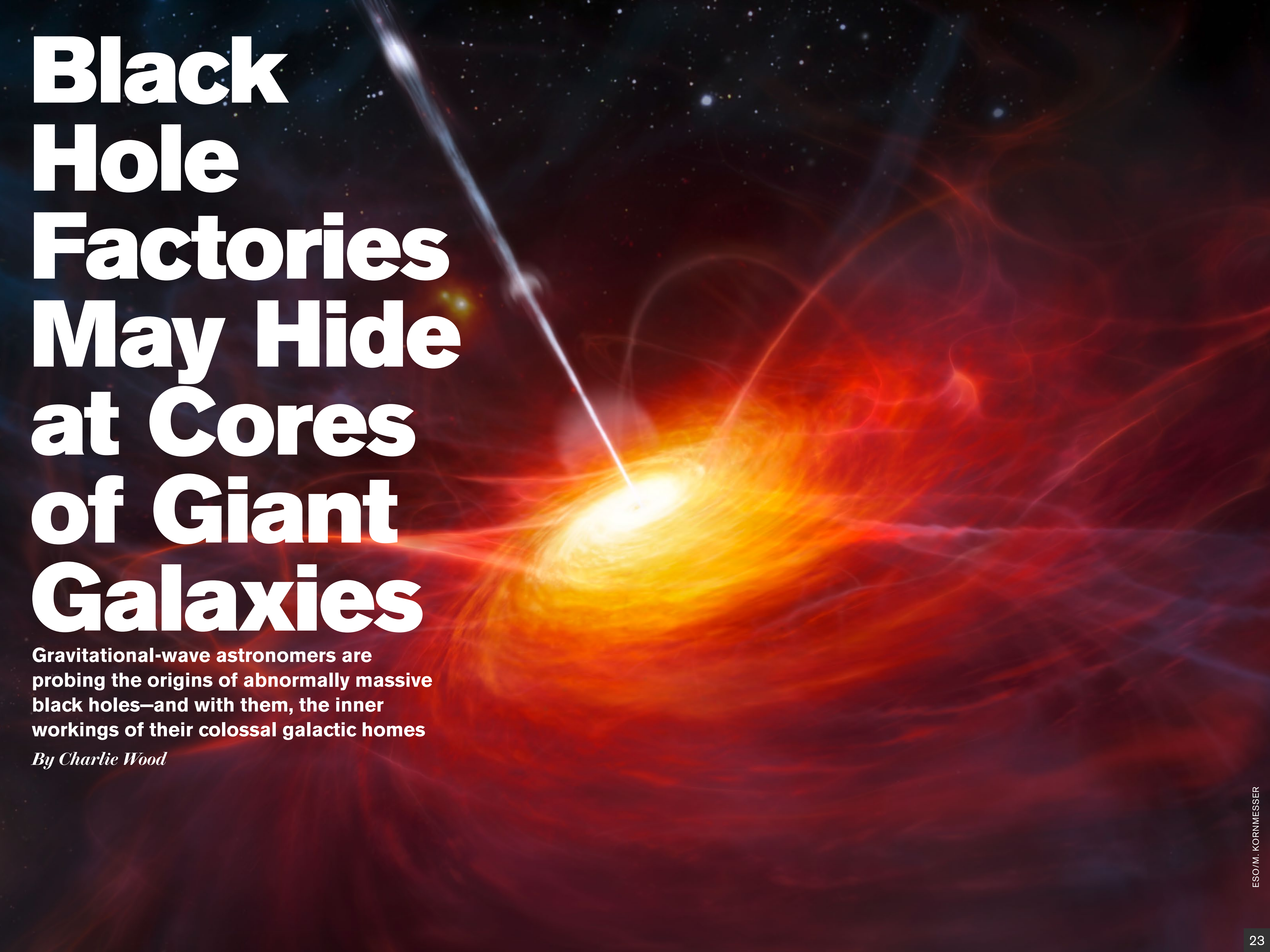
harnesses all this wasted heat and dumps it back to space," he says.

ELECTRICITY AT NIGHT, WATER IN THE DAY

Materials that dump heat from Earth into space could have unexpected applications. They could, for instance, make it easier to harvest water from the atmosphere in the daytime. At night, water vapor condenses into dew on surfaces that lose heat to the clear night sky, an effect harnessed for centuries to capture water. Zongfu Yu of the University of Wisconsin–Madison and Qiaoqiang Gan of the State University of New York at Buffalo found that an aluminum film coated in polydimethylsiloxane could not only stay cool but also enhance water condensation during the day. The pair of scientists started a company in Buffalo called Sunny Clean Water to commercialize the device.

The temperature difference between a supercool material and its surroundings could also be used to generate electricity at night—unlike solar panels, which work only in the day. Last September, Raman, Fan and Li managed to produce a trickle of electricity—milliwatts per square meter—from such a nocturnal device. That shows it's possible to make at least enough electricity at night to power a small LED. That's an exciting proof of concept, says Howard Branz, a technology consultant in Boulder, Colo. But electricity from solar panels can be stored in batteries to generate much larger flows of electricity, so it's not yet clear whether the idea will be useful.

This article is reproduced with permission and was first published in Nature *on December 31, 2019.*



Black Hole Factories May Hide at Cores of Giant Galaxies

Gravitational-wave astronomers are probing the origins of abnormally massive black holes—and with them, the inner workings of their colossal galactic homes

By Charlie Wood

ESO/M. KORNMESSER

Charlie Wood is a journalist covering discoveries in the physical sciences both on and off the planet. His writing has appeared in *Quanta Magazine*, *Popular Science*, and elsewhere.

In 2015, when scientists, for the first time ever, directly detected gravitational waves–ripples in spacetime–from colliding black holes, the result came as a shock to some astronomers.

Based on previous studies of black holes using x-rays, many experts expected each member of a merging pair would typically weigh about 10 times the sun's mass, but the 2015 merger featured twin giants three times that heavy. And the Laser Interferometer Gravitational-wave Observatory (LIGO), which enabled the discovery, has been spotting bizarrely big pairs ever since.

Black holes can certainly get supermassive—leviathans weighing billions of suns lurk at the hearts of most large galaxies. The question is: How could they grow so huge? Much of their bulk must be acquired after birth as they feast on gas and stars, but some theories suggest that mergers or chains of mergers may form a supermassive black hole's initial seed. Black hole matchmaking in the loneliness of space is not easy, though, so astrophysicists still puzzle over what circumstances could bring the objects together.

An emerging theory holds that LIGO's heavyweights arise near the cores of colossal galaxies, where violently incandescent disks of gas whirl around central supermassive black holes. Thanks to that omnipresent gas, these so-called active galactic nuclei (AGNs) could be factories for building big black holes out of smaller ones. If so, gravitational-wave detectors such as LIGO should be able to tease out signs of the hierarchical assembly of these swollen giants. Although the overall number of detections remains too low for conclusive classifications, some researchers have recently pointed to two hefty mergers as tantalizing hints of what AGN-facilitated black hole fusions might look like—a step toward using gravitational waves to study not only black holes but also the stars and galaxies that birthed them.

Figuring out how black hole pairs form "tells us a lot about stars," says Maya Fishbach, a LIGO member, who was not involved in the recent research. "Stars are the building blocks of galaxies. They are the atoms of astronomy."

Run-of-the-mill black holes, born from the remnants of an exploded star, would typically start off in orbits skewed against the plane of an AGN's disk of gas. Each time they would dip into that disk, however, friction would slow them and tip their paths in line with the disk. Once embedded, uneven pressures may shepherd those black holes from their initially scattered locations into special rings around the galaxy's central black hole—a trapping process analogous to the one that forms the seeds of planets in dusty disks around a single star but with black holes instead of microscopic piles of dust.

Imre Bartos, a LIGO collaboration member at the University of Florida, estimates that these galactic "migration traps" can quickly collect tens of thousands of black holes, many of which will get close enough to pair off. Then friction from the lingering gas would drive them to collide 1,000 times earlier than they otherwise would in empty space. "They will be forced to merge together," he says. It's like "a black hole assembly line, where we are adding black holes one after another."

Most of the universe's black hole mergers are thought to be one-off finales between stellar binaries—star couplets that were born, lived and died together—of moderate mass. But if AGN disks really are cranking out large black holes made from small ones, that population should eventually stand out in two ways from gravitational-wave observations.

Now in its third observing run, LIGO announced dozens of preliminary gravitational-wave candidates for astronomical observation last year. But only 10 black hole mergers appear in the published catalog from its first two observing runs, and nine of them seem to have come from pairs that spun slowly or not at all. A twirling crash—as would happen in an AGN disk—would, however, spin merging black holes up, typically causing subsequent generational mergers to spin even faster. Specifically, two black holes of even mass should spin at 70 percent of a theoretical top speed after colliding, so Bartos and his colleagues are on the lookout for collisions between already whirling dervishes.

They are also watching for mammoth mergers. Stars above a certain size are thought to undergo supernovae so savage that they blow their core to smithereens, preventing them from collapsing to form black holes. Theorists are unsure where the limit lies, but many expect the mass of stellar black holes to top out around that of 50 suns. "If you see a single event with 80 solar masses," says Davide Gerosa, an astrophysicist at the University of Birmingham in England, "that's a strong signature of some exotic formation channel." Black hole nurseries would be one explanation for heavy outliers.

Recent data, however, may complicate that simple picture. Last November astronomers announced the discovery of what seems to be a huge black hole born together with a partner star. If the current controversial estimate of the former's mass—roughly 70 suns—stands, then the 50-sun limit may be a less clear-cut line for generational mergers. "I don't think we've been hitting this problem hard enough," Gerosa says.

Globular clusters, small clumps of stars within a galaxy, are another possible cosmic construction site for abnormally heavy, quickly spinning black holes. In these star-rich regions, black holes presumably could form dense crowds in which they would occasionally bump into one another. But recent research by Gerosa and one of his colleagues found that the recoil from such collisions would likely eject most pairs from the globular cluster, preventing them from finding future companions to merge with. Larger groups of stars, such as those within AGN disks, are more likely locations for strings of mergers, Gerosa says, because black holes there require much more recoil to escape.

After years of theoretical speculation, some researchers are starting to see hints of what may be an extra heavy population beginning to reveal itself. LIGO's heaviest catalogued merger, GW170729, is exactly the kind an AGN disk would produce, Bartos and his colleagues proposed in *Physical Review Letters* in November. In that event, one of the black holes weighed roughly 50 suns, and a measure of the pair's collective spin clocked them turning at about 40 percent of top speed before the merger—a hint that that an earlier collision could have spun them up.

"Stars are the building blocks of galaxies. They're the atoms of astronomy."
—Maya Fishbach

Another candidate AGN-driven event appeared last October, when researchers at the Institute for Advanced Study in Princeton, N.J., posted a preprint paper announcing two possible mergers from LIGO's data that, while not meeting LIGO's criteria for publication, may well be genuine. Called GW170817A, and with a mass of roughly 56 suns and a combined premerger spin of 50 percent the maximal value, this candidate merger matches predictions for an AGN collision even more closely than GW170729, according to a not yet peer-reviewed preprint study posted on arXiv.org in late November. "This is exactly the same kind of event," Bartos says.

Neither candidate is a smoking gun for an AGN black hole assembly line, however. GW170817A only registered in one of LIGO's two detectors—a potential sign that it was a false alarm arising from contaminating noise on Earth rather than some far-off celestial cataclysm. Moreover, because only a small fraction of the universe's stars reside in AGNs, Bartos's group concluded that the suggestive properties of these two mergers are just as likely to reflect normal binary black holes that just happened to be extra heavy and to spin extra fast as they are AGN black holes.

Other researchers agree that AGN disks could occasionally smack black holes together but stress that the community will need more data, as well as better predictions, to conclusively prove the reality of this rare collision type or others. "I don't think there's anyone who would be able to pick one side, because they'll know that if they're proven wrong, it will be in, like, a year," Fishbach says.

Regardless the ability to distinguish one-off stellar binaries from AGN assembly lines and other putative production mechanisms for black hole mergers is coming. As LIGO's catalog swells, categories based on spin and mass should become much clearer. Bartos suggests that traditional astronomy based on light rather than gravitational waves could help, too. Gravitational crashes that align in the sky with known AGNs will supply further hints. And if astronomers can use their telescopes to rapidly observe gravitational-wave sources with AGN signatures as they are detected, a recent publication in the *Astrophysical Journal Letters* proposes, they may glimpse flashes of light hypothesized to come from postcollision shock waves in the gas.

In the midst of building this new black hole taxonomy, astrophysicists are already brainstorming what they will be able to do with it. Light reveals what a galaxy is made of, says Katelyn Breivik, an astrophysicist at the Canadian Institute for Theoretical Astrophysics, but gravitational waves may unmask its more subtle dynamics. "If you have black holes that are embedded in these disks," she says, "they are like literal gravitational probes into the shape of these disks," revealing mass and motion.

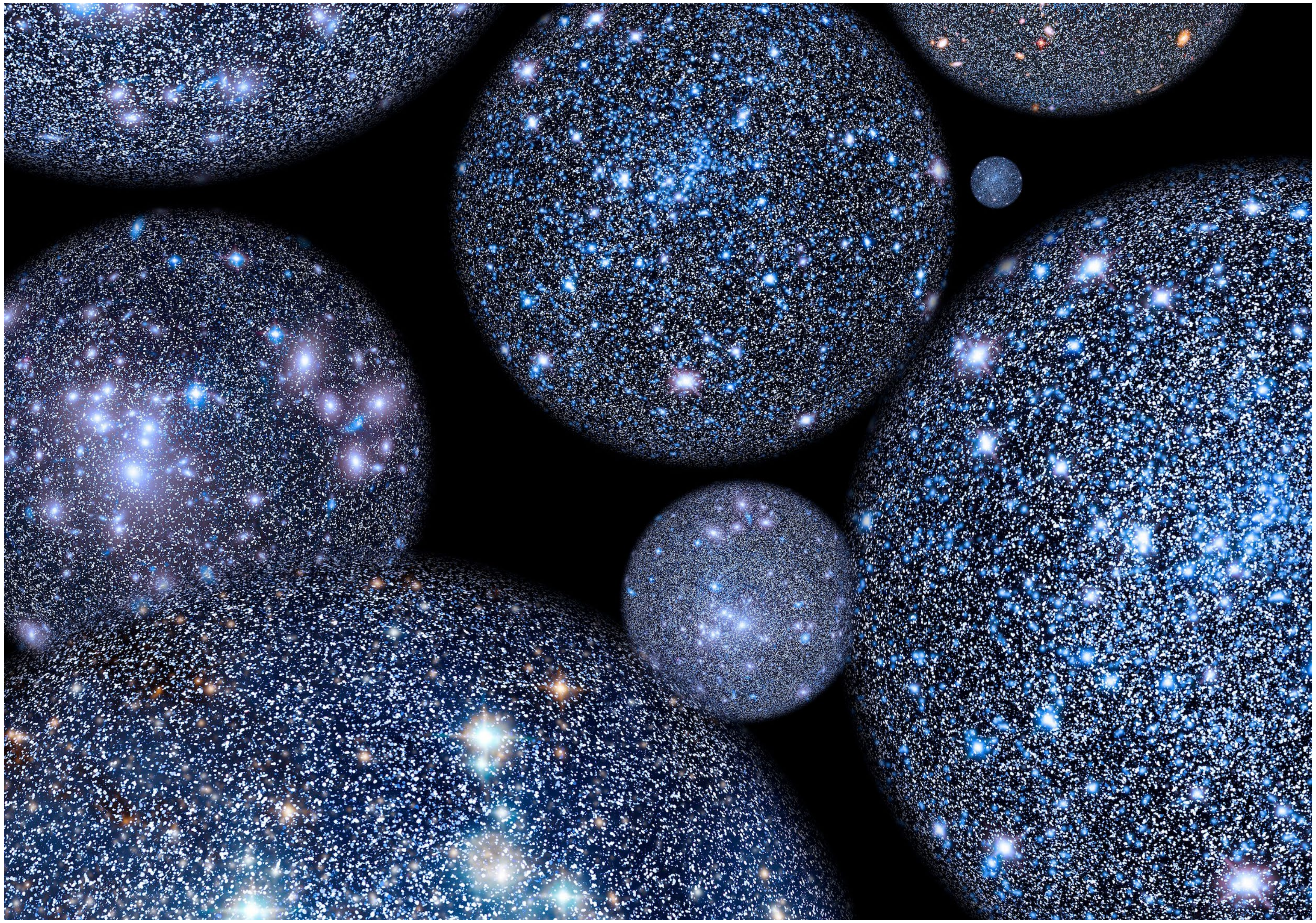
While those probes have yet to materialize, LIGO's big, spinning black holes encourage Bartos that they are not far off. "I was used to predicting the far future," he says. "Coming from there to having these black holes that basically reproduce what you're predicting is superexciting."

Tom Siegfried is author of *The Number of the Heavens: A History of the Multiverse and the Quest to Understand the Cosmos* (Harvard University Press, 2019).

OBSERVATIONS

Long Live the Multiverse!

The idea that our universe is just part of a much vaster cosmos has a long history—and it's still very much with us



VICTOR DE SCHWANBERG *GETTY IMAGES*

Ernst Mach, the Austrian physicist-philosopher of the late 19th century, famously denied the reality of atoms. "Have you ever seen one?" he mockingly asked of atom advocates. Today many scientists speak with similar derision about the idea that the visible universe is not alone, but rather is only one of many universes—a single bubble in a froth of cosmic carbonation known as the multiverse.

You can't see these other universes, so the idea is not testable, multiverse opponents allege. Besides, invoking a multiplicity of universes to explain reality is a violent violation of Occam's razor, the philosophical principle favoring simple explanations over complicated ones.

But Mach, of course, was wrong about atoms. And throughout history, those arguing against multiple universes have invariably turned out to be wrong as well. In fact, the first proponents of the multiverse were the same ancient Greeks who proposed the existence of atoms. Leucippus and Democritus believed that their atomic theory required an infinity of worlds ("world" being synonymous with "universe"). Their later follower, Epicurus of Samos, also professed the reality of multiple worlds. "There are infinite worlds both like and unlike this world of ours," he averred.

Aristotle, however, argued strongly that logic required one universe only. His view prevailed until 1277, when the bishop of Paris declared that medieval scholars teaching Aristotle's view would be excommunicated—for denying God's power to create as many universes as he wanted to. Centuries of debate followed. Some argued that God could create more universes but probably didn't; others maintained that reality comprised a "plurality of worlds."

In the 16th century, Copernicus turned the issue on its head. Instead of Aristotle's universe (Earth in the middle, surrounded by planets affixed to rotating spheres), Copernicus placed the sun in the middle, with the planets (including Earth) in orbit. The universe became a solar system, bounded by a sphere of stars. Shortly thereafter Thomas Digges in England redrew the Copernican picture, with stars littered throughout distant space rather than fixed to a single sphere. That raised the possibility of multiple solar system universes scattered throughout the heavens. Giordano Bruno, perhaps influenced by Digges, proclaimed that God is glorified "not in one, but in countless suns; not in a single earth, a single world, but in a thousand thousand, I say in an infinity of worlds."

Bruno's contemporary, the famed astronomer Johannes Kepler, didn't like that idea. He conceived the universe as the solar system. Similar worlds beyond our sight are not scientific. "If they are not seen," Kepler declared, "they for this reason are not pertinent to astronomy." Anything beyond what's visible, he insisted, "is superfluous metaphysics"—a view strikingly similar to the attitude of many toward the multiverse today.

Kepler was wrong, of course. Later telescopes revealed a multitude of stars at great distances, congregating in a lens-like disk, the Milky Way galaxy (of which the sun was one member). Just as Copernicus showed that the Earth is part of a solar system universe, the solar system became just one of many such "universes" in the Milky Way. Once again, the universe was redefined—no longer a set of spheres surrounding the Earth, or a set of planets orbiting the sun, but now a vast disk of stars surrounded by emptiness.

Except in that emptiness appeared fuzzy blobs, called nebulae. Immanuel Kant and others speculated that those blobs were actually galaxies themselves, just very far away—island universes, to use the term coined in the 1840s by the American astronomer Ormsby MacKnight Mitchel. This new vision of a multiverse also met with ridicule. "No competent thinker" believed in island universes, the astronomy writer Agnes Clerke declared at the end of the 19th century. It was an idea that had withdrawn "into the region of discarded and half-forgotten speculations."

But once again, the multiverse prevailed. In 1924 Edwin Hubble reported proof that some of those fuzzy nebulae, such as Andromeda, were indeed island universes as grand as the Milky Way. Hubble pioneered today's current definition of the universe as a vast expanding bubble of spacetime populated by billions and billions of such galaxies.

In the 1980s, a new explanation for how that universe came to be, called inflationary cosmology, revived the multiverse question in a novel way. If the initial big bang launching our universe into existence was followed by a burst of extremely rapid expansion (inflation), that same inflationary event could have recurred in other parts of space. If inflation theory turns out to be correct, our bubble would then be only one of many.

Of course, just because multiverse advocates have been right historically doesn't mean that they will certainly be right again this time. But multiverse opponents are certainly wrong to say that the multiverse idea is not science because it is not testable. The multiverse is not a theory to be tested, but rather a prediction of other theories that can be tested. Inflationary cosmology has, in fact, already passed many tests, although not yet enough to be definitively established.

For that matter, it's not necessarily true that other universes are in principle not observable. If another bubble collided with ours, telltale marks might appear in the cosmic background radiation left over from the big bang. Even without such direct evidence, their presence might be inferred by indirect means, just as Einstein demonstrated the existence of atoms in 1905 by analyzing the random motion of particles suspended in liquid.

Today, atoms actually can be "seen," in images produced by scanning tunneling microscopes. Atoms did not suddenly become real when first imaged, though; they had been legitimate scientific entities for two and a half millennia. Multiple universes have been a topic of philosophical-scientific discussion for just as long.

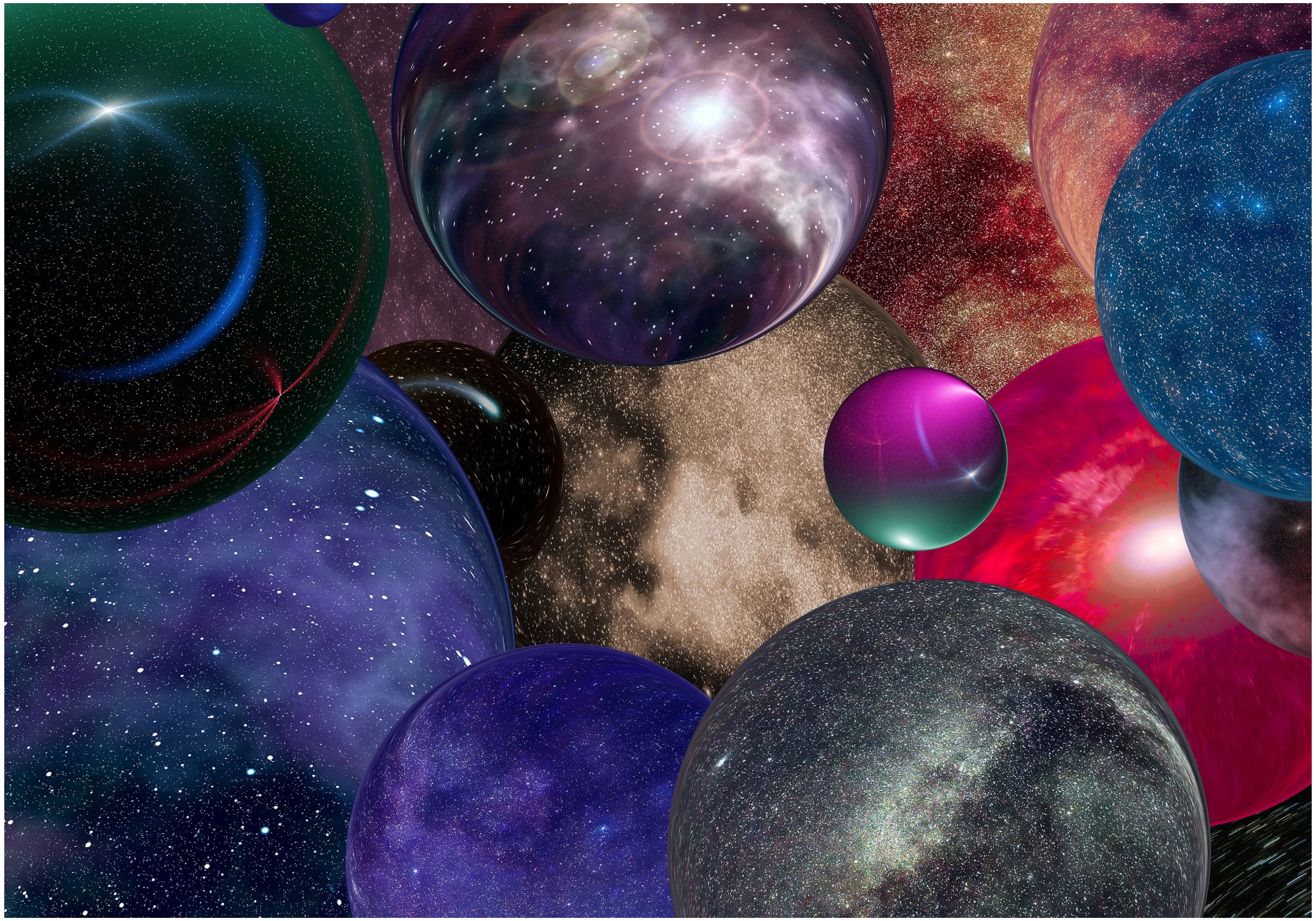
As for Occam's razor, you could check with William of Occam himself, the 14th-century philosopher who articulated that principle. In his day, he was the most enthusiastic of the advocates for a multiplicity of worlds.

John Horgan directs the Center for Science Writings at the Stevens Institute of Technology. His books include *The End of Science, The End of War* and *Mind-Body Problems*, available for free at mindbodyproblems.com.

SPACE

Multiverse Theories Are Bad for Science

New books by a physicist and science journalist mount aggressive but ultimately unpersuasive defenses of multiverses



IGOR SOKALSKI *GETTY IMAGES*

In 1990 I wrote a bit of fluff for *Scientific American* about whether our cosmos might be just one in an "infinitude," as several theories of physics implied. I titled my piece "Here a Universe, There a Universe …" and kept the tone light because I didn't want readers to take these cosmic conjectures too seriously. After all, there was no way of proving, or disproving, the existence of other universes.*

Today physicists still lack evidence of other universes or even good ideas for obtaining evidence. Many nonetheless insist our cosmos really is just a mote of dust in a vast "multiverse." One especially eloquent and passionate multiverse theorist is Sean Carroll. His faith in the multiverse stems from his faith in quantum mechanics, which he sees as our best account of reality.

In his book *Something Deeply Hidden*, Carroll asserts that quantum mechanics describes not just very small things but everything, including us. "As far as we currently know," he writes, "quantum mechanics isn't just an approximation to the truth; it is the truth." And however preposterous it might seem, a multiverse, Carroll argues, is an inescapable consequence of quantum mechanics.

To make his case, he takes us deep into the surreal quantum world. Our world! The basic quantum equation, called a wave function, shows a particle—an electron, say—inhabiting many possible positions, with different probabilities assigned to each one. Aim an instrument at the electron to determine where it is, and you'll find it in just one place. You might reasonably assume that the wave function is just a statistical approximation of the electron's behavior, which can't be more precise, because electrons are tiny and our instruments crude. But you would be wrong, according to Carroll. The electron exists as a kind of probabilistic blur until you observe it, when it "collapses," in physics lingo, into a single position.

Physicists and philosophers have been arguing about this "measurement problem" for almost a century now. Various other explanations have been proposed, but most are either implausible, making human consciousness a necessary component of reality, or kludgy, requiring ad hoc tweaks of the wave function. The only solution that makes sense to Carroll—because it preserves quantum mechanics in its purest form—was proposed in 1957 by a Princeton graduate student, Hugh Everett III. He conjectured that the electron actually inhabits all the positions allowed by the wave function but in different universes.

This hypothesis, which came to be called the many-worlds theory, has been refined over the decades. It no longer entails acts of measurement or consciousness (sorry, New Agers). The universe supposedly splits, or branches, whenever one quantum particle jostles against another, making their wave functions collapse. This process, called "decoherence," happens all the time, everywhere. It is happening to you right now. And now. And now. Yes, zillions of your doppelgangers are out there at this very moment, probably having more fun than you. Asked why we don't feel ourselves splitting, Everett replied, "Do you feel the motion of Earth?"

"As far as we currently know, quantum mechanics isn't just an approximation to the truth; it is the truth."
—Sean Carroll

Carroll addresses the problem of evidence, sort of. He says philosopher Karl Popper, who popularized the notion that scientific theories should be precise enough to be testable, or falsifiable, "had good things to say about" Everett's hypothesis, calling it "a completely objective discussion of quantum mechanics." (Popper, I must add, had doubts about natural selection, so his taste wasn't irreproachable.)

Carroll proposes, furthermore, that because quantum mechanics is falsifiable, the many-worlds hypothesis "is the most falsifiable theory ever invented"—even if we can never directly observe any of those many worlds. The term "many," by the way, is a gross understatement. The number of universes created since the big bang, Carroll estimates, is two to the power of 10 to the power of 112. Like I said, an infinitude.

And that's just the many-worlds multiverse. Physicists have proposed even stranger multiverses, which science writer Tom Siegfried describes in his book *The Number of the Heavens*. String theory, which posits that all the forces of nature stem from stringy thingies wriggling in nine or more dimensions, implies that our cosmos is just a hillock in a sprawling "landscape" of universes, some with radically different laws and dimensions than ours. Chaotic inflation, a supercharged version of the big bang theory, suggests that our universe is a minuscule bubble in a boundless, frothy sea.

In addition to describing these and other multiverses, Siegfried provides a history of the idea of other worlds, which goes back to the ancient Greeks. (Is there anything they didn't think of first?) Acknowledging that "nobody can say for sure" whether other universes exist, Siegfried professes neutrality on their existence. But he goes on to construct an almost comically partisan defense of the multiverse, declaring that "it makes much more sense for a multiverse to exist than not."

Siegfried blames historical resistance to the concept of other worlds on Aristotle, who "argued with Vulcan-like assuredness" that Earth is the only world. Because Aristotle was wrong about that, Siegfried seems to suggest, maybe modern multiverse skeptics are wrong, too. After all, the known universe has expanded enormously since Aristotle's era. We learned only a century ago that the Milky Way is just one of many galaxies.

The logical next step, Siegfried contends, would be for us to discover that our entire cosmos is one of many. Rebutting skeptics who call multiverse theories "unscientific" because they are untestable, Siegfried retorts that the skeptics are unscientific because they are "presupposing a definition of science that rules out multiverses to begin with." He calls skeptics "deniers"—a term usually linked to doubts about real things, like vaccines, climate change and the Holocaust.

I am not a multiverse denier, any more than I am a God denier. Science cannot resolve the existence of either God or the multiverse, making agnosticism the only sensible position. I see some value in multiverse theories. Particularly when presented by a writer as gifted as Sean Carroll, they goad our imaginations and give us intimations of infinity. They make us feel really, really small—in a good way.

But I'm less entertained by multiverse theories than I once was, for a couple of reasons. First, science is in a slump, for reasons both internal and external. Science is ill served when prominent thinkers tout ideas that can never be tested and hence are, sorry, unscientific. Moreover, at a time when our world, the real world, faces serious problems, dwelling on multiverses strikes me as escapism—akin to billionaires fantasizing about colonizing Mars. Shouldn't scientists do something more productive with their time?

Maybe in another universe Carroll and Siegfried have convinced me to take multiverses seriously, but I doubt it.

Caleb A. Scharf is director of astrobiology at Columbia University. He is author and co-author of more than 100 scientific research articles in astronomy and astrophysics. His work has been featured in publications such as *New Scientist*, *Scientific American*, *Science News, Cosmos Magazine, Physics Today* and *National Geographic*.

LIFE, UNBOUNDED

The First Alien

When did we start talking about life from elsewhere?

C. SCHARF 2019

In an age where we take the search for signs of life beyond the confines of Earth very seriously—as a scientific frontier—it's interesting to consider a little of the history of the very concept itself. This isn't entirely frivolous. The ways that we think about the natural world and the ways that we formulate our questions are always going to be biased and orientated by our preconceptions and speculations. Having a better appreciation of those predispositions may help us avoid obvious pitfalls.

Besides, the history of our ideas about aliens is plain fascinating in its own right.

One of the very earliest recorded examples was written in 200 A.D. by Lucian of Samosata (in eastern Turkey), a writer of satire and a practitioner of rhetoric of Assyrian descent (it is thought). Among his works is a novel called *Vera Historia,* or *True Story,* that details a journey to the moon and the discovery of a multitude of life there. That lunar life includes three-headed vultures, birds made of grass with wings of leaves, humans sweating milk, and fleas the size of elephants.

Clearly, the story is far from "true," and Lucian didn't hide that this was fantasy. In fact, he was in part making a philosophical point about the impossibility of real truth and the fallacy of other thinkers for claiming to be arbiters of truth, including hallowed folk like Plato.

But the tale is one of the earliest known where detailed alien life is imagined. The beings of the moon are even at war with beings on the sun. Aliens, it seems, would be susceptible to our kinds of flaws. Interestingly, the possible existence of solar life was still doing the rounds in the late 1700s and early 1800s thanks to astronomer William Herschel. Except Herschel wasn't writing fantasy: he really suspected that there could be living things on the sun, on a hypothetical solid surface.

The moon has always been a good incubator for ideas about other life. The 10th-century Japanese narrative (or *monogatari*) of *The Tale of Princess Kaguya* has versions where the titular princess has been sent to Earth from the people of the moon during a celestial war. But this story has the aliens as human in form.

In fact, it's interesting to see that from the earliest days, including the ideas of the ancient Greeks on cosmic pluralism, people have tended to either assume extraterrestrial life would be like us or go for the full, bizarre alien treatment. Despite that split, more often than not there's been a bias toward human forms, all the way up through the 1700s and 1800s when writers like Voltaire in his *Micromégas* has aliens from Saturn who (despite being 6,000 feet tall) are basically human.

It wasn't really until Darwin's theory of evolution broke ground that anyone tried to imagine aliens as living things with lineages that related to the environments of their origins. Up to this point, anything nonhuman was, like Lucian of Samosata's funky beasts, more often than not arbitrarily fantastic.

One of the slightly more forward thinkers was French astronomer Camille Flammarion (although he was also a pretty far-out advocate of a blend of Christianity and pluralism in which souls passed from planet to planet). In 1864 he wrote a book called *Real and Imaginary Worlds* and in 1887 a fictional piece called *Lumen*. Between these he concocted aliens that, in many ways, had a basis in the scientific thinking of the time. There were sentient plants whose digestive and respiratory systems were combined. Mermaidlike creatures swimming in rose-colored oceans and humanlike beings with extra toes on the heels of their feet and a single, conical ear on top of their heads.

Altogether, the history of our ideas about alien life has many anecdotes and side alleys. But one of the most striking facts is that while we've been thinking about these things for a very long time, we've really struggled to combine our imaginative fantasies with "workable" biology without just turning to the defaults of what we know on Earth.

Evolution is an astonishingly inventive phenomenon. We might look at a planetary environment and propose what kinds of strategies life could adopt, but beyond basic function (using sunlight, for example, or exploiting reducing and oxidizing chemistry), guessing what tricks and quirks life is going to experiment with is supremely difficult.

In other words, any aliens we find, whether microscopic or 1,000 feet high, are probably going to appear very, very strange at first.

Abraham Loeb is chair of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the advisory board for the Breakthrough Starshot project.

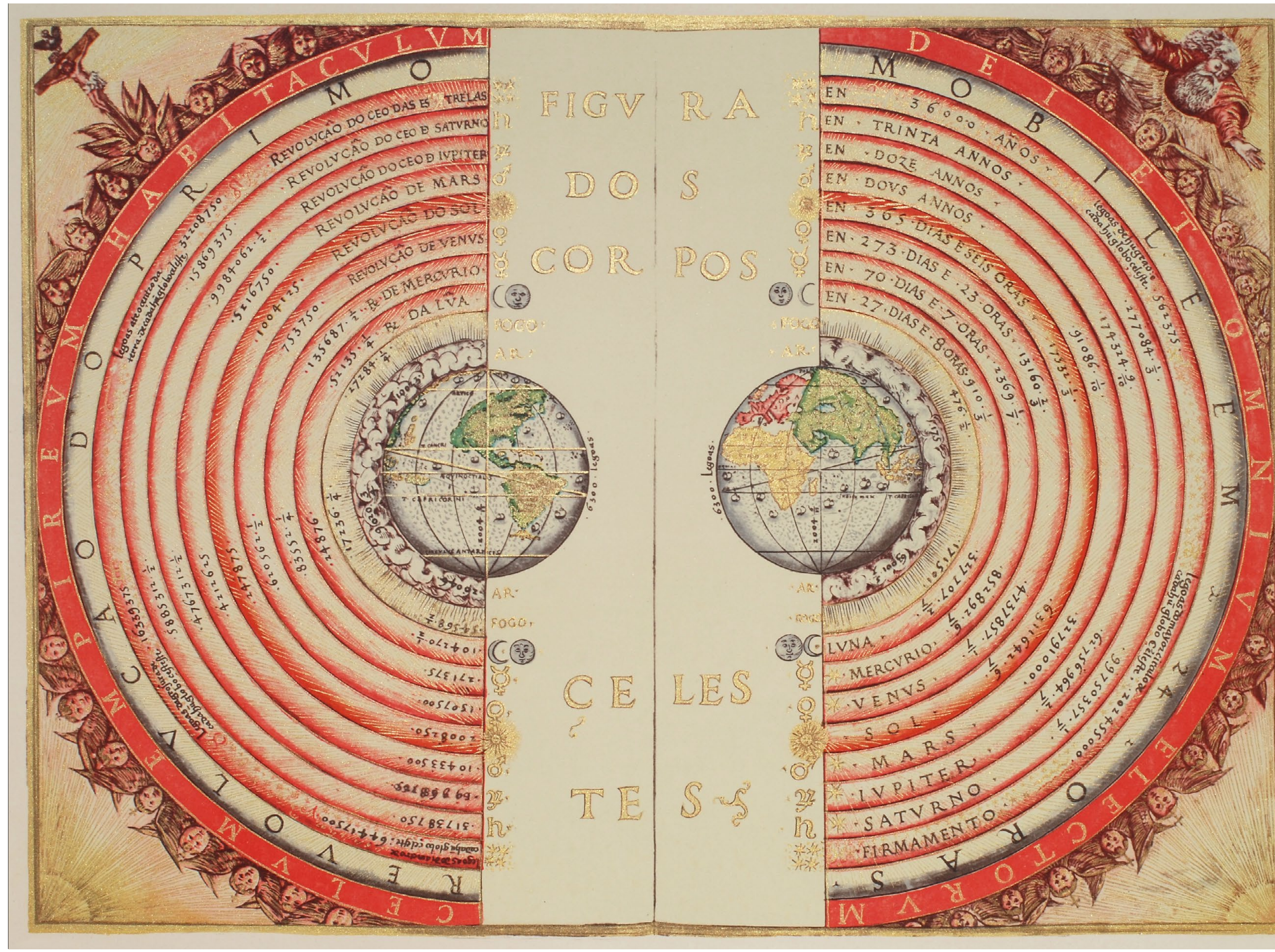
OBSERVATIONS

The Simple Truth about Physics

Theoretical models can be complex—but the most successful ones are usually not

At a recent group meeting, my postdoc raised a question: "Should we make our theoretical model more complex so that our explanation of the data will not appear too trivial?" I was surprised by this suggestion and felt obligated to explain why. "Simplicity is a virtue," I said, "not a deficiency. Excessive mathematical gymnastics is used to show off in branches of theoretical physics that have scarce experimental data. But as physicists, we should seek the simplest explanation for our data. This is the lifeblood of physics and the appropriate measure of success."

For decades, it was believed that our simple model of the early universe, characterized by a small number of parameters, was naive and the result of scarce data. By the beginning of the 21st century, we had collected enough to verify that the universe indeed started from the simplest possible initial state, being nearly homogeneous and isotropic with small fluctuations that developed into the complex structures we find in it



Ptolemy's model of the heavens was vastly more complicated than the Copernican system that supplanted it.

BARTOLOMEU VELHO *WIKIMEDIA*

today. This simple cosmological model, which has existed for a century, is the foundation for modern cosmology.

In today's fierce job market, fledgling scientists sometimes attempt to impress their senior colleagues with lengthy derivations marked by challenging mathematical complexity. Another postdoc told me recently: "The most fashionable trend for demonstrating exceptional skills in my research field involves writing extensive papers, sometimes hundreds of pages long or longer. I am facing the strategic dilemma of choosing between two options for my future career: Long complicated projects or short insightful papers?"

It is clear that accomplishing long projects requires more sweat, but is science supposed to be hard labor? Not necessarily. Our task as scientists is to explain phenomena based on the simplest theory whose predictions can be tested further by new experiments. And in the spirit of Occam's razor, if the answer is simple, why make it complicated?

Long-term, predictable projects may attract the attention of a funding agency by forecasting what they may find, but their legacy could be less influential than short reports of unexpected results. Long discussions are read by fewer readers, and so naturally their appreciation tends to be superficial. On the other end of the spectrum, an accessible short insight tends to stimulate follow-up work by the broad scientific community. The wider appeal of brief, intellectually rich reports improves job prospects, contrary to naive expectations.

The trendy attraction to complexity is shared by senior scientists who wish to make their work nuanced and less accessible to scrutiny. Although sophistication is often valued as a trademark of the elite, science is better served if its results are expressed in simple and transparent terms. When asked by reporters: "How do you manage to explain your research so clearly?" I often reply: "By describing only things that I understand and admitting what I do not know." Complexity is sometimes used as theatrical smoke and fog to obscure the unflattering image of ignorance.

"Just as a poet often has license from the rules of grammar and pronunciation, we should like to ask for 'physicists' license' from the rules of mathematics in order to express what we wish to say in as simple a manner as possible."

—Richard Feynman

Physicist Richard Feynman said: "Just as a poet often has license from the rules of grammar and pronunciation, we should like to ask for 'physicists' license' from the rules of mathematics in order to express what we wish to say in as simple a manner as possible." Indeed, the original Ph.D. thesis of Louis de Broglie, which established the wave-particle duality in quantum mechanics, was short and simple and earned him the Nobel Prize just five years later.

Simple insights can occur instantly, without hard labor, and lead to an exhilarating feeling that mathematician Henri Poincaré called "sudden illumination." When Julian Schwinger and Feynman suggested two different approaches to explain experimental data in the field of quantum electrodynamics, it appeared mathematically complicated to decide which one should be used until Freeman Dyson, then just 24, demonstrated elegantly that they were equivalent. Freeman had the simplifying insight on a Greyhound bus ride and afterward said: "It is impossible for me to judge whether the work is as great as I think it may be. All I know is, it is certainly the best thing I have done yet." He was rewarded with a permanent faculty appointment at the Institute for Advanced Study in Princeton, N.J., alongside Albert Einstein. Both Feynman and Schwinger shared the Nobel Prize thanks to this simplifying revelation.

Unwarranted complexity often requires the fine-tuning of parameters. The more fine-tuned a theory is, the less explanatory power it has relative to the simpler truth. A classic example is the mathematically sophisticated Ptolemaic theory of epicycles for describing the motion of planets, as compared to the simpler Newtonian alternative. The same reservation should apply when cosmologists reverse engineer flexible theories like cosmic inflation or the multiverse by introducing new free parameters to fit new data. This point was quantified in a recent paper that I wrote with Feraz Azhar, a philosophy postdoctoral fellow at Harvard's Black Hole Initiative, who just fulfilled his job-market aspirations by accepting a junior faculty position while formulating this idea.

Although simple insights appear trivial in retrospect, discovering them is a rare privilege. Complex arguments that are born after tedious labor can be regarded as fruits that are in plain sight but difficult to reach. Rare insights, on the other hand, are low-hanging fruits often hidden from view. These two options are the only ones left when all the visible low-hanging fruits are already picked up.

Celestial Movement

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

BRAD GOLDPAINT *GETTY IMAGES*

Astronomical Events
February 2020

Day • Event	
2	Moon: First quarter
3	Evening sky: Moon in the open star cluster Hyades, near Aldebaran in constellation Taurus
6	Moon reaches northernmost declination
9	Moon: Full moon
	Evening sky: Moon near Regulus in constellation Leo
10	Mercury greatest elongation east (18.2°)
	Moon at perigee (360,461 km), apparent diameter 33´ 08´´
15	Moon: Last quarter
18	Occultation of Mars by the moon
19	Dawn: Waning crescent moon right of Jupiter in constellation Sagittarius
	Moon reaches southernmost declination
20	Dawn: Waning crescent moon lower right of Saturn in constellation Sagittarius
23	Moon: New moon
26	Mercury in inferior conjunction
	Moon at apogee (406,278 km), apparent diameter 29´ 24´´

February—March 2020: Visibility of the planets

In February and most of March the order of the planets is reflected in the sky: the two interior planets Mercury and Venus are visible in the evening sky, while the superior planets Mars, Jupiter and Saturn rise in this order in the morning sky.

Mercury joins Venus in the evening sky in early February. The innermost planet of our solar system approaches the Venus from the west. This evening apparition favors observers in the northern hemisphere because for them the ecliptic presents a steep angle to the western horizon after sunset at this time of the year. Mercury reaches its greatest elongation east of 18.2° on February 10. On that day's evening sky, Mercury is as close to the sun as it is to Venus (23.5°). The best time to look at Mercury is between February 1 and February 15, about 40 minutes after sunset. Mercury is brightest during the first half of this period. After mid-February, the planet's light fades away in bright twilight. On February 26, Mercury is in inferior conjunction with the sun. The planet reappears in the morning sky around mid-March and reaches its greatest elongation west of 27.8° on March 24. The planet is very difficult to spot, however, because the angle of the ecliptic to the eastern horizon is small.

Venus is a bright object in the evening sky. As the planet moves in eastward direction from Aquarius through Pisces and Aries into Taurus during February and March, its elongation increases from 40° to 46°. Because of the steep inclination of the ecliptic, Venus remains visible for more than three hours every evening. On March 9, Venus passes 2.4° north of the faint planet Uranus. Both planets should fit into the field of view of binoculars, but because Venus is 10 magnitudes brighter than Uranus (corresponding to a difference in brightness of a factor of 10,000), its brilliance might hinder the detection of the fainter planet.

BRAD GOLDPAINT *GETTY IMAGES*

Astronomical Events
March 2020

Day • Event	
1	Evening sky: Moon between Hyades and Pleiades
2	Moon: First quarter
5	Moon reaches northernmost declination
7	Evening sky: Moon near Regulus in constellation Leo
8	Neptune in conjunction with sun
9	Moon: Full moon
10	Moon at perigee (357,122 km), apparent diameter 33´ 27´´
16	Moon: Last quarter
17	Moon reaches southernmost declination
18	Morning sky: Waning crescent moon below Jupiter and Mars
19	Dawn: Waning crescent moon lower left of Saturn in constellation Capricornus
20	Equinox
	Dawn: Mars 0.7° south of Jupiter
24	Mercury greatest elongation west (27.8°)
	Moon: New moon
	Moon at apogee (406,692 km), apparent diameter 29´ 22´´
	Venus greatest elongation east (46.1°)
28	Dusk: Moon near Venus in constellations Taurus/Aries
29	Evening sky: Moon near Aldebaran in constellation Taurus
31	Dawn: Mars 0.9° south of Saturn

February—March 2020: Visibility of the planets

In February and most of March the order of the planets is reflected in the sky: the two interior planets Mercury and Venus are visible in the evening sky, while the superior planets Mars, Jupiter and Saturn rise in this order in the morning sky.

Mars is visible as a reddish object in the southern part of the constellation Ophiuchus at the beginning of February. It appears above the eastern horizon about three hours before sunrise. Its westward elongation increases from 70° to 90° as it moves slowly through Sagittarius into Capricornus in late March. Initially Mars is the leading object in a row of three planets rising in the morning sky, followed by Jupiter and Saturn. Because of its faster motion in the sky, Mars passes Jupiter on March 20 and Saturn on March 31. Both close conjunctions make an impressive sight in the morning sky. On March 23, Mars also passes dwarf planet Pluto in a distance of less than one arc minute. But whereas Mars can be seen easily with unaided eyes, Pluto remains an object for large amateur telescopes (Pluto with an apparent visual magnitude of 14.4 is about as bright as Mars' moons Phobos and Deimos). Observers in North America can enjoy an occultation of Mars by the moon on February 18: the occultation starts around 04:45 Mountain Standard Time (MST), when the illuminated eastern limb of the waning crescent moon blocks the light of Mars and ends around 06:06 MST, when Mars suddenly reappears on the dark western limb of the moon.

Jupiter is moving slowly eastward in constellation Sagittarius. It can be seen low in the eastern predawn morning sky. Its visibility improves as its elongation increases from 28° to 77° between February 1 and March 31.

Saturn is in the eastern part of constellation Sagittarius and crosses the border to Capricornus on March 21. Having been in conjunction with the sun on January 13, the planet now starts its morning apparition.

BRAD GOLDPAINT *GETTY IMAGES*

SKY REPORT

February

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.

−1 0 1 2 3 4 5

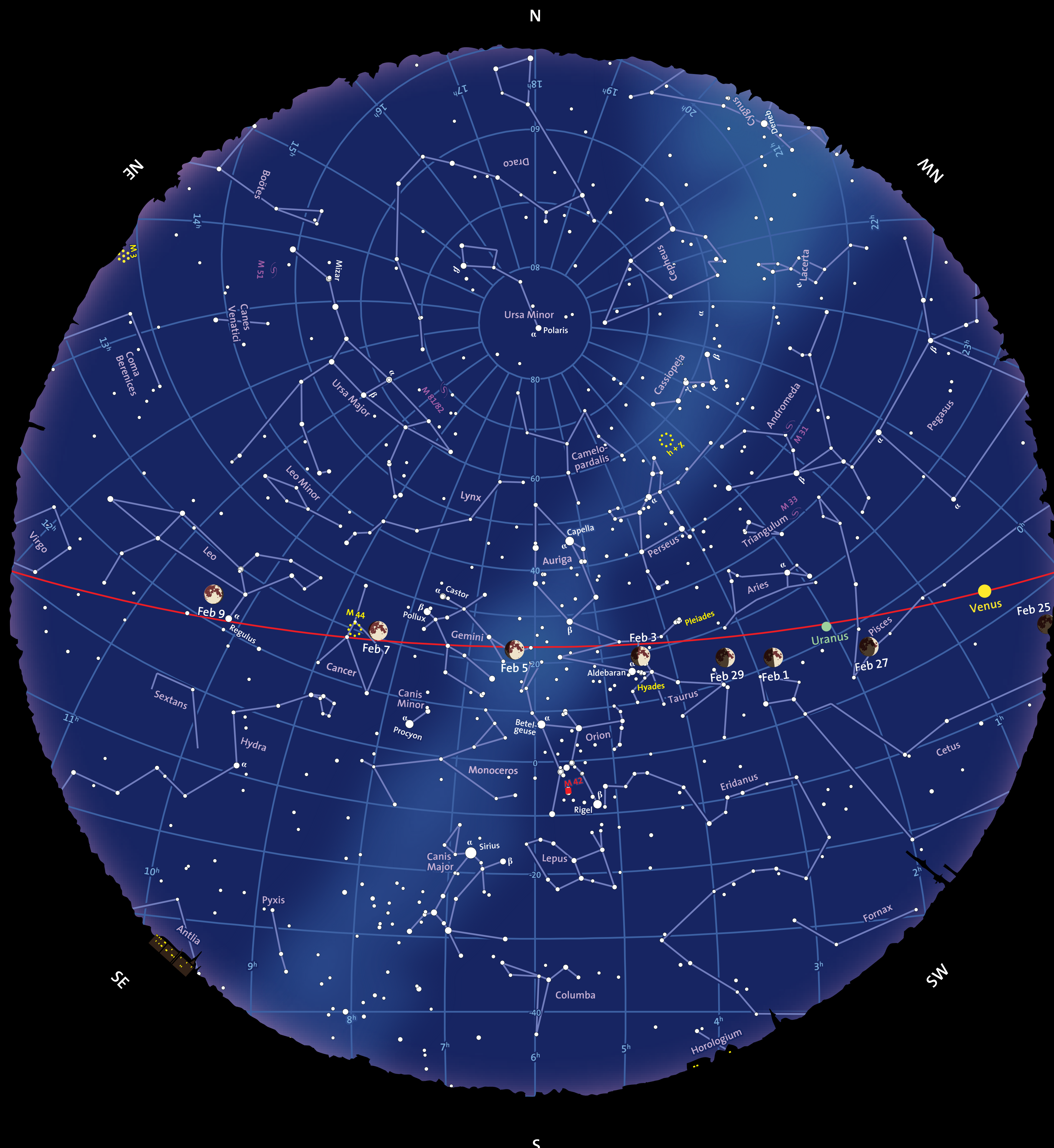
Apparent magnitudes

Open cluster

Globular cluster

Galaxy

Nebula



ERNST VON VOIGT

March

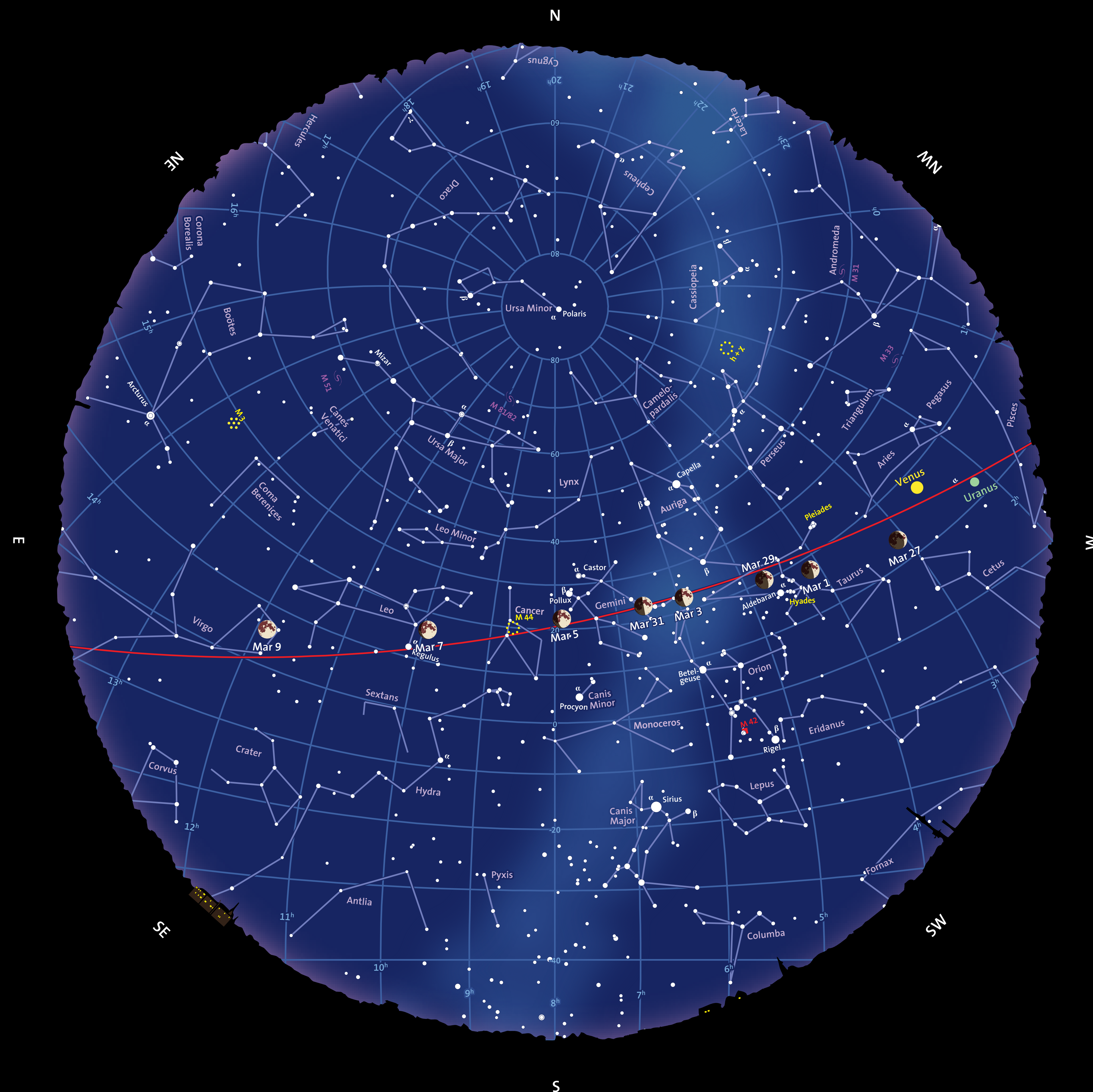
Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects 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.

−1	0	1	2	3	4	5

Apparent magnitudes

- Open cluster
- Globular cluster
- Galaxy
- Nebula



ERNST VON VOIGT

SCIENTIFIC AMERICAN Space & Physics

LETTERS TO THE EDITOR:
Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562, 212-451-8200 or editors@sciam.com.
Letters may be edited for length and clarity. We regret that we cannot answer each one.

HOW TO CONTACT US:
For Advertising Inquiries: Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562, 212-451-8893, fax: 212-754-1138 For Subscription Inquiries: U.S. and Canada: 888-262-5144, Outside North America: Scientific American, PO Box 5715, Harlan IA 51593, 515-248-7684, www.ScientificAmerican.com

For Permission to Copy or Reuse Material From Scientific American: Permissions Department, Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562, 212-451-8546, www.ScientificAmerican.com/permissions. Please allow three to six weeks for processing.